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DEFORMATION PROCESSING OF STAINLESS STEEL

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ABSTRACT

This report covers the state of the art of both primary and secondary fabrication methods for stainless steel. Methods currently employed for primary fabrication of these alloys include: rolling, extrusion, forging, and drawing of tube, rod, and wire.

Secondary metalworking operations are those processes that produce finished or semifinished parts of sheet, bar, or tubing using additional metalforming operations, The following secondary forming processes are discussed: brake bending, deep drawing, spinning, shear forming, drop hammer, trapped rubber, stretch forming, roll forming, dimpling, joggling, and sizing. Equipment and tooling used for the various operations are discussed and illustrated wherever possible.

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PREFACE

This report is one of series of state-of-the-art reports being prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract No. DA-01-021-AMC-11651(Z) in the general field of materials fabrication.

This report on practices used to deform the stainless steels into useful shapes is intended to provide information that may be of use to designers and fabricators. Recommendations are considered to be reliable guides for selecting conditions, tools, and equipment for specific operations and the causes for many of the problems encountered are identified and precautions for avoiding them are mentioned.

The report summarizes information collected from equipment manufacturers, technical publications, reports on government contracts, and by interviews with engineers employed by major stainless steel fabrication companies in the United States. A total of 134 references are included, most of which cover the period since 1960.

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DEFORMATION PROCESSING OF STAINLESS STEEL

SUMMARY

This report is a summation of current information available on deformation processing of stainless steels.

Reports of experience in forming stainless steel from various Government and industrial sources have been compiled and summarized to offer assistance and guidance in performing many of the deformation processes. More detailed information on many of the processes is available by consulting the extensive reference list.

Stainless steels find wide use in applications requiring high strength and good corrosion resistance at room temperature. The superior corrosion resistance of the stainless steels compared with carbon steels has made them very attractive in such applications as automobile trim and curtain wall panels where the surface of the material is exposed to the atmosphere for long periods of time. They are also used in applications requiring oxidation resistance at elevated temperatures. Aircraft skins made of stainless steel are used around hot areas of aircraft.

Stainless steel, sheet, strip, and plate are produced by rolling stainless steel. Wire, rod, and tubing are made by drawing. Both tubing and structural shapes have been produced by hot extrusion process and special shapes are made by forging. Sometimes the extruded shapes, such as tees and angles, are cold drawn to improve'tolerances and to achieve thinner webs. Stainless steel tubing is extensively used for piping in the petroleum and food processing industries as well as for hydraulic equipment and de-icing systems in aircraft.

Stainless steel rod and wire are used for fasteners and sometimes springs where corrosion or oxidation resistance is important.

Stainless steels are formed by secondary deformation methods at room temperature. Brake bending, deep drawing, spinning, and other sheet metal forming processes are used in the manufacture of stainless steel parts throughout the metalworking industry,

INTRODUCTION

The commercial stainless steels have been used extensively in the manufacture of parts resistant to atmospheric corrosion or chemical corrosion. The corrosion resistance of these alloys results in minimum maintenance of structures fabricated from them. In applications at slightly elevated temperatures, up to 600 F, stainless steels retain a significant fraction of their room-temperature strength. Consequently, they have been used for skins in high-speed aircraft.

All of the commercial stainless steels are iron-base alloys that develop their properties either through cold work, as with the austenitic and ferritic types, or through heat treatment as with the martensitic types. They may be grouped according to the final structure of the material as either austenitic, ferritic, or martensitic grades. In the annealed condition, the materials may be cold worked at room temperature. The austenitic types workharden very rapidly, however, and may require frequent intermediate anneals for severe forming. Working at elevated temperatures is generally not desirable due to the high cost of this operation. The hot-working temperatures are generally above the mill-anneal temperature for the stainless steels. Dimensional stability of most stainless steels during thermal cycling is comparable to commercial steels at room temperature, consequently no special thermal processes are required as with the precipitation hardenable stainless steels to assure dimensional control on large parts.

The purpose of this report is to summarize the present status of primary and secondary deformation processes for commercial stainless steels. Primary deformation processes are designed to reduce an ingot or billet to a standard mill product such as sheet, plate, bar, forging, extruded shapes or drawn rod, tube, or wire. Secondary deformation processes produce semi-finished or finished parts by additional forming operations on such primary shapes as sheet, bar, or tubing. Deep drawing, spinning, brake bending, etc., are typical secondary deformation processes.

All of the stainless steels have much higher tensile strengths in the annealed condition than carbon steels with the same carbon contents. They are work hardened by cold deformation processes to various degrees, some at a greater rate than carbon steels. The thermal conductivity of these materials is considerably lower than that of carbon steels, by as much as one-third; so is the electrical conductivity. The coefficient of thermal expansion is considerably higher. Most of the stainless steels have very good corrosion resistance provided the surface of the material has been properly cleaned and no iron from forming tools is left on the surface. The stainless steels with high chromium contents have good resistance to oxidation at elevated temperatures.

Stainless steels may be grouped by their metallurgical structure into ferritic, austenitic, and martensitic types. The ferritic and martensitic types are magnetic while the austenitic steels are not. Some of the austenitic types, upon cold working or being cooled to sub-zero temperatures, can transform partially to a martensitic or ferritic structure which makes them slightly magnetic.

Since most of the stainless steels (ferritic and austenitic) develop their mechanical properties after cold work a considerable range of yield and tensile strengths is obtainable. Temper designations normally given to the work hardening grades of stainless steel are annealed, 1/4-hard, 1/2-hard, 3/4-hard, and full hard. These temper designations correspond to tensile strengths of 75,000, 125,000, 150,000, 175,000, and 185,000 psi, respectively, in a widely-accepted military specification, MIL-S-5059.

The martensitic-type alloys can develop higher strengths through heat treatment.

The compositions and properties of typical stainless steels are available in the literature (Ref. 1). The general characteristics of the different types of stainless steel are given in the following sections.

AUSTENITIC STAINLESS STEELS (TYPE 200 & 300) (Ref. 2)

The austenitic stainless steels differ in metallurgical behavior from carbon steel. They are normally nonmagnetic, highly susceptible to work hardening and usually resistant to corrosion and oxidation. They also retain their strength over a wide temperature range. The high-yield strength due to the alloy additions requires greater power to form these alloys than is required for carbon steels. The yield strength for various annealed austenitic stainless steels are in the range of 30,000 to 40,000 psi.

The good ductility of stainless steel results from the austenitic structure. The face-centered-cubic structure of austenite is typical of very ductile metals such as gold, copper, nickel, and aluminum. As would be expected, the austenitic stainless steels are generally quite ductile, withstanding tensile elongations up to 50 percent.

Additions of chromium without nickel to iron will not maintain the austenite structure. The presence of nickel, which is a strong austenite stabilizer, causes the 18-8 grades of stainless steel to be austenitic at room temperature. In Type 200 stainless steels, some of the nickel is replaced by manganese which is also a austenite stabilizer. The replacement of nickel by manganese reduces the cost of stainless steel at the sacrifice of some resistance to corrosion under certain conditions.

Cold working of the austenitic stainless steels will cause some gradual transformation of the structure to ferrite which is magnetic. This tendency decreases as the nickel content increases. The original austenitic structure and mechanical properties can be restored by proper annealing treatments.

The presence of precipitated carbides in stainless steel reduces their resistance to corrosion, particularly to intergranular attack. The corrosion resistance is impaired bacause the formation of chromium carbide is accompanied by a depletion of chromium in adjacent regions. This undesirable condition can be avoided by suitable heat treatments.

The alloys should be heated to a temperature high enough to dissolve all of the carbon and then cooled rapidly to room temperature.

FERRITIC STAINLESS STEELS (TYPE 400) (Ref. 2)

There has been a strong trend toward the use of ferritic stainless steels in recent years because they offer a slight price advantage. The total alloy content of these steels is substantially less than equivalent austenitic stainless steels but they can be used when certain qualities of the latter grades are not essential. The ferritic stainless steels, which contain about 17 percent chromium and no nickel, form a thin adherent scale at temperatures as high as 1550 F and resist further oxidation. This characteristic permits these grades to be used in applications involving intermittent heating. Care should be exercised in forming material that has been heated intermittently because the ductility is impaired when the metal is cooled after being heated at a temperature of about 900 F for long periods. To restore ductility, the material should be given an annealing treatment at a temperature between 1100 F and 1400 F.

The corrosion resistance of ferritic steels is more limited than that of the austenitic stainless steels but they are resistant to a wide range of reagents. The resistance is improved if the surface of the material is properly polished and cleaned. The ferritic stainless steels resist normal atmospheric conditions when dirt is not permitted to accumulate on the material surface. Ferritic stainless steels are generally lower cost than the austenitic grades since they do not contain as much alloy addition. They are widely used for auto trim and kitchen sinks. No aerospace applications were found.

The ductility of ferritic stainless steels at room temperature is less than the austenitic stainless steels. Most forming operations require more power and die clearance and better lubrication than is required for carbon steels. The material can be formed to difficult shapes by using intermediate annealing and pickling treatments between forming stages.

Some of the ferritic stainless steels have chromium contents up to 27 percent which permits them to be used at high temperatures ranging from 1500–2100 F. Most of the higher chromium alloys, however, are low in ductility and are very difficult to form, with yield strengths of 35,000 to 50,000 **psi.**

The ferritic– stainless steels are nonheatreatable and develop their strength through cold working. They do not work harden as rapidly, however, as the austenitic grades.

MARTENSITIC STAINLESS STEELS (TYPE 400) (Ref. 3)

The martensitic stainless steels are similar in composition to the ferritic stainless steels except that they contain more carbon and can be hardened by heat treatment. Within the martensitic stainless steel grades, there are three classes:

L The materials which contain chromium up to 14 percent and carbon up to 0.15 percent can be hardened and tempered to a wide range of mechanical properties without appreciably impairing their corrosion resistance.

2. Those that have carbon contents above 0.15 percent have poorer corrosion resistance when tempered and are usually used in the hardened and stress relieved condition.

3. The materials with both higher chromium and carbon contents can be hardened to high hardnesses. They have good corrosion resistance in the hardened and stress relieved condition but not so good when tempered.

The martensitic stainless steels are magnetic in the hardened condition. The heat treatments differ slightly from those used for low alloy steel in that higher austenitizing temperatures are required for maximum oxidation resistance. These materials are generally deep hardening. They are inclined to be sluggish in their transformation reactions so must be held at temperatures for longer periods of time. They also have low rates of thermal conductivity. They are generally hardened at higher temperatures than low-alloy steels and a protective atmosphere is desirable. Typical heat treatment procedures are given in Table I. The range of tempering temperatures produces a wide range of mechanical properties for the martensitic stainless steels.

In the annealed condition the martensitic stainless steels are less ductile than the austenitic stainless steels. They require more power to form than the carbon steels because of their higher yield strengths which vary widely from 30,000 to 90,000 psi according to composition. Preheating the blanks to 200 F is sometimes helpful in forming operations.

TABLE I. HEAT TREATMENTS FOR MARTENSITIC STAINLESS STEELS (REF. 3)

Alloy Type AISI	Hardening Temperature of	Quench Medium	Temper Temperature of	Tensile Properties: Tensile Strength, 1000 psi	Yield Strength, 1000 psi	Elongation in 2 inche percent
403	1700–1850	---	400–1300	120–200	105–150	15–20
410	1700–1850	Oil/Air	over 1100	60–200	35–180	25–2
414	1800–1900	---	400–1300	120–200	105–150	15–20
416	1700–1850	---	400–1400	90–190	60–145	12–25
420	1800–1900	---	300–700	230	195	8
431	1750–1800	Oil/Air	over 1100	105–220	90–185	25–10
440 A	1850–1900	Oil/Air	over 1100	95–275	55–240	20–2
440 B	1850–1950	---	330–800	280	270	3
440 C	1850–1950	---	300–800	285	275	2
501	1600–1700	---	400–1400	115–175	90–135	15–20

PRIMARY DEFORMATION PROCESSES

This section of the report describes the essentials of fabrication procedures for rolling, extrusion, forging and drawing of stainless steels. For this report, these processes are considered as primary deformation processes although some of the products are essentially finished articles. Table 11 lists the mill-products available in some typical stainless steel compositions,

The mill practices for the 200, 300, and non-hardening 400 type stainless grades are quite similar. The hardenable varieties of the 400 type requires slower heating and cooling rates and more cautious conditioning practices to avoid cracking.

Almost 900,000 tons of stainless steel products were made in 1965 of which 69 percent was flat-rolled products like sheet, strip and plate. Eighteen percent was contour-rolled products like bars, rods and structural shapes. Products drawn from extruded or rolled bar, like wire and tubing, accounted for another 7 percent. The remaining stainless tonnage was accounted for by forgings, slabs, and billet (Ref, 4).

According to Market Research (Service of the International Nickel Company) (Ref. 5), the leading applications for stainless steel in 1965 were steel industry construction and metal stampings. This source gives about 100 other outlets for stainless steels.

TABLE II. PARTIAL LISTING OF AVAILABLE MILL FORMS OF STAINLESS STEELS

Alloy Type, AISI	Sheet	Strip	Plate	Bars and Rods	Rolled Structural Shapes	Extrusions	Forging Billets	Pipe and Tubing	Wire
201	B	B	B	B	C	C	C	C	B
202	B	B	B	B	C	C	B	B	3
301	A	A	B	a	C	C	B	C	3
302	A	A	A	B	C	C	B	B	B
303	C	C	B	A	C	C	B	C	B
304	A	A	A	A	B	A	A	A	A
305	B	B	B	C	C	C	B	B	B
309	A	A	A	B	C	C	C	B	B
310	A	A	A	A	C	C	B	B	B
314	C	C	C	B	C	C	B	C	B
316	A	A	A	A	B	A	A	A	B
317	B	B	B	B	C	C	B	3	B
321	A	A	A	A	C	C	A	A	B
347	A	A	A	A	C	C	B	A	B
403	B	B	B	B	B	C	A	C	B
405	B	B	B	B	B	C	B	C	B
410	A	A	A	A	B	C	B	A	B
414	C	C	C	B	C	C	B	C	B
416	C	C	B	B	C	C	B	C	B
420	C	C	C	A	C	C	B	C	B
430	B	B	B	A	C	C	B	C	B
431	B	C	C	A	C	C	B	C	B
440 A	B	B	B	A	C	C	a	C	B
442	B	B	B	B	C	C	B	C	B
446	B	B	B	B	C	C	B	C	B

CODE

A Available generally from major distributors.

B' Available generally on a mill-order basis.

C Specialty item, not normally stocked.

While most constructional shapes like I-beams, channels and angles are rolled from carbon and low-alloy steels, these shapes are usually extruded from stainless steels. This is because the quantities of such stainless products are not large enough to justify a rolling setup.

ROLLING

The 22 companies in the United States actively rolling flat products employ a total of roughly 150 rolling mills, about 100 of which are used for cold finishing of steel strip. Production rolling mills vary in width from about 2-feet to 14-feet, most being about 60 to 80-inches wide. Stainless steels are generally rolled to widths of 48" or less for most sheet applications although wider stainless strips are rolled when needed.

To produce flat products, heated ingots are first rolled in a slabbing mill or forged on presses to large rectangular slabs which are then cropped and conditioned. Then the slabs a-e reheated and rolled in multiple passes to the desired size. Initial rolling is usually done hot. After annealing, the strip is cold rolled to provide a smooth surface and re-annealed to provide the necessary corrosion resistance and for formability.

The rolling practices for bar stock differ in that the ingot is rolled on the primary mill to a bloom having a square cross section. This bloom is conditioned extensively by grinding to remove seams. and other defects, then reheated for rolling in the secondary mill to final size. The secondary mill for bar consists of rolls having several matched circumferential grooves which shape the bar to either a round or square in sucessive hot-rolling passes. (In some mills these are called "closed-pass" rolls.) After rolling, the bars are annealed, straightened, pickled, conditioned, and inspected. The sequences of rolling strip and bars of stainless steel are given in the flow chart shown in Figure 1.

Unlike the carbon steels, the stainless grades scale very little during heating for rolling. Consequently, surface defects originating in the ingot or from handling do not burn off during processing but must be removed by extensive grinding. The slight differences in rolling-mill practices for austenitic and martensitic grades are related to the need for preventing excessive hardening in the latter group, which can lead to cracking especially during conditioning.

Rolling Equipment. Detailed information on the design and operation of steel-mill rolling equipment is available elsewhere (Ref. 6); therefore, only a brief discussion of equipment and rolling nomenclature is provided here as a background for the process descriptions provided in the report.

Reversing two-high and three-high mills are commonly used for breakdown and semifinishing operations in the fabrication of both flat products and shapes. Single-stand two-high mills are reversible so that the workpiece can be deformed while traveling in either direction.

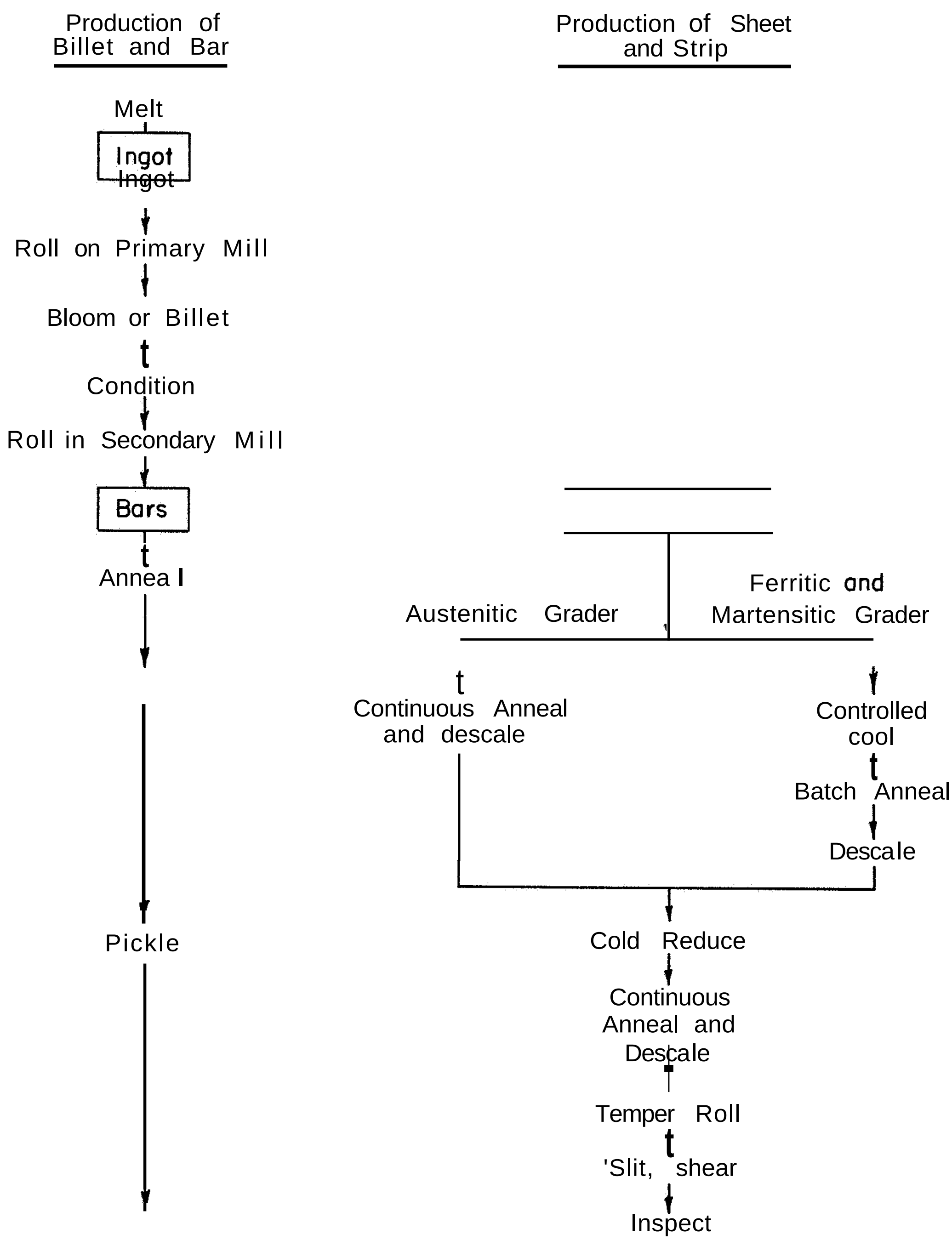


FIGURE 1. FLOW SHEET INDICATING PRINCIPLE STEPS IN PRODUCTION OF STAINLESS STEEL PRODUCTS (Ref. 6)

Heavy pieces and long lengths can be handled conveniently on this type mill for fabrication of slabs, blooms, plates, billets, rounds, and partially formed sections. A three-high mill does not require any drive reversal as the direction of rolling depends upon whether the piece is traveling above or below the center roll. This type of mill is generally used for products other than plate or sheet.

For rolling of narrow material where thickness control is not too critical, two-high and three-high rolling mills are adequate. For rolling of wide material, four-high mills are used to achieve better roll rigidity and closer thickness control. Four-high mills are used for producing both hot- and cold-rolled plate and sheet. Several of these mills are used in tandem for continuous rolling of sheet.

Cluster mills are used for rolling very thin sheet or strip where very close thickness control must be maintained. The most popular cold finishing cluster mills are of the Sendzimir Type which give maximum roll support during the finishing of sheets up to 50-inches wide. The third tier of rolls is backed up with heavy segmented bearings to improve control of shape. The operator can apply greater pressure at the Center of the roll to correct for deflections which would result in thicker centers.

Because the stainless steels are substantially stronger and develop higher contact pressures than mild steels, the Sendzimir type of cluster mill is preferred for cold finishing. The largest known Sendzimir mill (Ref. 7) is located in France and is capable of rolling strip up to 80-inches wide. There are over 200 Sendzimir mills in the Free World.

The planetary hot mill recently developed by Sendzimir permits rolling of heavy slab to thin strip in only one pass. There are fewer than twenty planetary mills in the Free World of which four are known to have a capability for rolling strip wider than 30-inches. The largest known mill of this kind was installed recently at Atlas steel Limited of Canada where it is being integrated with their continuous casting facility. The facility is being used for rolling both carbon and austenitic stainless steels.

Figure 2 illustrates the essentials of a planetary mill layout comprised of a continuous furnace, feed rolls, the planetary mill and subsequent tensioning, planishing, and coiling facilities.

The rolling operation is illustrated Figure 3 which shows how two large drive rolls are surrounded by smaller work rolls which revolve around them. The smaller rolls are supported by a ring cage which rotates aroung the back-up rolls. The slab is forced between these work rolls by feed rolls which reduce the plate thickness only enough to provide the necessary feeding force. The plate enters the mill slowly at roughly 6 to 9 fpm but the exit speed often reaches 120 fpm or more because of the large reductions being accomplished. The most significant advantage of this mill design is that only one pass and mill is necessary to roll strip that otherwise would require several conventional rolling stands in sequence. A dissadvantage is the entire rolling capability is out of operation in the event of break-down. In all probability these mills will always be used to complement the multiple-stand facilities rather than replace them entirely.

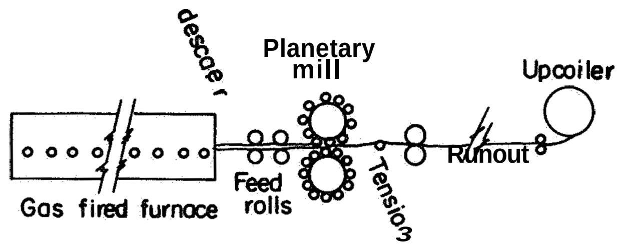


FIGURE 2. SCHEMATIC OF PLANETARY MILL LAYOUT (Ref. 9)

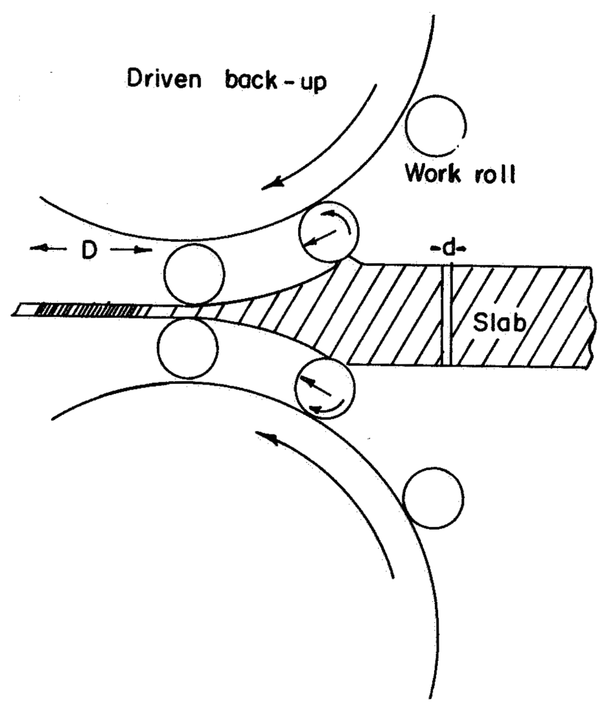


FIGURE 3. SCHEMATIC SHOWING PLANETARY ROLLING OPERATION (Ref. 9)

According to a recent article (Ref. 8) the plasticity or workability of stainless steel must be good to permit rolling on a planetary mill. For example, small amounts of impurities like lead or selenium can cause pronounced edge cracking. An increase of from 0.001 percent to 0.003 percent lead resulted in serious edge cracking of 301 stainless. Lead contents above 0.005 Pb caused catastrophic cracking while below 0.001 Pb the sheets were virtually free of significant edge cracks. In conventional rolling, small amounts of such impurities are hardly noticed.

On the basis of data generated in rolling of over 1000 coils of type 301 and 304 stainless steel strip, the following conclusions were reached by representatives of Atlas:

(a) The surface quality and mechanical properties of strip produced by continuous casting and planetary-mill rolling are comparable to those of conventional strip.

(b) The mode of deformation, however, imposes greater demands for good hot workability.

(c) The significant difference between this and conventionally rolled sheet is that a "re-entrant V" or fish-mouth forms at the edge of the strip. This, in turn, is partly responsible for the increased sensitivity to develop edge cracks.

Rolling Practices for Stainless Steel. It is worth listing how the practices for rolling stainless steel differ from those for constructional steel.

(1) Heating should be done in low-sulfur atmospheres to prevent sulfur contamination and subsequent surface rupturing. Initial rolling is usually done at temperatures between 2000 F and 2250 F finishing off at above 1550 F.

(2) Rolling forces are on the order of 25 to 50 percent higher than for mild steels. This means smaller reductions must be taken on any particular mill.

(3) Close temperature control is essential to control grain size.

(4) Since the stainless steels do not scale as much during heating, they must be conditioned much more thoroughly than the mild steels. The latter are "self cleaning" by virtue of the scaling action.

(5) Descaling of hot-rolled stainless strip is usually done either in molten salt (Na OH + Hydride) or in successive etching operations in heated sulfuric acid and nitric acid.

(6) Light gages of strip are generally cold rolled in tandem mills to achieve the best gage control. There are times when austenitic stainless strip is furnished as "cold-rolled" to provide increased strength at the expense of some corrosion resistance.

(7) Stainless strip is often "bright annealed" to a high luster in a hydrogen atmosphere furnace. This provides the highest polish next to buffing (Ref. 10).

(8) Rod sizes at about 5/16-inch diameter are rolled as starting material for wire drawing. This rod is generally coiled.

Stainless bar is hot rolled in sizes up to 4-inches square. Billets of 4-inches square up to 6-inches are generally closed-pass rolled. Larger billets are usually rolled in billet mills having **either open or semi-closed passes (rolls with shallow, stepped grooves).**

Sizes and Tolerances of **Rolled** Products. The classification as "sheet", "strip", "foil", or "plate" depends on the relationship between width and thickness of the products. The distinctions can be generally defined as follows:

Product	Dimensions. inches: Width	Thickness
Plate	Greater than 10	Greater than 0.1875
Sheet	Greater than 24	Less than 0.1875
Strip	Less than 24	Less than 0.1875
Foil	Less than 24	Less than 0.005
Bar	3-15/16 and smaller	--
Billet	4 and larger	--

Plate. Stainless steel plate is generally not stocked by the mills. The normal practice is to take an order and roll available slabs to the desired dimensions. AISI tolerances generally apply. Some **of** the industrial capabilities **for** rolling wide plate are;

190-inch widths at Lukens Steel Company

180-inch widths at United States Steel Corporation

210-inch widths, soon to be installed at United States Steel

Sheet and Strip. The availability of stainless steel sheet and strip at various mills differs depending on rolling equipment and/or preheating equipment. Table 111 gives an example of the way a mill lists stock materials of differing dimensions and surface finish. A complete specification listing is available in the Steel Product Manual "Stainless and Heat Resisting Steels" published by the American Iron and Steel Institute (Ref. 11).

Sheets wider than 48-inches are generally not stock items but are sold individually on a "mill-order" basis. The widest stainless steel sheet produced to date is about 125-inches by 240-mil long. This was "sandwich" rolled on a plate mill by United States Steel Corporation for an Air Force sponsored research program. (Ref. 12) The "sandwich" rolling process involves the construction of a multiple layer assembly of stainless steel plates, sandwiched between outer plates of carbon steel and welded at the edges to hold the plates together. The composite is rolled in a plate mill to a predetermined thickness, the edges are sheared and the layers are again separated to form three or four thin stainless sheets of roughly the same gage. Although the practice is expensive, it is less costly than developing a huge sheet mill that would otherwise be necessary to roll such wide sheets. The comparatively small demand for such large sheets does not justify the alternatives.

TABLE III. TYPICAL SIZES OF STAINLESS SHEET AND STRIP GENERALLY AVAILABLE ON STOCK ITEMS

	Size and Thickness, in.	Metallurgical Conditions	Surface Finishes
Flat, Cut lengths, SHEET	0.10 to 0.156 thick 24 to 48 wide up to 164 long	1. Annealed 2. Special anneal 3. Cold rolled to designated temper	No. 2D Dull, smooth, cold rolled finish (for deep drawing) No. 2B Bright, smooth cold rolled finish (for moderate drawing) Lusterglow* Special rolled finish moderatly reflective
Coils, SHEET	0.010 to 0.187 thick 24 to 48 " wide		No. 3 Polish– Coarser than 4. No. 4 Polish– Polish with 120-150 mesh grit. No. 6 Polish— Tampico–brushed finish. No. 7 Polish— High luster, buffed
Flat, cut lengths, STRIP	0.010 to 0.156 thick 1/4 to 23 15/16 wide up to 192 long	1. Annealed 2. Special anneal 3. Cold rolled to designated temper	No. 1 Dull, smooth, cold–rolled similar to 2D in sheets. No. 2 Bright, smooth, cold–rolled similar to No. 2B in sheet Lusterglow* Special rolled finish was moderatly reflective Bright annealed— Bright, highly reflective finish. Note: Buff or grit polishes not available in strip or sheet in coil form.

* Lusterglow– Armco designation

Data courtesy of Armco Steel Corporation

Foil. Stainless steel foil is a flat-rolled product of less than 0.005-inch thick, coiled, and under 24-inches wide. Most of the 200 and 300 type stainless steels and ferritic 400 grades (430, 442) are rolled to foil. Stainless steel foils represent a rather new product so each mill offers a specialized range of tolerances and surface finishes. Generally, a thickness tolerance of ± 5 percent is considered practical.

Rolled Billet, Bar, and Rod. Generally semifinished hot-rolled squares larger than 4 x 4 or rectangles larger than 16 square inches in cross-sectional area are called billets or slabs and are generally used for subsequent hot working operations such as forging, extruding, or rolling. Tolerances for billet are generally agreed upon mutually between mill and customer.

Bars hot rolled in closed-pass mills are generally more uniform and precise than products of billet mills. Some of the larger steel manufacturers are installing bar mills capable of rolling squares, and round-cornered squares, up to 8 inches; and rounds up to 6 inches. Examples of AISI standards for some hot-rolled and cold-rolled bars are given in Table IV. As indicated, bar standards are available for sizes of 1/2 inch to 4 inches. A complete list of specifications is given in the reference. (Ref. 11)

TABLE IV. TYPICAL DIMENSIONAL TOLERANCES FOR HOT AND COLD ROLLED BARS (Ref. 11)

Specified Size Inch	Size Tolerances, Inch: Hot Rolled Rounds and Squares (+)	Hot Rolled Rounds and Squares (-)	Rounds (+)	Rounds (-)	Squares (+)	Squares (-)
er 5/16 to 7/16 inclusive	006	006	.002	002	0	.004
" 7/16 to 5/8 "	.007	.007	002	002	0	004
" 5/8 to 7/8 "	.008	.008	002	002	0	004
" 7/8 to 1 "	.009	.009	.002	.002	0	.004
' 1 to 1-1/8 '	010	010	0025	.0025	0	.00[illegible]
" 1-1/8 to 1-1/4 "	.011	.011	.0025	.0025	0	.006
" 1-1/4 to 1-1/2 "	.014	.014	0025	0025	0	.006
" 1-1/2 to 2 "	1/64	1/64	003	003	0	008
" 2 to 2-1/2 "	1/32	0	003	003	0	.008
" 2-1/2 to 3-1/3 "	3/64	0	.003	.003	Over 3-inches 0	.010
" 3-1/2 to 4-1/2 "	1/16	0	to 4" .003	.003		
" 4-1/2 to 5-1/2 "	5/64	0				
" 5-1/2 to 6-1/2 "	1/8	0				
" 6-1/2 to 8 "	5/32	0				

* These tolerances double if the cold-finished bar is subsequently heat treated

Rolled Structurals. Channels, angles, and tees are furnished as hot-rolled products in leg sizes up to 6-inches. Demand for such shapes is generally insufficient to permit stocking of only a few sizes. In many cases, it is more economical to extrude them. Some typical dimensional tolerances for rolled shapes are given below:

Angles with legs up to 6-inches- ± 1/8-inch on leg length

Channels: up to 1-1/2-inch- ± 3/32-inch for channel depth and flange width.

1-1/2-inch to 3-inches - ± 3/32-inch for channel depth and flange width.

Tees: up to 1-1/2-inch to 1-1/2-inch - ± 5/64 for width and for flange depth

1-1/2-inch to 2-inches- ± 3/32 for width and for flange depth

2-inches to 3-inches- ± 9/64 for width and for flange depth.

Size limitations on specialty precision-rolled shapes of these and airfoil shapes are illustrated in Figure 4. These dimensional tolerances given are substantially closer than those specified by AISI but the products cost more to produce (Ref. 13). This precision-rolling process is said to offer better surface quality than either conventional rolling or extruding practices; and substantial weight savings are possible. The last point is increasingly attractive for the more expensive stainless grades.

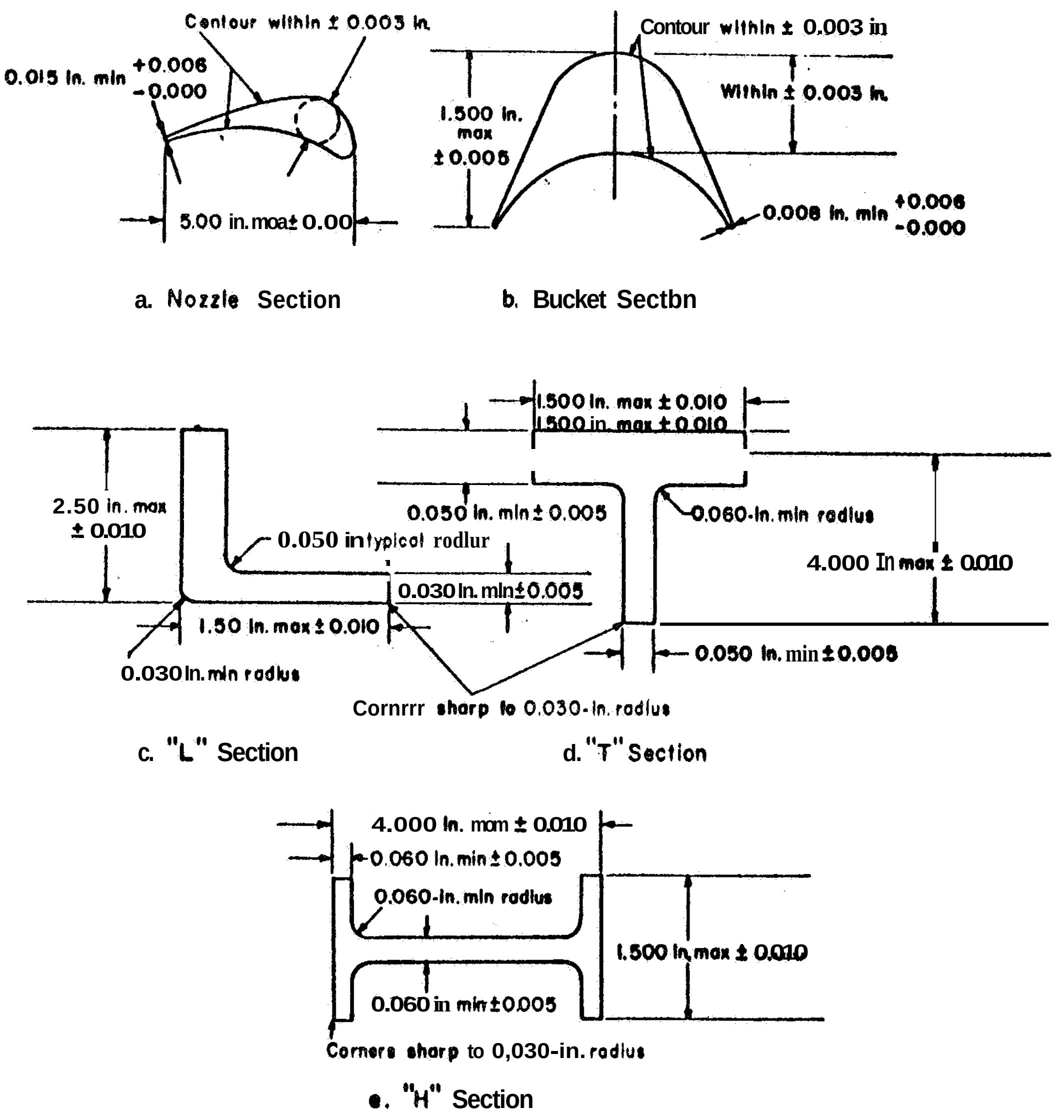


FIGURE 4. SIZE AND TOLERANCE LIMITATIONS ON PRECISION-ROLLED SHAPES (Ref. 13)

Future Rolling Capabilities. The addition of United States Steel's 210-inch-wide plate mill will undoubtedly extend the size capability for rolling stainless steels. The point deformation rolling mill, being built by Lodge and Shipley for Titanium Metals Corporation of America on an Air-Force-sponsored program, is designed to produce rolled shapes from titanium as sections up to 24-inches wide (Ref. 14). It is hoped that integrally stiffened sheets with precise gage control can be produced by the process from both titanium and stainless steels.

A relatively new process applying to the cold-rolling of stainless steels is that of "zerolling". This process consists of cold-rolling sheet at subzero (to about -100 F) temperatures to produce low-carbon martensite in 18-8 stainless steels (Ref. 15). Tensile strengths on the order of 300,000 psi can be obtained with the process. For comparable levels reduction, rerolling of an 18-8 stainless at its Ms temperature produces greater strengthening than ausforming its higher carbon modification. It is believed that zerolling offers a practicable alternative to ultra-high-strength steels in situations requiring corrosion resistance.

The rolling of precise shapes other than structurals has been advancing steadily. A rolling process developed on an Air Force Contract (Ref. 16) is now producing such rolled contours as blade and buckets for jet engines to finish dimensions. Most of the initial work has been on titanium and nickel-base superalloys, however, the process applies readily to stainless steels if economics prove favorable.

The present capabilities and future requirements for large sheets and plates were reviewed ex·iansively by a panel of the Materials Advisory Board (Ref. 17). The panel identified future aerospace needs for stainless sheet and plate as wide as 240 inches and with thickness tolerances of plus or minus 5 percent or better. These targets are well ahead of the present state-of-the-art.

EXTRUSION

The extrusion process has been long recognized as an economical technique for producing fairly long structural shapes with complex cross-sections. While most of the earliest commercially extruded shapes were aluminum, the development of fused-glass lubrication coupled with the installation of very large presses has made possible the extrusion of quite complex shapes from alloy steels, stainless steels, titanium, and even some of the heat-resistant refractory metals. Extruded stainless steels are offered on a commercial basis.

Some structural shapes of up to about 22-inches wide have been extruded successfully from aluminum alloys on one of the largest presses in the U.S. (14,000-ton). Because stainless steels require substantially more pressure to extrude, widths in the vicinity of 7 inches are considered a practical limit for stainless steel structural shapes. About 5-1/2 inches across is considered about maximum practical limit for more complex shapes.

The extrusion industry has grown significantly in the past 20 years from a 50,000-ton per year business to about 700,000 tons per year in 1965. In this same period, the number of plants has grown from less than 10 to over 200. (Ref. 18). However, only a small percentage of these plants hot-extrude stainless steel products.

Many of the structural shapes produced by extrusion are also produced by rolling such as tees, angles, channels, and "H" sections - structural shapes that are not characterized by re-entrant angles. Rolling is generally the more economical method for volume production of standard shapes. Extrusion is preferred only if the quantity is small or if a quicker delivery offers enough advantage that the added cost is justified. The field of extrusion for alloy and stainless steels is generally confined to:

(1) Sections with shapes which are impossible to roll;

(2) Non-standard sections, especially small quantities;

(3) Sections of material that have generally poor workability in rolling or forging.

On the last point, the essentially compressive deformation, characteristic of the extrusion process, permits greater deformations in a difficult-to-work material than are normally possible by rolling or forging. This is not a major factor favoring the extrusion of the stainless steels because most of them are quite workable.

Government and privately sponsored development programs have led to the successful extrusion of some rather slender profiles from stainless steels. A tee section with a web of .062 inch has been extruded from two heat resistant austenitic stainless steels (See Figure 5). While extruding such thin sections may not be the most economical route to producing this shape, the process development work involved has substantially advanced the state-of-the art (Ref. 19). In that program the A286 alloy was successfully extruded to the research "tee" indicated in Figure 5. At present, roughly double the tolerances indicated in the figure would be required.

Extrusion is also used as a breakdown operation for materials with large as-cast grain sizes (Ref. 20). Alloys that are prone to crack during rolling or forging of the cast ingot are extruded at an extrusion ratio of to 1 to eliminate the cast structures and to provide a round or rectangular section suitable for subsequent forging or rolling. This practice is used mainly in the initial working of developmental stainless alloys cast in small ingots.

Classification of Extrusion Processes. In the extrusion process, the billet is forced under compressive stress to flow through the opening of a die to form a continuous product,

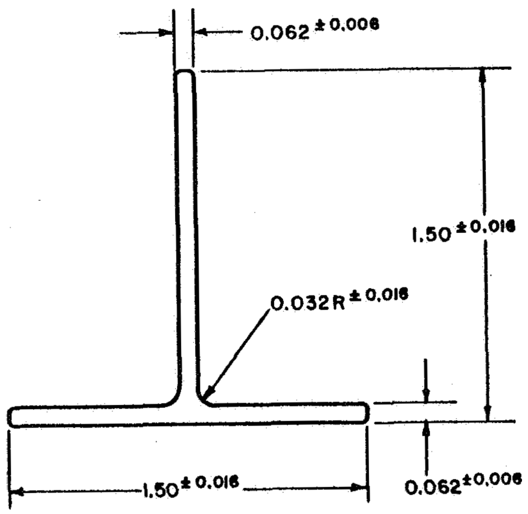


FIGURE 5. RESEARCH SHAPE FOR A–286 AND PH–15–7 Mo (Ref. 19)

The process can be used to produce rounds, shapes, tubes, and/or cups.

The most common method of extrusion is referred to as direct extrusion. In this technique, the ram moves through the container to force the billet material through a stationary die. The ram, billet, and extrusion all move in the same direction. In the indirect or inverted method of extrusion, a hollow ram and die move against a stationary billet causing the billet material to flow in the opposite direction through the die and ram. These processes are shown schematically in Figure 6 which includes diagram illustrating methods for tube extrusion.

The indirect process requires lower pressures for extrusion since friction between the container and the billet is largely eliminated. This practice is generally confined to vertical presses having a hollow ram so that the extruded products can flow upward through it. For example, Cameron Iron Works extrudes heavy-wall pipe vertically through the hollow ram of its 20,000-ton hydraulic press.

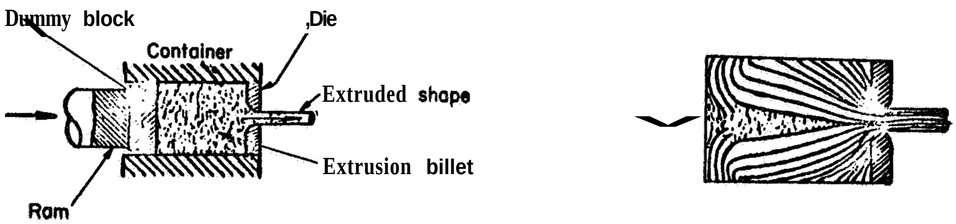
Besides these mechanical differences, there are three additional subcategories of extrusion processing generally identified by the extrusion industry namely:

(a) Hot Extrusion - extrusion of metals at temperatures above their recrystallization temperatures

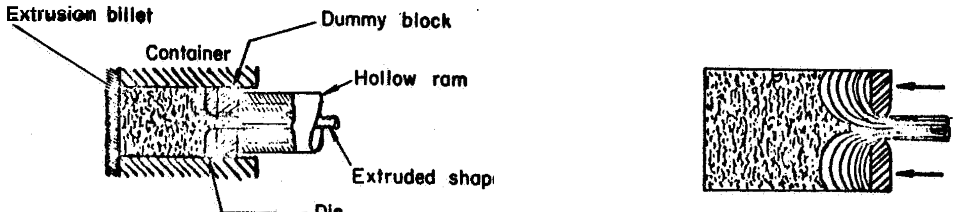
(b) Cold Extrusion - extrusion of metals at ambient temperature

(c) Warm Extrusion - extrusion of metals at temperatures above ambient but below their recrystallization temperatures.

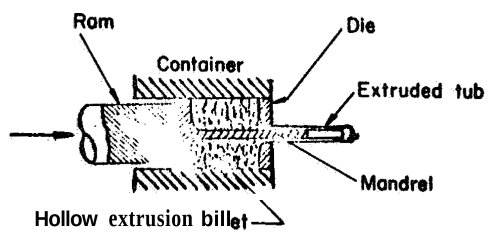
Stainless steels are not usually cold or warm extruded because they require deformation pressures substantially higher than mild steels and they work



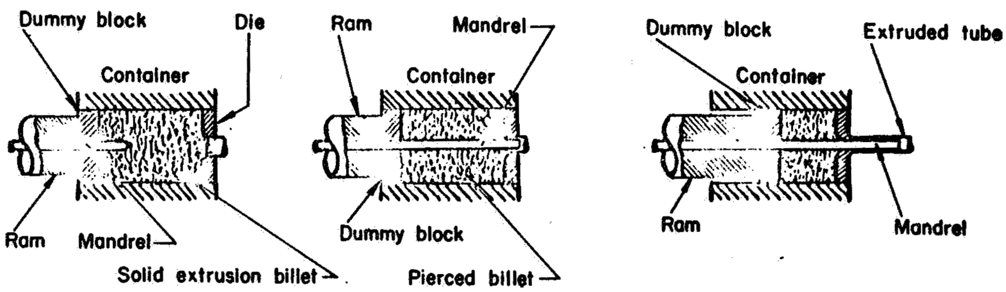
a. Direct Extrusion of a Rod or Shape



b. Indirect or Inverted Extrusion



c. Extrusion of a Tube From a Hollow Billet



d. Extrusion of a Tube From a Solid Billet

FIGURE 6. DIAGRAMMATIC REPRESENTATION OF DIFFERENT TYPES OF EXTRUSION PROCESSES (Ref. 21 and 22)

harden faster. However, the development of the low work-hardening stainless steels may bring about increased usage by the cold extrusion segment of the industry.

Extrusion Eauipment and Tooling. The ram which applies force to the billet is actuated hydraulically or mechanically. Hydraulic presses are driven directly by high-pressure oil pumps or by hydropneumatic accumulators. Mechanical presses utilize the energy of electrically driven fly wheels.

Horizontal Presses. Horizontal presses are ordinarily used for hot-extrusion operations and are available with capacities up to 14,000 tons. The largest presses of this kind were built on the U.S. Air Force heavy-press program. Presently, there are nine of these heavy presses in the United States, ranging in capacity from 8,000 to 14,000 tons. The largest press equipped for extrusion of stainless steels is Curtiss-Wright's press rated at 12,000 tons.

The majority of extrusion presses used for carbon, low alloy, and stainless steels range in capacity of from 1600 tons to about 2500 tons. A representative of the Harper Company, a major extruder of stainless steels, has stated essentially that presses larger than 2500 tons become increasingly difficult to justify economically on a purely commercial business (Ref. 23). This is one of the reasons why the U.S. Air Force subsidized the installation of larger presses in its Heavy Press Program.

In general, the large presses designed for extruding aluminum or magnesium do not have adequate ram velocity for extruding steels. For example, the Alcoa 14,000-ton press will operate at ram speeds of about 60 inches/minute while Curtiss-Wright's 12,000-ton press will extrude at a ram speed of nearly 200 inches per minute. The faster ram speeds are required to minimize temperature losses in the heated billet during extrusion of stainless steel.

Extrusion presses known to have high-speed press capability for extruding stainless steels are located at the following companies:

	Press Capacities
*Allegheny Ludlum Steel Corp.	1780 ton
*Babcock and Wilcox Co.	2500 ton
Bridgeport Brass Co.	3850 ton
*Curtiss Wright Corp.	12,000 ton
E. I. du Pont de Nemours and Co.	2500 ton
*Harvey Aluminum	8000 ton; 12,000 ton
*H. M. Harper Co.	1650 ton
Nuclear Metals, Inc.	1000 ton
United States Steel Corp.	2500 ton

*Stainless Steel Extrusions offered on a commercial basis.

As Indicated, five of the nine companies listed are known to offer stainless steel structural extrusions commercially. They all use horizontal presses.

Vertical Presses. Vertical presses are preferred for producing small-diameter, thin-wall tubes. The design simplifies the solution to problems of alignment of tooling and securing high production rates. The maximum capacities of such presses usually range from 650 to 2400 tons. The larger presses are also used for cold extrusion and operations resembling hot forging.

Cold Heading Machines. One of the fastest growing commercial industries is the cold extrusion field. Hundreds of parts that were formerly made by either hot forging or machined from bar stock on screw machines are now being cold extruded. Spark plug bodies and ball joint sockets are good examples of carbon-steel parts now being cold extruded on heading machinery.

To date most of the cold extrusion of stainless steels has been confined to fasteners. This may change as the newer low-work-hardening stainless steels develop. Armco"s 18-9LW is one example. The chief feature of cold-extruded products is that they are almost as precise as screw machine products and are generally characterized by lower scrap losses.

Extrusion Practices. The hot-extrusion process is employed for the production of long sections. Virtually all extruders of stainless steel employ the Sejournet glass process. The use of glass as an extrusion lubricant was originally developed by the Comptoir Industrial d'Etirage et Profilage de Metaus, Paris, France, for extruding ferrous materials. As glasses were found that could be employed over a wider range of temperatures, the process was adopted for titanium, superalloys, stainless steels, and refractory metals.

The practices employed by the American licensees of the Sejournet glass process for extruding stainless steels are essentially identical. Billets are transferred from the heating furnace to the charging table of the extrusion press. As a billet rolls into position in front of the container, it passes over a sheet of glass fiber or a layer of glass powder that fuses to the billet surface. In addition, a fibrous glass pad is placed in front of the die, providing a reservoir of glass at the die face during extrusion.

For tubes, either a fibrous glass sock is placed over the mandrel or powdered glass is sprinkled on the inside surface of the hollow billet.

The glass pad at the front of the die fuses slowly enough to provide a thin continuous film over the surface of the extrusion. This effect is illustrated in Figure 7.

In addition to providing lubrication, glass serves as an insulator to protect the tools from contact with the hot billet during extrusion: excessive

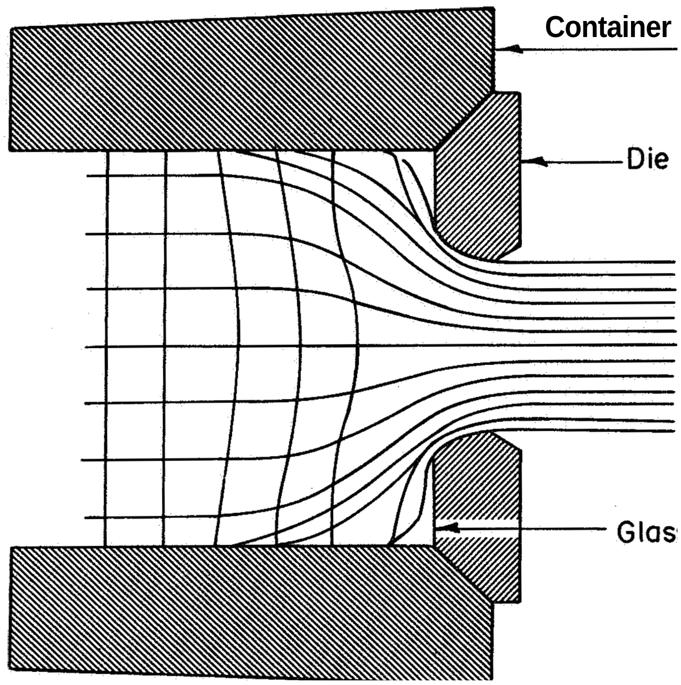


FIGURE 7. SCHEMATIC SHOWING LOCATION OF FUSED GLASS AT THE DIE FACE DURING THE EXTRUSION OF STEEL

overheating of tools does not occur, tool life is increased, and die costs are reduced.

Billets can be heated in either gas- or oil-fired furnaces, by induction or by salt-bath heating (Ref. 20). Stainless grades generally take longer to heat than carbon steels because of their lower thermal conductivity.

It is important to recognize that the stainless steels require substantially more extrusion force than carbon steels. For example, some compressive strength data on three stainless steels are compared below to carbon steel (Ref. 24):

Extrusion Temperature	Approximate Resistance to Deformation, ksi			
	Carbon Steel	Type 410	Type 304	Type 316
2100	21	28	35	37
2200	20	23	28	32
2250	17	20	26	28

As indicated, a relatively small temperature drop of 150 F can mean nearly a 40 percent increase in deformation force. Thus, transfer and ram speeds are that much more critical for stainless steels.

A generalized sequence of steps used in the extrusion of a typical 300 series stainless steel structural shape is given below:

Forge ingot to desired round
Machine billet to final diameter
Cut to length
Heat billet (induction coil) to 2300 F
Place glass pad in container at opening
Roll-hot billet in glass fiber or powder
Place billet in container
Place dummy block behind billet
Extrude onto run-out table
Cut off extrusion at die
(Slow cool martensitic stainless grades)
Straighten and detwist extrusions
(Optional: cold draw for size control)
Cut to length
Inspect

Extrusion Forces. Three factors having pronounced effects on the pressure necessary to extrude steels are billet length, extrusion ratio, and die angle. Briefly:

Extrusion Ratio - is the ratio of the cross-sectional area of the billet to that of the extrusion. A one-inch rod extruded from a 6-inch billet, for example, represents at 36:1 extrusion ratio.

Die Angle - is the angle between the centerline of the container and the die face. A 90 degree die, for example, is essentially a flat disk with a hole through it.

Fundamentally, the extrusion pressure increases as the extrusion ratio increases and the die angle decreases. (Ref. 25)

Friction at both the die and container wall also has an important influence on extrusion forces. Attempts to reduce the pressure by decreasing the container size (hence the extrusion ratio), for example, may actually result in an increase in extrusion pressure because the longer billet then exhibits more area in frictional contact with the container liner.

Several investigators have conducted extensive investigations about these and some of the other influencing relationships. (Ref. 25,26,27,28) Listed below are some other factors which tend to increase the required pressure during hot extrusion:

Increased strain rate
Thinner section size at a given extrusion ratio
Lower container temperature.

Details of data and experiments are given in the references. (Ref. 25,26,27,28)

Widely accepted formulas for determing pressures required for hot extruding steels is:

$$P = K \ln Re^{4fL/D} \qquad \text{for direct extrusions (1)}$$

$$P = K \ln R \qquad \text{for indirect extrusions (2)}$$

where

P = punch pressure

K = resistance to deformation

R = extrusion ratio

f = coefficient of friction

L = length of billet

D = diameter of billet

The extrusion constant K for 304 stainless for example ranges between 26 and 40 for respective temperatures of 2400 F and 2150 F (Ref. 27).

Availability of Stainless Steel Extrusions. Since stainless steels require more force to extrude, the size capability and shape definition are more restricted than for aluminum or low-alloy steel. For example, where structural steel can be extruded to a tee section having 118-inch-thick legs, stainless steels tees would be roughly 114-inch thick. This is done to keep the extrusion pressures at reasonable levels so as not to damage the tooling or press components. The largest stainless steel "tee" that could be extruded on Curtiss-Wright's 12,000-ton press is roughly 18-inch-wide flange, with a 9-ingh leg weighing roughly 48 pounds per linear foot of extrusion. (Ref. 29) Some shapes have been extruded in sections of up to about 140 pounds per foot. Forty-foot long, 8-inch round tubes, having walls 1-1/8-inch thick, were extruded from 304 stainless to produce periscope tubes. The majority of commercial extrusions are smaller than these examples, however, and the standards listed in Table V are considered representative of the industry. The circumscribing circle denoted in the table refers to the smallest diameter circle that would completely enclose the cross section of the shape being extruded. For the 1650-ton press this is about 4-1/2 inches. For the 12,000-ton press it is nearly 20 inches for stainless steels. Thus, the circumscribing circle is considered as one measure of extrusion press size. As indicated in the table, a 7-inch diameter is considered a practical economical limit.

Figure 8 illustrates some of the many cross sections that have been extruded successfully from stainless steel. The developmental shapes indicated have been extruded from alloy steel but represent outlines that are more difficult but not impossible to extrude from stainless. Figure 9 shows an unusual hollow shape recently extruded by Allegheny Ludlum Steel Corporation.

The length of the extrusion is governed by the relation between billet volume and extrusion area. However, practical limits on lengths of individual extrusions are set by the straightening and detwisting equipment available at the mill.

Hot extruded austenitic stainless steel shapes can be furnished in the temper conditions described earlier for rolled products only if the shapes can be cold drawn later with enough uniform reduction to achieve the working hardening required. Tubes, flats, and common structural shapes permit cold drawing but the process is much more difficult to apply to complex shapes. Individual companies impose their own limits on sizes and shapes to be cold finished.

<u>Extrusion Developments</u>. A considerable amount of research and development work is being conducted on almost all phases of the extrusion process. Some of the developments apply directly to or involve stainless

TABLE V. STANDARD MANUFACTURING LIMITATIONS AND TOLERANCES FOR STAINLESS STEEL EXTRUSION (Ref. 30)

Manufacturing Limitations

Dimensional Limitations

Circumscribing Circle Diameter: the diameter of the smallest circle that will completely enclose the cross section of the shape — 7-in. maximum

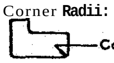
Cross Sectional Area: — 0.50-sq. in. minimum

Finished Cutting Length: — 17-ft maximum

Finished Weight Per Piece: — 300-lb. maximum

Section Thickness: — 0.150-in. minimum

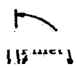
Corner Radii:



0.093-in. standard; 0.062-in. minimum

Fillet Radii:

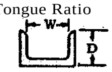
Included angle (α) less than 70 deg — 0.375-in. standard; 0.250-in. minimum



Included angle (α) greater than 70 deg — 0.250-in. standard; 0.188-in. minimum

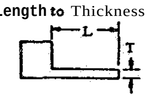
Design Proportions

Tongue Ratio



Tongue width (W) should be equal to or greater than tongue depth (D) — $\frac{W}{D} = \frac{1}{1}$

Leg Length to Thickness Ratio:



Leg length (L) should not exceed I4 times the leg thickness (T) — $\frac{L}{T}$ = [illegible]

Tolerances

Cross-Sectional Tolerances

Dimensions:

Specified Dimension, inches	Tolerance, inches
Up thru 1.999	±.030
2.000 thru 2.999	±.040
3.000 and up	±.050

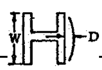
Corner and Fillet Radii:

Radii	Tolerance
Corner	±0.025 in.
Fillet	±0.062 in.

Angles

Specified Leg Thickness (T)	Angular Tolerance (α)
Less than 0.250 in.	± 2 deg
0.250 in. and over	± 1-1/2 deg

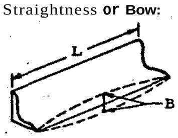
Transverse Flatness:



Allowable deviation (D) from flat:
0.010 in. per inch of width (W)
0.010 in. minimum on dimensions less than 1 in.
D = 0.010 in. x W (inches),
0.010 in. minimum

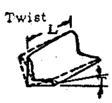
Longitudinal Tolerances

Straightness or Bow:



Maximum allowable bow (B) in inches: 0.025 inch per foot of length (L)
B = 0.025-in. x L (ft)

Twist



Maximum allowable twist (T) in degrees:
1 deg per foot of length (L);
5 deg maximum = 1 deg x L (ft);
5 deg maximum

Length:

Tolerance in cutting length = ±1/4 in. -0.00 in

Surface Finish

Roughness:
Maximum roughness = 250 rms (this value is used as a guide only since rms standards are established primarily for machined surfaces and may not be directly applicable in all respects to extruded surfaces)

Local Defects:
Local defects, such as gouges, dents, handling marks, and linelaps, may extend a maximum of 0.015 in. below the minimum dimensional tolerance

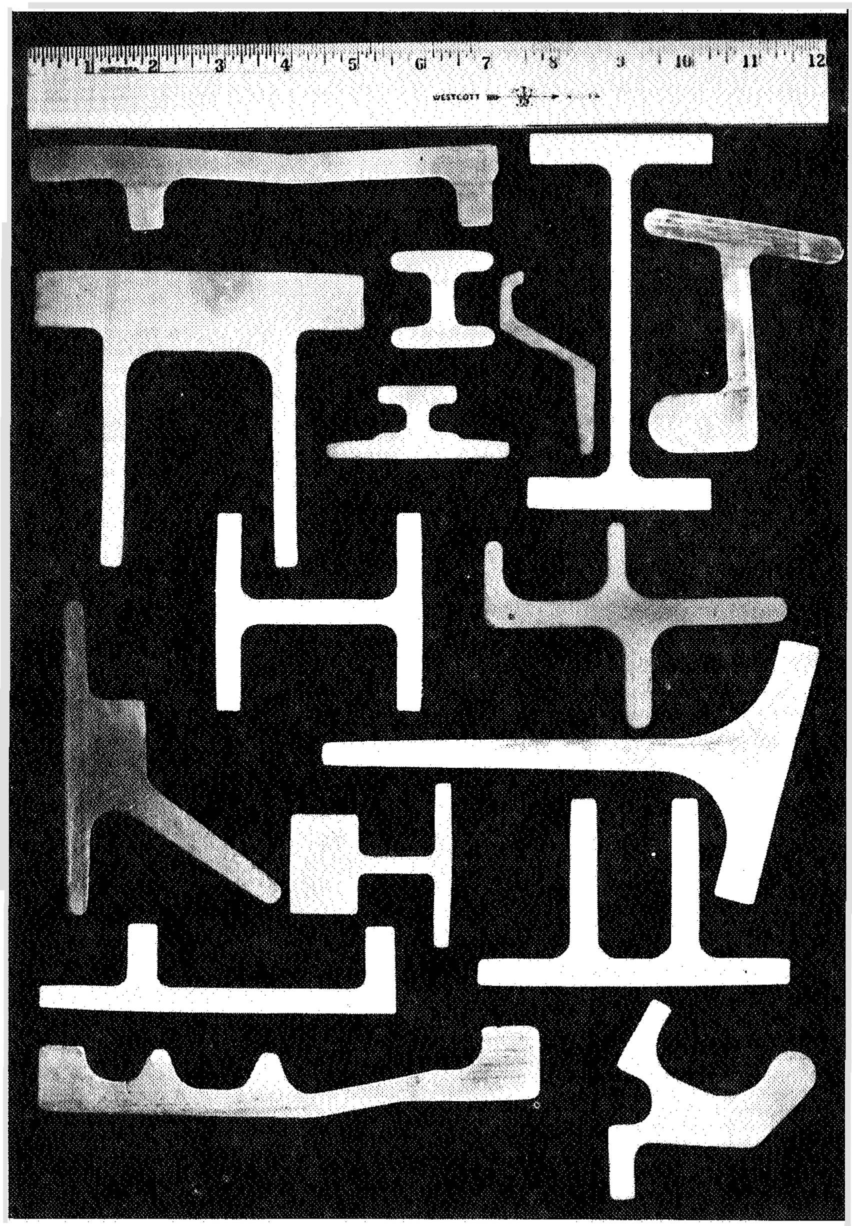


FIGURE 8. SOME TYPICAL CROSS SECTIONS THAT HAVE BEEN EXTRUDED SUCCESSFULLY FROM STAINLESS STEEL

Courtesy of Harvey Aluminum Company.

FIGURE 9. UNUSUAL HOLLOW EXTRUSION RECENTLY EXTRUDED FROM **304** STAINLESS STEEL FOR USE IN HEAT EXCHANGER

Courtesy of Alleghemy Ludlum Steel Corporation

steels. Some of the more pertinent active programs are concerned with:

- Development of improved methods, processes, and techniques for producing steel extrusion (Ref. 19)
- Investigation of hydrostatic extrusion at warm working temperatures (Ref. 31)
- Extrusion of refractory metals and super alloys at temperatures from 2000 to 4000 F (Ref. 32)
- High velocity extrusion of metals in a press powered by electrospark discharge (Ref. 33)
- Development of improved lubricants for hot extruding aerospace materials (Ref. 34)
- Development of high temperature ceramic containers and ceramic dies for extruding refractory metals (Refs. 35 and 36)
- Extrusion of precise shapes from heat resistant stainless (Ref. 37)

Thus, the state-of-the-art of extruding stainless is expected to advance significantly in the next few years.

FORGING

Most of the stainless steels listed in this report can be forged readily into a variety of shapes and sizes, both in contoured dies and on open or flat dies. However, the forging designs are generally restricted to poorer shape definition than those for lower-alloy steel forgings, because the stainless steels require higher forging forces.

Stainless steels can be hot forged in all types of forging equipment including hydraulic and mechanical presses, drop hammers, high-energy rate devices, and headers. Because they work harden faster, the alloys are not usually cold forged. Cold heating of 304 and 305 stainless for fasteners is a known exception to this generality.

Most of the shops that forge carbon and alloy steel can forge stainless steel. One of the largest known closed-die forgings from stainless steel is a 10,000 pound steam chest or steam valve manifold, forged by the Ladish Company on its 125,000 m-kg counter blow hammer. One of the largest open-die stainless forgings started with a 298,000 pound ingot of 410 stainless (Ref. 38) and finished up as a 21-foot-long rotor shaft weighing over 55,000 pounds just before finish machining.

While not a true stainless steel, a 28,000 pound, 18 percent nickel steel ingot was recently contour-roll forged to a 260-inch-diameter seamless ring over three feet high varying from two-to three-inches thick. (Ref. 39). That alloy forges much like the 400 type stainless grades, thus reflecting capability for forging large rings in stainless grades.

The two 50,000 ton presses at Wyman-Gordon and Alcoa owned by the Air Force are capable of forging steel parts up to 22 feet long (Ref. 40). Although the longest known stainless steel closed-die forging is about 10 feet long, these presses can handle parts closer to the 22-foot length should the need arise.

There are over 200 companies classified as customer-forging producers and they account for roughly 1-1/4-million tons of closed-die forgings annually. About one percent of this tonnage consists of stainless steel forgings. (Ref. 41)

On the average, stainless steels require roughly twice the forging force necessary for carbon steels and the loads generally increase as both the chromium and nickel contents increase. This means that larger equipment is necessary to forge stainless steel forgings comparable in size to those in other materials.

Classification of Forging Processes. Descriptions of several types of forging operations and the specialized equipment needed for them are given in Table VI and the principles are illustrated in Figure 10. It is considered closed-die or impression-die forging, when at least one of the two opposing dies contains recesses for shaping the metal. Illustrations E, F, and G are all forms of closed-die forgings. Most commonly, both dies have recesses, and during forging, excess metal is forced out between the dies and later trimmed off. The operations of forging a particular part often combine several of the types listed. For example, the respective forging sequences for two different parts, a steam valve and a pipe fitting, are given below:

Steam Valve	Welding-Neck Flange
Heat stock	Heat stock
Upset	Draw out on corners
Draw out one end	Upset
Flatten opposite end	Die forge in blocking die
Reheat	Die forge in finishing die
Die forge in blocking die	Hot trim flash
Reheat	
Die forge in finishing die	

Thus, it is not always possible to characterize the forging of a part by a single forging process.

Forging Equipment. The operating principles of the many types of forging equipment are described in greater detail elsewhere. (Ref. 42,43,44) A brief summary of the types and sizes is given in roughly increasing ram velocity below:

TABLE VI. DESCRIPTION OF AND MACHINERY USED FOR SEVERAL COMMON TYPES OF FORGING OPERATIONS (Ref. 42)

Type of Forging	Method of Operation	Commonly Used Machinery
Upsetting	Compression parallel with the longitudinal axis of the work	Single-action and counterblow hammers Upsetting machines Hydraulic, air, and mechanical presses High-energy-rate machines
Drawing out	Stretching of the work by a series of upsets along the length of the workpiece	Single-action hammers Hydraulic and air presses
Die forging	Compression in a closed, impression die	Single-action and counterblow hammers Hydraulic and mechanical presses High-energy-rate machines Impacters
Ring rolling	Radial compression on a ring shape to increase diameter	Ring-rolling mills Hammers and presses with supported mandrel
Swaging	Radial compression by shaped dies to lengthen a workpiece	Swaging machine Single-action hammers Air and hydraulic presses
Core forging	Displacing metal with a punch to fill a die cavity	Multiple-ram presses
Extrusion forging	Forcing metal into a die opening by restricting flow in other directions	Hydraulic and mechanical presses Multiple-ram presses High-energy-rate machines
Back extrusion	Forcing metal to flow in a direction opposite to the motion of the punch with respect to the die	Single-action and counterblow hammers Hydraulic and mechanical presses Multiple-ram presses High-energy-rate machines

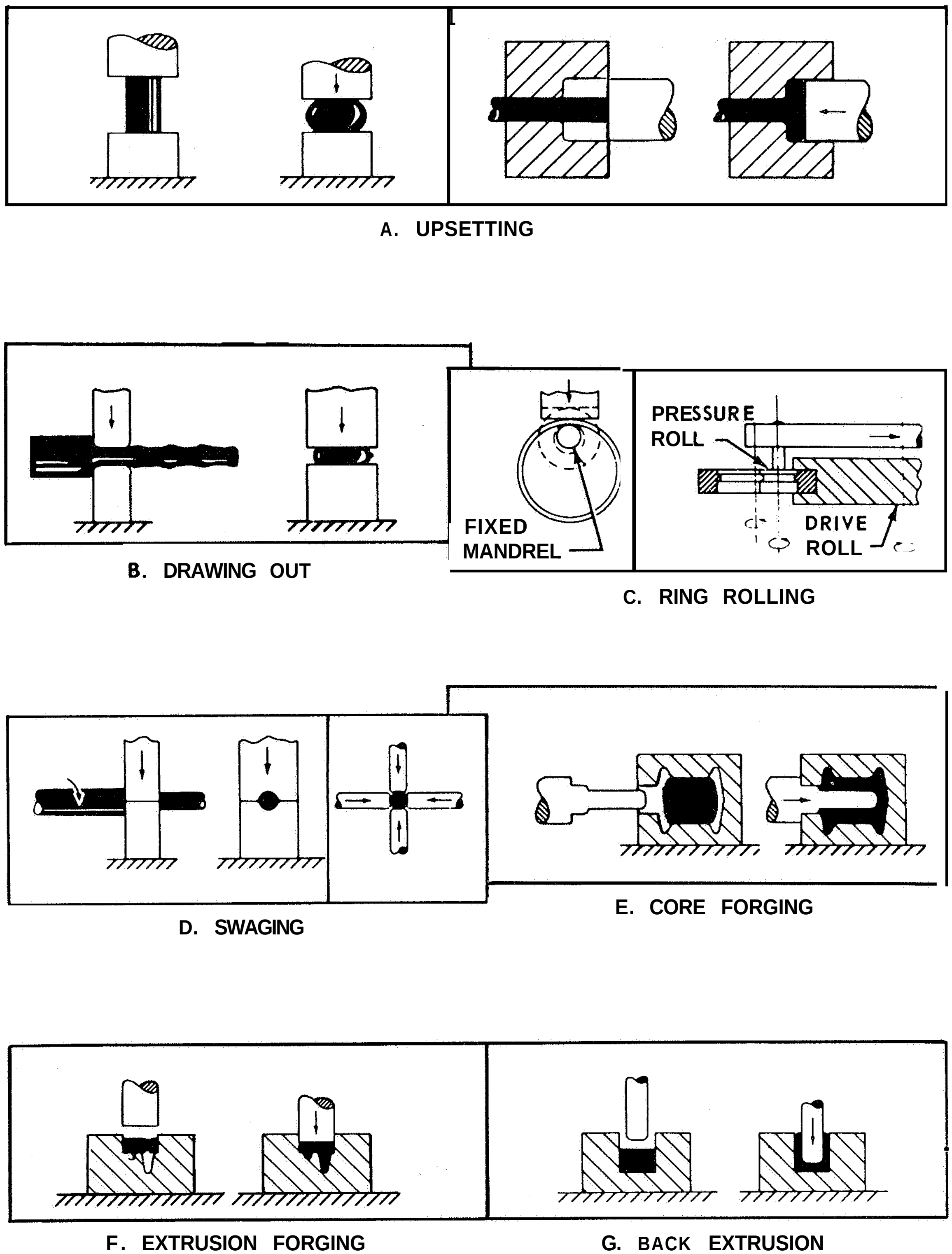


FIGURE 10. PRINCIPLES OF SEVERAL TYPES OF FORGING OPERATIONS (Ref. 42)

Hydraulic Forging Presses. These presses range in size from about 1000 tons to 50,000 tons in pressing capacity. In general, the smaller presses are used for upsetting or drawing out of ingots to billets suitable for subsequent working. The larger presses are used principally for closed-die forging of light metals like aluminum, magnesium, and titanium although they may also be used for forging stainless steels. A rule-of-thumb useful for selecting forging equipment is to figure roughly 50 to 70 tons for each square inch of plan area. The plan area is the projected area of a forging viewed at right angles to the flash plane. A 10" x 30" stainless steel structural shape, for example, requires:

300 square inches x 60 tons/square inch =
18,000-ton forging load

Hydraulic presses are usually characterized by large beds and long strokes which permit maximum shape versatility. The most versatile presses have side-acting pistons in addition to the main ram. They allow hollow shapes to be produced by core forging techniques, by which metal is displaced laterally from the center to fill die cavities. This practice conserves material and saves some rough machining. A listing of larger hydraulic presses is given below:

Company	Press Sizes
Aluminum Company of America	8,000 ton; 35,000 ton; 50,000 ton
Cameron Iron Works	20,000 ton*; 11,000 ton*; 5,000 ton*
Ladish Co.	23,000 ton*
Harvey Aluminum Co.	8,000 ton
Wyman Gordon Co.	50,000 ton; 35,000 ton*; 18,000 ton; 7,700 ton*; 6,000 ton; 5,000 ton*.

* Denotes presses equipped with side rams.

Mechanical Presses. Mechanical presses are usually powered by a rotating shaft connected to a heavy flywheel and characterized by a comparatively short working stroke. These presses are capable of forging at very high production rates, at times exceeding 1000 pieces per hour thus being a preferred choice for high production operations such as found in automotive forge shops.

Mechanical presses range in size up to 16,000 tons but most are *4000* tons or smaller.

Some of the more precise, no-draft forgings weighing up to about 30-pounds are forged on mechanical presses. Heavy-duty ejectors are used in these cases to remove the forgings from the dies. The largest mechanical forging press (16,000 ton) is being installed at the Wyman Gordon Company **(Ref. 45)** Thompson Ramo Woldridge has the next largest forging press at a capacity of 8,000 tons.

All forgeable grades of stainless steel are readily forged on mechanical presses with roughly double the size capacity of equipment used for equivalent carbon-steel forgings.

Forge Hammers. Drop and counter blow hammers range in size upward from about 1000 pounds of falling weight. The largest single-action hammers are rated at 50,000-pound capacity while the counter blows range from about 20,000 pound to 150,000-pound ratings,

Depending on forging shape and complexity hammers of increasing ratings are capable of forging parts with progressively larger plan areas as shown in **Table VII.**

TABLE VII. PLAN AREAS OF FORGINGS THAT CAN BE MADE ON DIFFERENT SIZE HAMMERS

Hammer Size, pounds	Nominal Plan Area of Forging, sq in. Carbon Steel	Stainless Steel
2000	38 to 40	16 to 25
5000	75 to 120	40 to 75
8000	175 to 220	85 to 120
12,000	200 to 320	100 to 170
20,000	350 to 550	175 to 220
35,000	600 to 900	300 to 450
50,000	700 to 1100	350 to 550
75,000	1100 to 1500	550 to 800
150,000	2000 to 5500	1000 to 3000

It should be recognized that hammers forge with repeated blows thus accounting for the wide ranges of plan areas. A very rough rule-of-thumb for selecting hammer sizes for stainless steels is 100 pounds of falling weight for each square inch of plan area.

The locations of some of the larger hammers are listed below:

Rating, pounds	Locations
150,000 (125,000 m-kg counter blow)	Ladish Company
100,000 (80,000 m-kg counter blow)	Ladish Company
80,000 (63,000 m-kg counter blow)	Ladish Company Taylor Forge and Pipe Co.
50,000 (steam drop)	Ladish*(2) Taylor Forge and Pipe Co. Kropp Forge Co. Arcturus Co.
35,000 (steam drop)	Kropp Forge Co. Wyman Gordon Co.*(2) Aluminum Company of America
25,000 (steam drop)	Arcturus Co. Ladish Co.

* Two hammers available at these facilities.

Additional large hammers of about 20,000-pound capacity are located at Park Drop Forge, Wyman Gordon Co., and Ladish Company.

High-Energy Rate Machines. There are 11 companies in the United States that are production forging steel on high-energy rate machines (HER). The most widely used machines are (1) The Dynapak produced by the Electro Dynamic Division of General Dynamics, and (2) the HERF produced by U.S. Industries, Inc. The details of operating these machines are given elsewhere (Ref. 26,46,47). The significant differences between these machines and conventional presses and hammers are that:

(1) ram speeds are about 10 times as fast as hammers; and

(2) energy levels for succeeding strokes are very accurate providing excellent repeatability.

Among the advantages cited for these machines by the builders are:

(1) Capital cost for a machine providing a given foot-pound rating is roughly 25 to 50 percent less than conventional equipment.

(2) Installation is economical because machines are self-contained.

(3) Machines are capable of forging to thin sections not producible by conventional means because the rapid speed permits the metal to fill the die cavities before it cools.

(4) This permits billet-weight savings that occasionally reach 50 percent.

Examples of forgings produced on high-energy-rate machines are shown later. At the present time, the machines compete quite favorably with mechanical presses for moderate quantities of forgings. The production rates being achieved, of 100 to 200 forgings per hour, are not as fast as those for mechanical presses and the latter are still preferred for very large production quantities. Short die life was a problem associated with the machines but more rapid ejection has resulted in substantial improvements recently. A listing of domestic companies actively producing steel forgings with high-energy-rate machines is given below:

Company	Machine Type
Alloy Flange and Fitting Co.*	Dynapak 1220 C
Babcock and Wilcox Co.	U.S.I. 3500 C
Bendix Products*	Dynapak 1210
Bethlehem Steel Co.	Dynapak 1220 C
Ladish Company*	Dynapak 1220 C
Charles E. Larson and Sons, Inc.*	U.S.I. 2000 C
Latrobe Steel Co.	U.S.I. 2000 C
Precision Forge Co.*	Dynapak 1220B and 620 D
Spencer Mfg. Co.	U.S.I. 2000 C.
Sunstrand Aviation	Dynapak 1220 D
Varel Manufacturing Co.	Dynapak 1220 D and 620 C

There are roughly 100 more other machines around the country being used for forming aluminum, for powder compaction, for forging other non-ferrous metals, and for research and development. Most of these machines can also be used for forging stainless steels. Since stainless steels generally cost several times more than carbon steels, weight savings possible through high-energy-rate forging are particularly attractive.

Ring-Rolling Equipment. The growing uses of jet engines, missiles, and larger conventional and. nuclear-steam generators have brought about the

* Denotes companies known to be forging stainless steels actively.

** Three newer companies beginning to build high-energy-rate machines are: Ken-0-Matic Corporation of Redona, California; Precision Metals Products Division of Fairchild Camera and Instrument Corporation in El Cajone, California; and International Electronic and Research Corporation, Burbank, California.

need for larger forged seamless rings from heat-resistant alloys, stainless steels and high-strength steels. Three examples of the largest rings so far rolled are (Ref. 39):

(a) A 173,000-pound, 24-ft diameter ring having a face height of nearly 50 inches and a wall thickness of over 2 feet. Use: a large steam vessel

(b) A 13,000-pound, 10-ft diameter ring with a face height of over 6 feet and a wall thickness of about 1-1/2-inches thick. Use: a large rocket motor case

(c) A 28,000-pound, 22-foot diameter ring having a face height of about 30 inches and a wall of varying thickness of 1-1/2 to 3 inches. Use: large prototype rocket motor case.

While these huge example rings were rolled at The Ladish Company, other large ring-rolling mills are located at such companies as:

Cameron Iron Works

Standard Steel Division of Baldwin Lima Hamilton

There are many other smaller ring mills located at the other leading forge shops. The restrictions on ring diameter depend only on the handling equipment available and dimensions of the buildings, furnaces, etc. around the ring-rolling mills. Diameters of about 25 feet are considered the practical limit at the present time. The face height is essentially controlled by the distance between bearing journals and the maximum driving power. In this respect, the largest mill at the Ladish Company is capable of rolling rings with face heights of up to 80-inches. For stainless, this capability is probably closer to 50 inches because of the greater power requirement for rolling stainless.

Forging Practices for Stainless Steels. Establishing the proper forging temperatures is one of the first steps in forging the stainless grades. As a rule-of-thumb, the highest forging temperature for the 18-8 basic composition is about 2300 F adjusted downward €or smaller reductions and for subsequent in-process heatings. The 12 per cent chromium grades are forged at temperatures ranging downward from about 2200 F--the approximate temperature at which delta-ferrite begins to form on heating. Forgeability drops substantially if higher temperatures are used. The lower practical limit for hot forging both basic stainless grades is about 1500 F.

Basically, the grain size of forged austenitic stainlesses is determined by the finishing temperature and amount of reduction, while grain refinement can be achieved in martensitic grades by thermal treatments.

Forging temperature ranges for various stainless steels are given in Table VIII.

The martensitic stainless steels require slow cooling after forging to prevent cracking. The austenitic grades, on the other hand, are cooled quickly to prevent excessive carbide precipitation.

Since they scale much less during heating than carbon steels, the stainless grades require greater care in lubrication for forging, to prevent pressure welding of the forgings to the dies. Glass frit is often used as an effective addition to forging lubricants particularly €or those used with the Type 300 of stainless, The high nickel stainless alloys should be heated in low-sulfur atmospheres to prevent sulfur attack, which reduces forgeability. Use of an oxidizing furnace atmosphere is the best choice to condition the light scale for easy removal.

The billets used for forging are generally conditioned extensively, by grinding or turning, before forging. Economic factors govern whether this is done by the steel supplier or the forge shop.

TABLE VIII. FORGING TEMPERATURE RANGES NORMALLY USED FOR SEVERAL STAINLESS STEELS (Ref. 3, 42)

Alloy	Forging Temperature, F	Alloy	Forging Temperature, F
Austenitic		Martensitic	
301	1700 - 2300	403,410	1600 - 2200
303	1700 - 2300	414	1600 - 2200
304	1600 - 2350	416	1600 - 2250
310	1800 - 2350	420	1600 - 2250
316	1700 - 2350	431	1600 - 2200
321	1600 - 2350	440A	1500 - 2150
347	1600 - 2350	440B	1500 - 2100
		440C	1500 - 2050
Ferritic			
442	1600 - 2250		
446	1600 - 2250		

Notes: Preheating of sections larger than 4-inch thick, to prevent stress cracking and to insure thorough heating, is recommended.

The dies and toolings used for forging stainless steels are made of the same materials (e.g., Cr-M-V and Cr-Ni-M-V die steels containing 0.40 to 0.50 C) as used for carbon and alloy steels. Overlaying punches and some projections in dies with cobalt- or nickel-base weld metal is helpful in extending die life.

After forging, stainless parts are generally annealed or heat treated with essentially the same practices as used for rolled and/or extruded products. Similarly, stainless forgings are descaled in acids or salts like those used for hot-rolled sheet.

Forging Design. For stainless steel hammer forgings, it is common practice to provide 50 to 100 percent larger fillet and corner radii in the die cavities than is standard forging industry practice for carbon steels. (Ref. 42). Dimensional tolerances on stainless steel parts are also 50 to 100 percent higher. The surface finish allowances are about the same. High-energy-rate forgings of stainless can be forged without draft to dimensional tolerances similar to those for alloy steels. Unlike most alloy steels, as-forged surfaces are used in many service applications for stainless forgings because mechanical properties of surface layers are not significantly affected by scale or decarburization.

An unusual example of a roll forging is shown in Figure 11.

Future Developments in Forging. Many current government and industrial programs are devoted to advancing the state-of-the-art of forging. In terms of equipment, the desirability of building a 200,000-ton hydraulic press is being studied by the Air Force (Ref. 48). High-energy-rate forging machines with capacities over 112-million foot pounds are being built (Ref. 49).

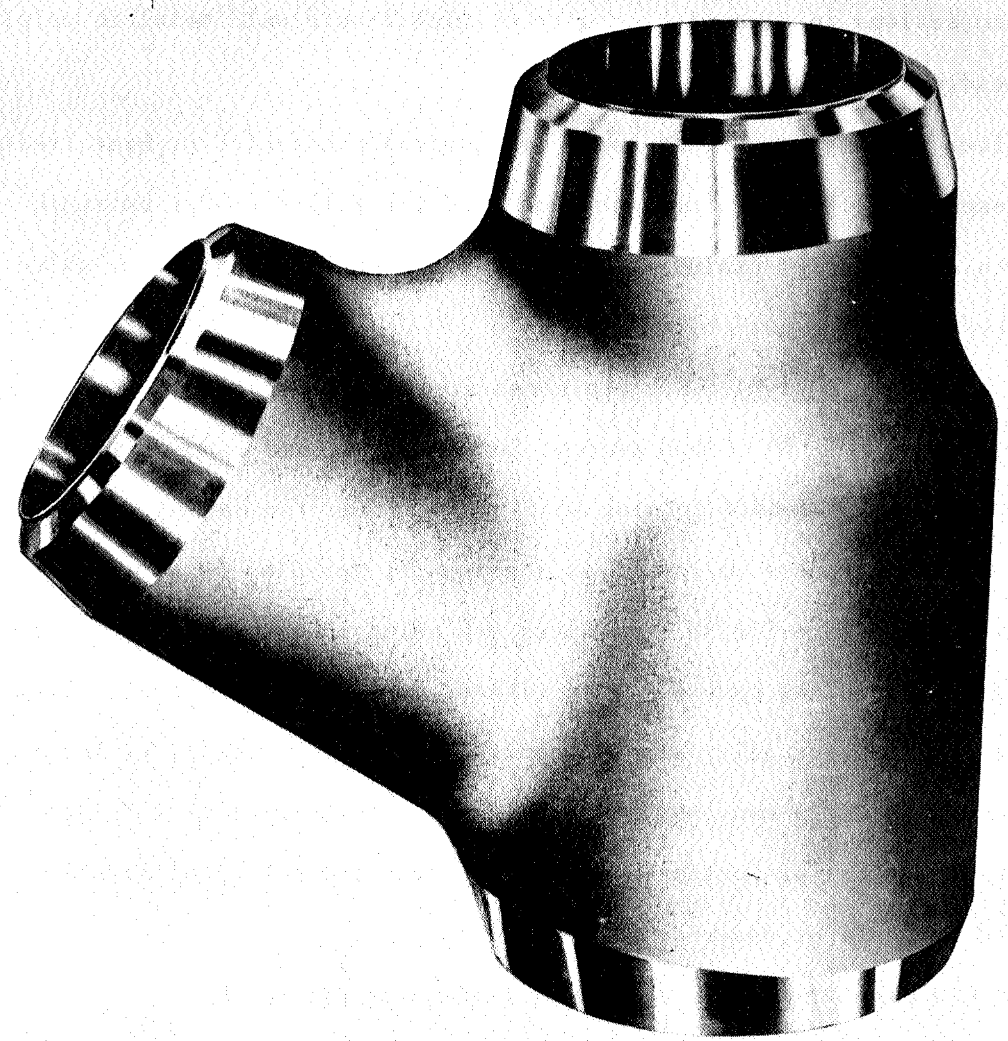


FIGURE 11. TYPE 304 STAINLESS STEEL FORGED HIGH PRESSURE TUBE FITTING FOR STEAM REACTOR

Courtesy of Taylor Forge and Pipe Works

Mechanical presses of up to 20,000 ton capacity are also being studied (Ref. 50). These programs are aimed at increasing the capability for producing forgings closer to the final dimensions desired, or in larger sizes, mostly for aircraft application.

A proposed method for making precision forgings from heat resistant stainless steels, as an alternate to high-energy-rate forging, is that of forging in dies heated to incandescent temperatures. (Ref. 51). If developed, this could mean stainless steel parts forged to dimensional-tolerances and shape complexities now available as large parts only in aluminum and magnesium alloys; and as small stainless parts forged on the high-energy-rate machines.

Other known programs related to advancing the state of the art of forgings are given below:

(a) Die sinking with 3-axis numerical controlled machines.

(b) Sinking of hard die blocks up to 100 inches long by electric discharge-machining.

(c) Automating the forging shop with the

(d) Casting dies by shell molding process to lower costs.

(e) Improving glass lubricants for forging.

(f) Redesigning hammer anvils for maximum life.

DRAWING

Drawing is a cold-working process in which the cross section of a long workpiece is reduced by pulling it through a die. Semi-finished shapes are cold drawn into rod, wire, and tube products for a variety of applications. Drawing is capable of producing products with better finishes, closer tolerances, higher strengths and thinner sections than hot-working processes. Cold-drawn products made from stainless steel wire have found extensive use in the production of 304 stainless steel wire have found extensive use in the production of helical, high-temperature compression springs. Type 304 stainless steel form-rolled tubes are used as components in the production of helicopter rotor blades. Seamless and welded tubing and pipe in grades such as 304, 316, and 430 find extensive use in such diverse applications as conveyor pipes for food components and piping in the chemical and petroleum industries. Types 501 and 502 are extensively used as oil refinery tubing and tubing for steels in references.

Stainless steel fasteners have been produced by cold heading. Most popular cold heading grades include Types 302, 303A, 304, 305, 410, 430, 431, and the high-nickel grades. In recent years, grades with lower work hardening rates than the regular stainless steels have been developed especially for use in severe cold forming operations such as cold heading. One such grade developed by Armco is named Armco 18-9 LW (Ref. 52). It is similar in composition to Type 302 except that it contains 3-4 percent copper. Type 308 stainless steel finds extensive use as welding rod. Wire of Type 310 and 430 stainless steel commonly is used in woven belts for service at temperatures up to 1900 F. Stainless wire rope for use as aircraft control cable, yacht rigging, slings, and anchor cable usually is made from Types 302, 304, or 316 stainless steel in the full hard condition (Ref. 3).

ROD AND WIRE DRAWING

Large-diameter rod is cold drawn in straight lengths on a standard drawbench. Individual bull blocks are used for drawing 1/2 to 1-inch-diameter rod. A bull block is a drum, ordinarily driven by an individual motor, that pulls the rod or wire through the die and produces a coil.

Hot-rolled wire rod approximately 0.25 inch in diameter is annealed and pickled prior to the start of cold drawing. The techniques for drawing stainless steel are very similar to those used for the carbon steels. In general, the stainless grades may be cold reduced about 75 percent between anneals although some of the austenitic grades have been drawn up to 98 percent without annealing.

The drawing of wire through dies increases both the hardness and strength of stainless steel wire. The austenitic grades (300 series of stainless steels) are strengthened to a greater extent than the ferritic grades (405, 430, and 446 stainless steels) for a given cold reduction as is shown in Figure 12 (Ref. 52).

Cleaning of Wire. The first step in the drawing of wire is to remove scale resulting from hot extrusion, hot rolling, annealing, or hot pointing. Where scaling is heavy, it is usually "rotted" in a bath containing either 20 weight percent caustic soda and 8 weight percent potassium permanganate at 190-200 F, or in a molten caustic bath at 750 to 950 F. Treatment in these baths chemically changes the scale so that it can more easily be removed by subsequent pickling.

The modified scale usually is removed by pickling in an 8-10 volume percent aqueous solution of sulfuric acid at 160-180 F. This solution is used

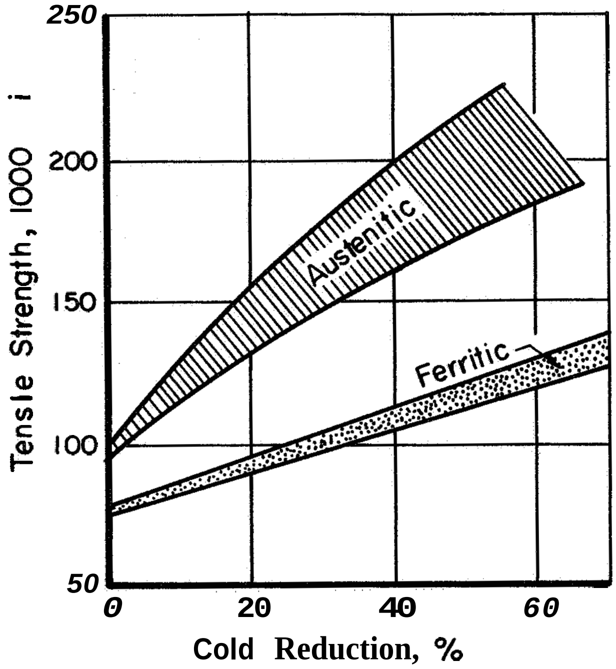
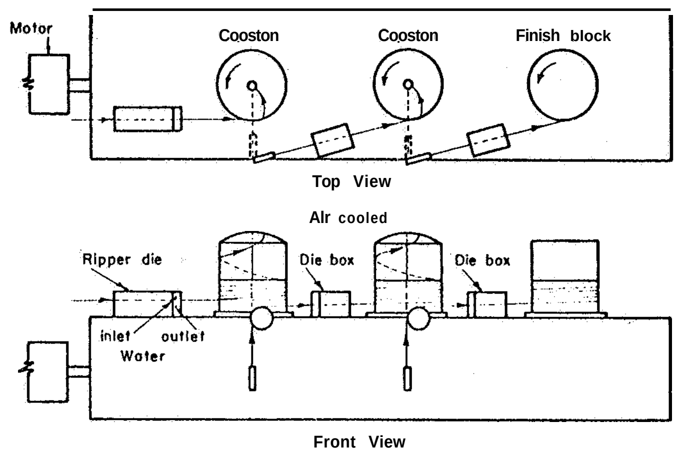


FIGURE 12. INCREASE IN TENSILE STRENGTH WITH INCREASING COLD REDUCTION FOR AUSTENITIC AND FERRITIC GRADES OF STAINLESS STEEL (Ref. 52)

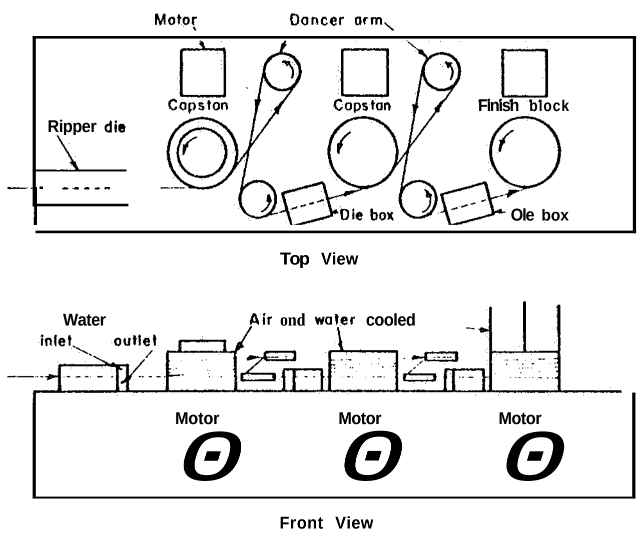
in preference to pickling in 20-25 volume percent hydrochloric acid at room temperature. Not only is pickling in hydrochloric acid more costly, but the possibility of chloride embrittlement also is present (Ref. 53). The surface produced by pickling in either solution is not bright and the austenitic grades usually are brightened in a nitric-hydrochloric acid solution containing from 20-2 to 14-3 volume percent of nitric and hydrochloric acid, respectively. The ferritic and martensitic grades may be brightened in 30 volume percent nitric acid at room temperature.

Coatings. A number of materials have been used as lubricant carriers during the drawing of stainless steel wire (Ref. 53). These include lead, copper, lime, borax, and oxalate coatings. Breakdown of stainless wire rod is often accomplished dry with lime coatings and soap lubricants. Sometimes borax is used in conjunction with lime for coating. Oxalate coatings frequently are used in conjunction with liquid lubricants for light finishing reductions on hard drawn wire. Copper coatings often are used on wire that is to be cold headed after drawing. Lead coatings, once frequently used, have largely been replaced by other coating materials. This has come about because of the toxicity associated with the use of molten lead and the need for good ventilation systems when lead is used. In the manufacture of spring wire, once a principal user of lead coatings, the lead coatings have largely been replaced by oxalates in recent years (Ref. 53).

Equipment. Drawing of the stainless steels in sizes down to about 0.050-inch diameter is usually done on multiple-die machines with dry-soap lubricants. Figure 13 shows schematic drawings of two types of machines used to draw stainless steel wire with dry lubricants. In the first type of machine, shown in Figure 13a, the wire is



a. Single- Motor. Accumulolor Block Type



b. Individual, Direct-Current , Vorioble- Speed Motor Type

FIGURE 13. SCHEMATIC DRAWINGS OF TWO TYPES OF WIRE–DRAWING MACHINES (Ref. 53)

drawn and stored on accumulator blocks before passing to the next die. A single motor is used to drive all the blocks that mechanically engage and disengage the main drive shaft. Capstans and blocks usually are air cooled.

The second type of machine as shown in Figure 13b is characterized by individual, variable-speed, direct-current motors whose speeds are regulated by a dancer arm that controls the speed at which the capstan revolves. Both air and water cooling is utilized with this type equipment. Wires drawn to about 0.050-inch diameter are drawn with dry-soap lubricants.

For wire sizes smaller than about 0.050-inch diameter, wet-wire-drawing techniques are used. Figure 14 shows a schematic drawing of one type of machine used with this practice. The wire is first passed through a ripper die where it is drawn with a dry-soap lubricant. The wire then is passed into the wire-drawing tub and is alternately passed from one capstan through the die to the other capstan and then back to the first capstan. The capstans either may be stepped, as shown, or tapered. This cycle is repeated to achieve the desired number of reductions. The drawing tub is filled with a liquid lubricant, which may contain vegetable soaps and emulsions as lubricants. After passing through the finish die, the wire is straightened on the "killer" or straightener and then spooled.

Figure 15 is a photograph of a versatile wire-drawing machine designed to draw wire having a maximum diameter of 0.037 inch either wet or dry. The machine has a self-contained lubricant tank and pump for circulating the liquid lubricants. Machines of this type, containing up to about 20 dies, are available.

Pointing. Rods and wires must be pointed prior to drawing through dies. This may be done mechanically by swaging or roll pointing, or chemically by acid etching or by electrochemical means. Where practical, mechanical points are preferred since the wire is strengthened by deformation thus increasing

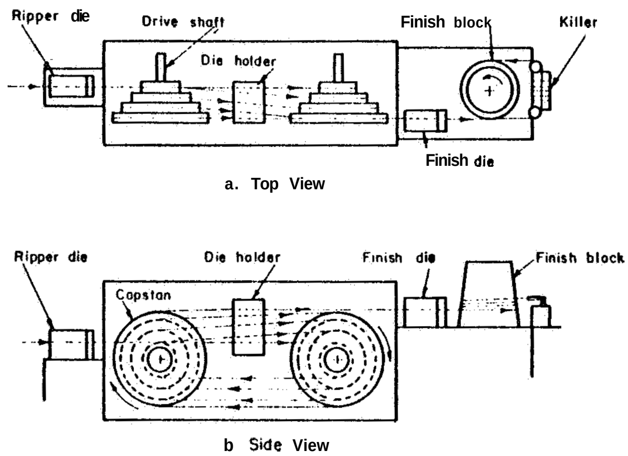


FIGURE 14. SCHEMATIC DRAWING OF WET-WIRE-DRAWING MACHINE (Ref. 53)

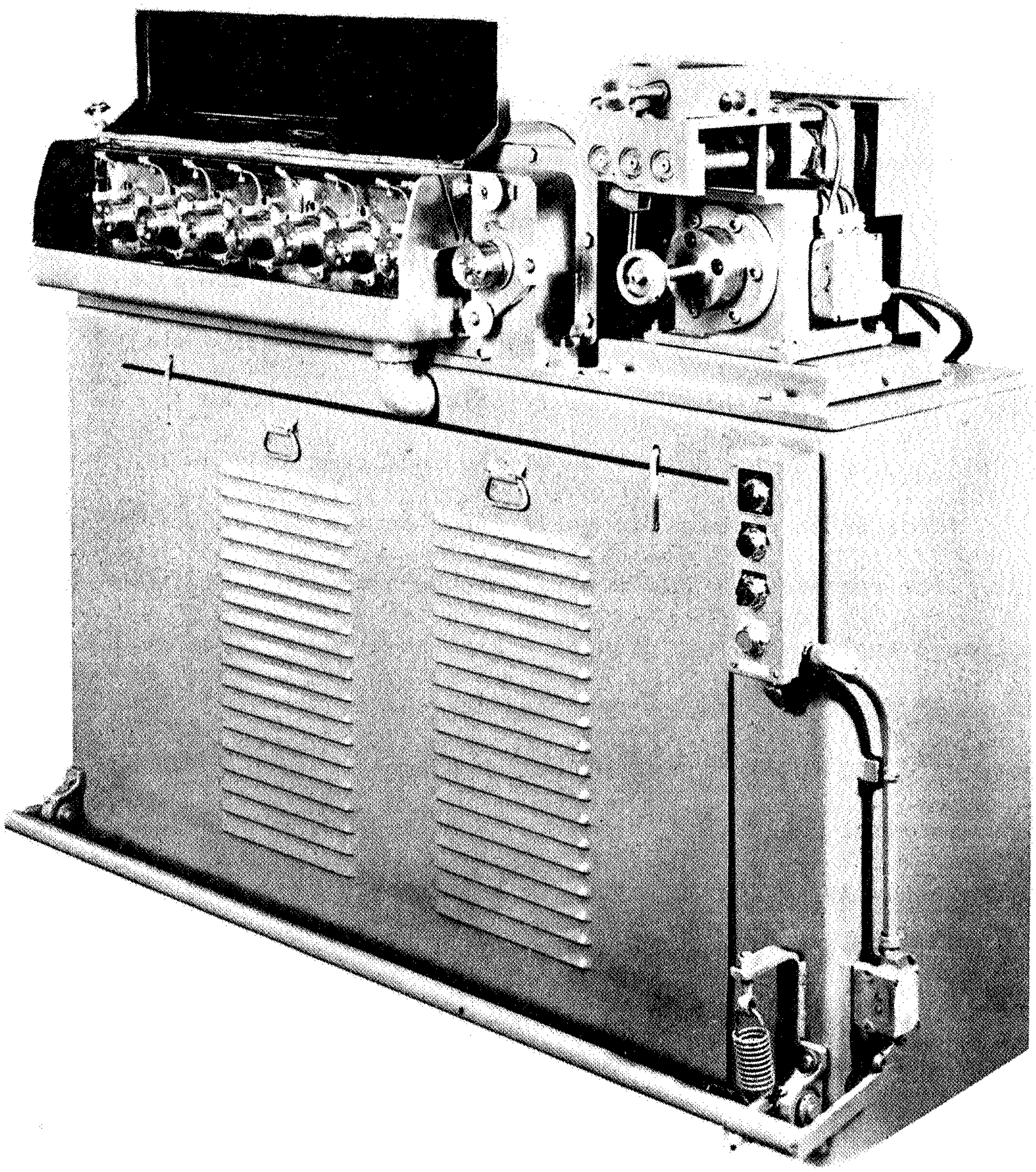


FIGURE 15. EIGHT–DIE FINE–WIRE MACHINE

Courtesy of the Vaughan Machinery Company, Cuyahoga Falls, Ohio.

the load that it can support in subsequent drawing operations. Acid pickling and electrochemical methods are most often used for pointing wire too fine to point mechanically.

Drawing Dies. Dies used for production drawing of stainless steel wire commonly contain tungsten carbide inserts in sizes down to about 0.044-inch diameter. Wire finer than 0.044-inch diameter is drawn with diamond dies. When it is necessary to maintain very close tolerances on size or to produce extremely brilliant surface finishes, diamond dies may also be used in drawing heavier wire. The dies are always water cooled in production drawing to keep the temperature of the wire and dies as low as possible and the friction coefficient as low as possible by minimizing the breaking down of the lubricant film during drawing.

There is an optimum die angle for a particular reduction at which the force required to pull a wire through a die is a minimum. Die entrance angles used for drawing stainless steel wire range from about 12 to 18 degrees. The approach angles usually are well blended into a bearing equal to 25-50 percent of the diameter which in turn is blended into a relief angle of 90 degrees. Sometimes dies with sharp interfaces between the approach angle and the bearing are used to produce wire that has a very bright and shiny surface finish.

Lubricants for Wire Drawing. Along with the lubricant carrier or coating, the lubrication of wire during drawing is extremely important. Some mills adopt the practice of drawing dry using tungsten carbide dies until the wire has achieved a diameter of about 0.044 inch. The lubricant for such operations is often a soap containing other additives such as molybdenum disulfide (MoS_2). One mill reports that new levels in operating economy can be achieved by adding 7 percent of MoS_2 to a calcium soap (Ref. *54)*. Special attention also must be paid to obtaining the correct proportion of fine and coarse particles in the soap mixture. Greater reductions, increased drawing speed, and reduced power consumption all have been achieved by one company by the addition of MoS_2 to the drawing compound. (Ref. 55)

For wet wire drawing, generally for drawing the finer stainless steel wire sizes with diamond dies, the wire-drawing lubricant can be either an oil or an aqueous-type lubricant (Ref.56). Oil-type lubricants generally are mineral oils containing proprietary additions such as soaps and/or active agents such as chlorinated or sulphonated compounds (Ref. 56). The aqueous types are better coolant3 and soap solutions and water soluble or emulsifiable compounds frequently are used for the wet drawing of stainless steel wire. The trend appears to be toward oils containing extreme pressure additives. Molybdenum disulfide also is frequently used in wet wire drawing lubricants.

Fluorocarbon materials also show promise as lubricants for stainless steel wire drawing (Ref. 57). However, the applicability of these materials in drawing (wet or dry) for the common grades of stainless steel may be limited by their relatively high price.

A rather interesting lubrication system that has been developed independently by British and Russian investigations in recent years is the pressure or hydrodynamic lubrication systems. The usefulness of hydrodynamic lubrication in wire drawing was demonstrated as early as 1955 by Christopherson and Naylor (Ref. 58) as a means for improving die life. **Figure** 16 shows the arrangement of the die in this lubrication system. The liquid lubricant clinging to the wire is forced between the wire and a close-fitting pressure tube and develops inlet pressures ranging from 10,000 to 40,000 psi for wire drawn at 600 feet/minute (Ref. 59). Under these conditions of high pressure, the wire is deformed prior to entering the die. The promise of providing adequate lubrication by this method generally has not been fulfilled in practice. One obstacle is that hydrodynamic lubricating conditions exist only when the wire is being drawn at relatively high speeds and not when starting and stopping of drawing. In addition, the wire-drawing industry has been reluctant to use the relatively long tubes (about 2 to over 30 inches) with their small clearances (about 0.002 in.) ahead of the die. (Ref. 60).

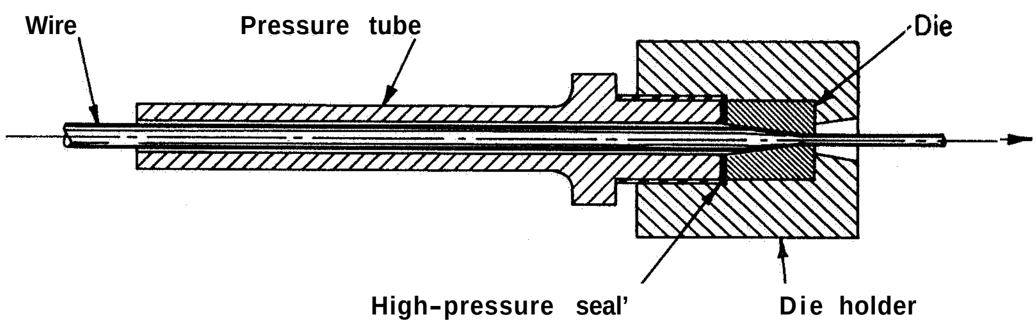


FIGURE 16. TYPICAL ARRANGEMENT OF INLET TUBE AND DIE FOR HYDRODYNAMIC LUBRICATION (Ref. 60)

More successful has been the adaptation of the hydrodynamic principle to dry soap drawing as embodied in the patented nozzle-die unit developed by the British Iron and Steel Research Association (BISRA) (Ref. 60). Figure 17 shows the cross section of the BISRA nozzle-die. The powdered soap that clings to the moving coated wire is carried from the soap box to the bell-shaped opening of the nozzle where it is compacted and liquified in the parallel portion of the nozzle. Pressures of 60,000 psi at the die

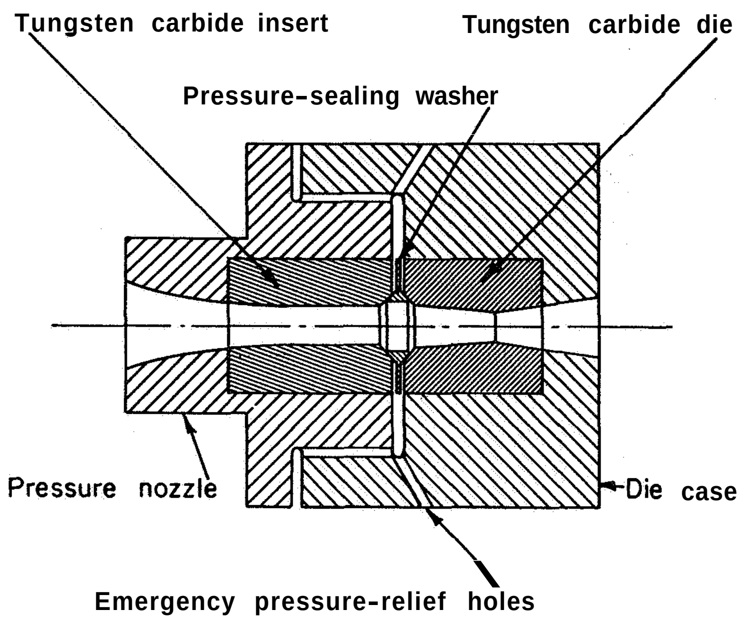
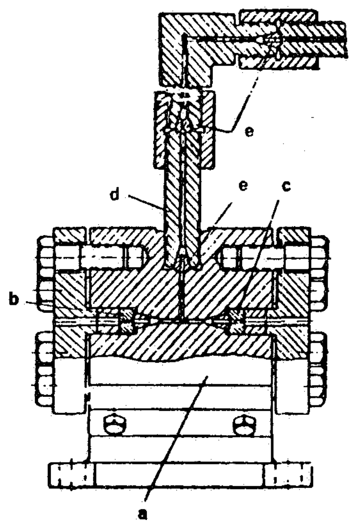


FIGURE 17. CROSS SECTION OF BISRA NOZZLE DIE UNIT FOR HYDRODYNAMIC LUBRICATION DRAWING WITH DRY SOAP (Ref. 60)

entry compact seventy to eighty times as much soap on the drawn wire as is obtained in normal dry drawing. This type of die unit has been used for the single die drawing of stainless steel wire. Industrial trials have shown a die life 3 to 8 times longer than with conventional dry drawing dies.

More recently, Moseev and Korostelin (Ref. 61) and Butler (Ref. 62) have studied the possibility of obtaining hydrodynamic lubrication conditions by pressurizing the lubricant with an external pump. Figure 18 shows the dieholder used by the Russians (Ref. 61) which is very similar



a = dieholder

b = first die to seal and reduce wire 1 to 3 percent

c = drawing die to achieve major reduction

d = vertical tube to feed lubricant from hydrocoinpressor to high-pressured drawing chamber

e = emergency pressure relief hole.

FIGURE 18. SKETCH OF DIEHOLDER FOR LIQUID LUBRICATION AT HIGH PRESSURE (Ref. 61)

to that used by Butler. Both studies indicated that this method makes the fluid pressure applied to the die controllable and independent of fluid viscosity, drawing speed, and die geometry. The method has been successfully used in drawing trials at drawing speeds of about 900 feet/minute for a single-pass reduction in areas of 30 to 35 percent. Butler found SAE 30 oil more effective than lighter oil for pressurizing the chamber. Both methods (Ref. 61,62) are best suited to continuous wire drawing since the systems must be depressurized before the tail end of the wire enters the first (ironing) die. The method has not yet been used in commercial wire-drawing applications.

Available Forms. Stainless steel wire commonly is available in the following four tempers:

Annealed temper - soft wire not drawn after the last annealing heat treatment.

Soft temper - wire that has been given a single light draft after the final annealing treatment. Various dry drawn surface finishes are available.

Intermediate temper - wire drawn one or more drafts after annealing to produce minimum strength or hardness. The properties of such wire vary widely between those of soft temper and those approaching spring temper.

Spring temper - wire drawn several drafts as required to produce the high tensile strengths needed for spring wire.

Stainless steel spring wire is used to produce extension and compression springs. The strengths of straightened and cut lengths may be as much as 10 percent lower than the values given in the literature (Ref. 63).

Stainless steel wire also is available by product and commodity names generally connected with the purpose for which the wire has been designed. Included would be such materials as free-machining stock used for automatic screw machines, cold heading wire, spring wire, rope wire, weaving armature binding wire, slide forming wire, wool wire, reed wire, lashing wire, and cotter pin wire (Ref. 63).

TUBE DRAWING

Tube drawing consists of reducing the diameter and/or wall thickness of a hollow cylindrical shape by drawing the shape through a die. The drawing usually is done cold and is accomplished to obtain closer dimensional tolerances, higher strengths, better surface finishes, thinner walls or smaller diameters than are possible in hot-formed tubes. Irregular tubular shapes can also be produced by drawing. The starting material or preform for tube drawing may be produced by hot extrusion, hot rolling and piercing of a billet, or welding of a roll-formed strip, plate, or sheet.

Tubes often are drawn on drawbenches. Figure 19 shows schematically the operation of continuous chain-type drawbenches using plug and bar mandrels. Drawbenches powered by hydraulic cylinders also are available. Sometimes the outside diameter of a tube is sized by drawing the tube through a die without supporting the inside diameter of the tube. Such tube drawing is called tube sinking.

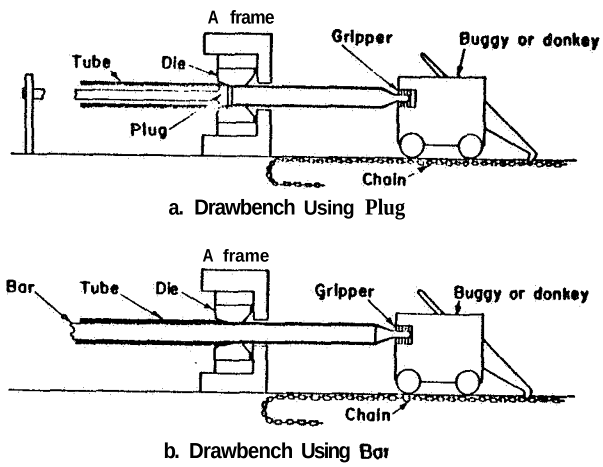


FIGURE 19. SCHEMATIC DRAWING OF TUBE DRAWBENCH (Ref. 53)

The length of a tube that can be produced on a drawbench is limited by the length of the bench. Commercially 50- to 100-foot-long benches are commonly used although benches as long as 200 feet are available. Drawing speeds ranging from 20 to about 150 **fpm** are typical to draw the stainless steels. Some benches are automatically controlled *so* that the tube is started through the die at a slow speed and as soon as it is fairly started, the speed is increased to a predetermined drawing rate. Some benches are equipped to permit the drawing up to *6* tubes at a time.

Dies for stainless steel tube drawing are similar to those used for wire drawing. Dies up to 3-inch-diameter holes are made with tungsten carbide inserts. Larger dies are made from hardened tool steels which are chromium plated on the wear surfaces (Ref. 6). Dies for drawing very small tubes most often have diamond inserts as for wire drawing. A 12-degree approach angle is common for drawing the stainless steels, and the bearing length depends on the material being drawn and the amount of reduction (Ref. 64). The intersection between the approach angle and the bearing length in the dies is well blended. As for wire drawing, oxalate coatings on the tubes are widely used. Sometimes the tubes are plated with copper to assist in drawing. Lubricants generally are the oil type often consisting of a mineral oil with proprietary additives including soap and active agents such as chlorinated or sulphonated compounds.

Reductions in area of 35 percent per drawing pass are not uncommon when drawing the austenitic grades of stainless steel tubes especially in the smaller diameters. Total reductions of 50 percent often are possible between in-process anneals. However, the frequency of the in-process anneals depends to a large extent on the work-hardening rate of the particular grade of stainless steel being drawn. Some grades with a high work-hardening rate may require annealing after each drawing pass.

A rather recent development in the drawing of stainless steel tubing in straight lengths is the commercial use of ultrasonic vibrations to activate the stationary plug mandrel during drawing (Ref. 65). This system, which is covered by patents, has been used in the drawing of thin-walled tubing in Types 304, 316, and 321 stainless steel. Its use permits the tubes to be drawn without chatter and also enables the drawing of larger sizes without exceeding the capacity of available drawbenches. Since these systems have only been in use for relatively short periods of time, their influence on tube drawing practice cannot yet be assessed.

Although most of the stainless steel tubing is sold in straight lengths, tubing also is commercially available in the smaller diameters in coils which may contain up to about 1500 feet. Such tubing is produced on a drawing block using a floating plug mandrel. Figure 20 **shows** the floating plug mandrel along with four other types of mandrels used in tube drawing. The other mandrels are used for the drawing of shorter tube lengths on a drawbench. The speeds on drawing blocks are continuously variable up to about 1600 fpm and the diameters of the drums on the blocks vary from about 20 to 114 inches. The drums may be mounted either vertically or horizontally.

Another means of reducing the diameter and wall thickness of stainless steel tubing is by use of a tube reducing machine. The operation of this machine is shown in Figure 21. The machine operates on the principle of the Pilger mill and reduces the diameter and wall thickness of the tube simultaneously by rolling while the tube is in tension. The tube to be reduced is passed over the mandrel bar. The leading end of the mandrel has a conical shape. The tube is moved back and forth hydraulically in 1/8 to 1/2-inch increments while the mandrel remains stationary. Twin roll shafts carry the half dies and tapered grooves to accommodate the incoming tube. These are mounted on a rack and pinion and rock over the tube effectively reducing it to the contour of the tools. The tube and mandrel is rotated 60 to 90 degrees between each reciprocating motion of the rolls to iron out and prevent fins from forming and to improve the concentricity of the tube. The cost of tools on these machines is high and separate tools and mandrels are required for each tube diameter. The machines can only be justified where the quantity of one size of tube to be reduced is very large and the machine can be operated continuously.

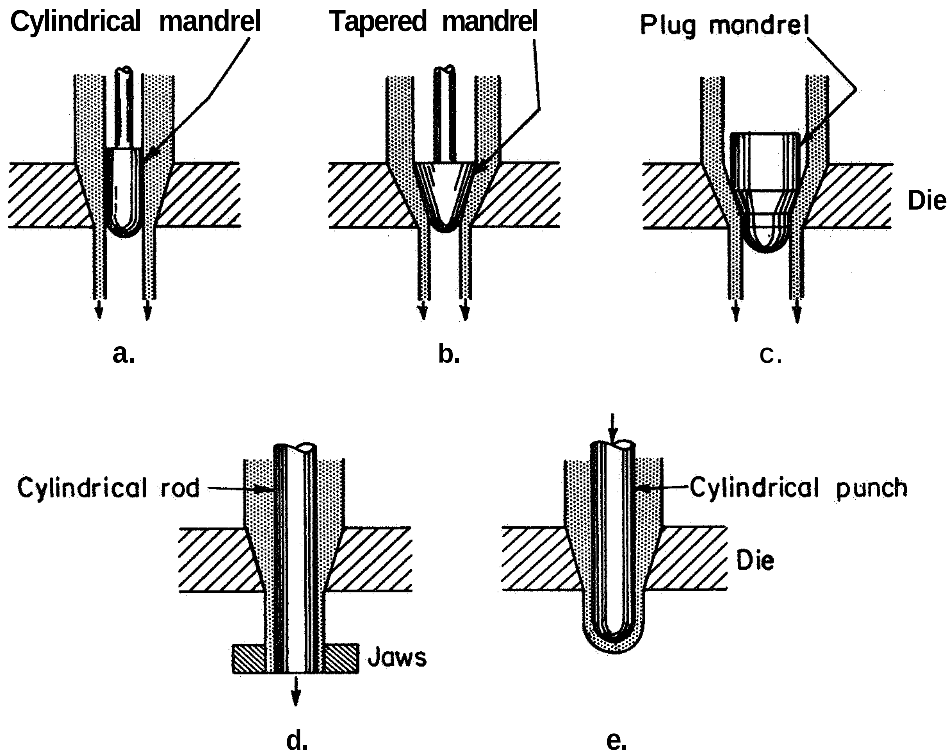


FIGURE 20. TUBE–DRAWING METHODS

(a) Stationary cylindrical mandrel; (b) conical (tapered) stationary mandrel; (c) floating plug mandrel; (d) moving rod; *(e)* pushed with punch. (a), (b), (d), and (e) courtesy of McGraw–Hill Book Company, New York (1961).

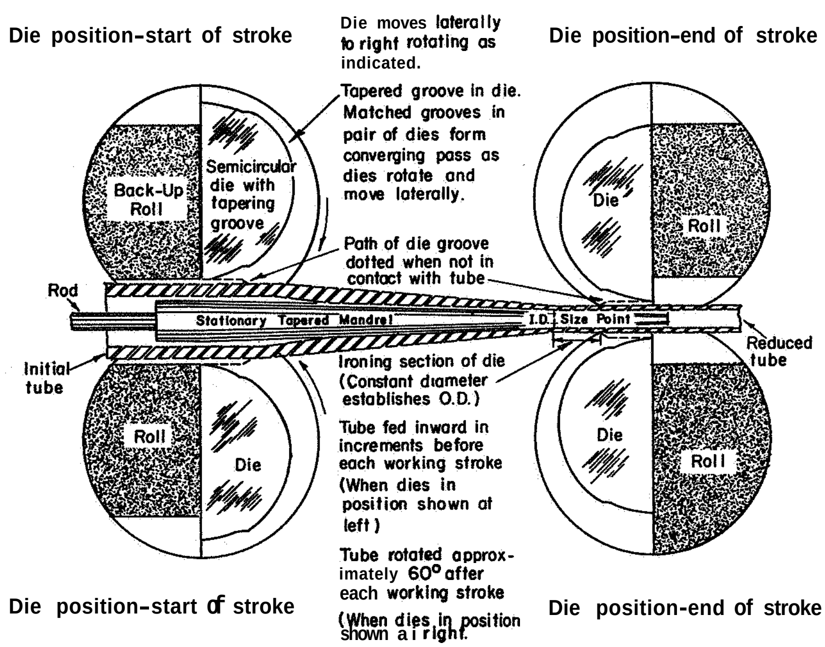


FIGURE 21. OPERATION OF TUBE REDUCING MACHINE (Ref. 6)

Courtesy of United States Steel Corporation, Pittsburgh, Pennsylvania

Reductions up to about 70 percent are possible in a single pass with the stainless steels on a tube reducer.

Available Tube Sizes. Stainless steel tubing and pipe are available commercially in sizes ranging from about 0.008-inch outside diameter with 0.002-inch wall to about 30-inch diameter with 2-inch-thick wall. The larger pipes are made by roll forming or brake bending and welding techniques while the very small tubes are usually seamless. Intermediate sizes up to about 2-1/2 inches in diameter are supplied either as seamless or welded tubing.

The tubing is available in random lengths, selected randon lengths, and multiple lengths. In outside diameters under 1/8 inch, commercial random lengths range from 1 to 15 feet; in diameters 1/8 inch and larger, random lengths range from 5 to 24 feet for seamless and 5 to 30 feet for welded tubing.

Selected random lengths may be designated within acceptable production limits. It is sometimes feasible for the mill to produce in a full random range and bundle the material in 2- or 30-foot increments when packing. Multiple lengths fall into the following three ranges: multiples under 3 feet, multiples 3 to 6 feet, and multiples 6 feet and over. Cut ends are furnished burr free.

The coiled tubing is furnished in the following coil diameters unless otherwise specified:

Below 1/8-inch OD - 9- or 18-inch-diameter coil

1/16-inch OD to below 3/8-inch OD - 18- and 30-inch-diameter coil

3/8-inch OD to 5/8-inch OD - 30- and 36-inch-diameter coil.

Stainless steel tubing generally is available in the following three conditions of temper:

Temper No. 1 - soft annealed

Temper No. 2 - half hard drawn

Temper No. 3 - full hard drawn.

The various tempers are obtained by a combination of cold drawing and heat treatment. In addition, the intermediate tempers, 1/4 hard, 3/4 hard, and hard drawn and stress relieved also are available for special applications. When an annealing heat treatment is required to produce the soft annealed temper condition, stainless steel tubing often is heated in a protective atmosphere of pure hydrogen at the 2100 F annealing temperature prior to straightening.

SECONDARY DEFORMATION PROCESSES

Sheet, plate, bar, tubing, and extrusions can be converted to more useful shapes by secondary deformation processes. All of the conventional techniques used for that purpose have been applied successfully to stainless steels. Descriptions of many of the common sheet and tube-forming processes and the limits imposed by the characteristics of the materials of interest are covered in this section of the report. To aid the design engineer in selecting the process for making a particular part, Figure 22 has been included.

The severity of deformation required to produce a part depends on the relative shapes and dimensions of the blank or preform and the completedpart shape. The properties of the workpiece material determine whether the desired change in shape can be accomplished successfully. Failures in forming are caused by rupture, buckling, or a combination of these. Rupture or fracture results from lack of ductility under imposed tensile stresses; excessive compressive loading causes elastic or plastic buckling. Methods for predicting the formability of sheet materials from their mechanical properties in simple tests were developed during an extensive study for the U.S. Air Force by Ling-Temco-Vought, Inc. (Refs. 66,67). That investigation indicated that failures in conventional forming operations result from the mechanisms shown in Table IX. (Ref. 68). The table also shows the mechanical properties found to correlate with limiting deformations and different types of forming operations. Higher values of the parameters indicate better formability. The mechanical properties needed to calculate the formability parameters for a particular material can be determined from tensile and compressive tests conducted at the desired forming temperature. Other organizations are also investigating the correlations between standard mechanical properties and the performance of materials in

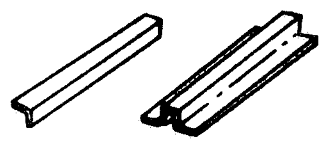
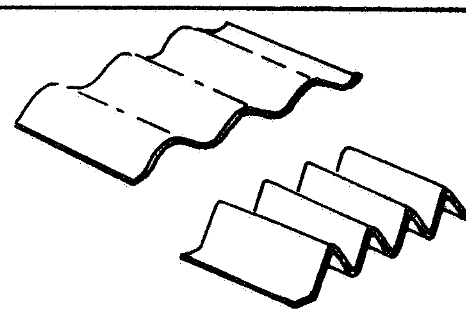
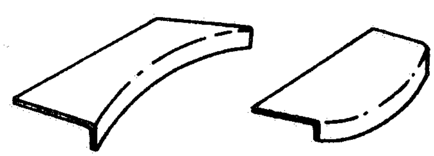
Type of Forming	Forming Process		Applicable Part Shapes
	Low Energy Rate	High Energy Rate	
Bending straight flanges	Brake press Roll press	None	
Bending straight corrugations	Mechanical press Drop hammer Rubber press	None	
Bending curved flanges	Rubber press Drop hammer Mechanical press Hydraulic press	High explosive open system	

FIGURE 22. FORMING PROCESSES AND PART SHAPES (Ref. 66)

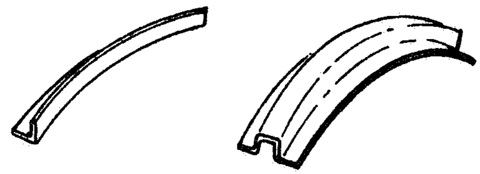
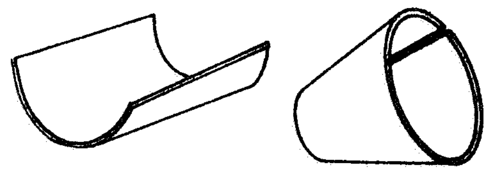
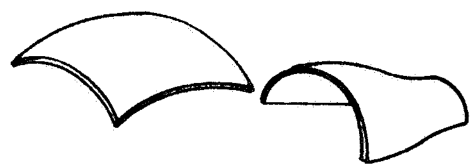
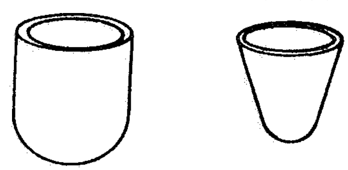
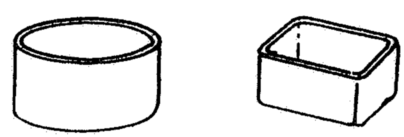
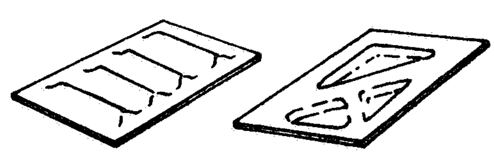
Type of Forming	Forming Process: Low Energy Rate	Forming Process: High Energy Rate	Applicable Part Shapes
Contouring formed sections	Extrusion strech press Extrusion roll formed Mechanical press Drop hammer	None	
Single curvature sheet contouring	Sheet roll former	None	
Compound curvature sheet contouring	Sheet stretch press Drop hammer Rubber press Sheet incr. former Fluid forming	High explosive open system Explosive gas Electro-hydraulic	
Spinning	Power Monual	None	
Deep processing	Mechanical draw die Mechanical press Rubber press Hydraulic press High pressure fluid Drop hammer	Low explosive closed system High explosive open system Pneumatic mechanical Electro-hydraulic Electro-magnetic Explosive forming	
Shallow processing			

FIGURE 22. FORMING PROCESSES AND PART SHAPES (Ref. 66) (Continued)

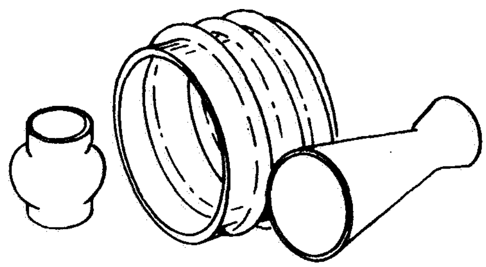
Type of Forming	Forming Process		Applicable Pari Shapes
	Low Energy Rate	High Energy Rate	
Tube bulging	Rubber Plug Expanding mandrel High pressure fluid	Low explosive closed system Electro-hydraulic Electro-magnetic Explosive gas	

FIGURE 22. FORMING PROCESSES AND PART SHAPES (Ref. 66) (Concluded)

TABLE IX. TYPES OF FAILURES IN SHEET-FORMING PROCESSES AND MATERIAL PARAMETERS CONTROLLING DEFORMATION LIMITS[a] (Ref. 68)

Process	Cause of Failure: Splitting	Cause of Failure: Buckling	Ductility Parameter[b]	Buckling Parameters[c]
Brake forming	x		ε in 0.25 in.[d]	
Dimpling	x		ε in 2.0 in.[e]	
Beading				
Drop hammer	x		ε in 0.5 in.[d]	
Rubber press	x		ε in 2.0 in.[d]	
Sheet stretching	x		ε in 2.0 in.	
Joggling	x	x	ε in 0.02 in.[f]	E_c/S_{cy}
Liner stretching	x	x	ε in 2.0 in.[g]	E_t/S_{ty}
Trapped rubber, stretching	x	x	ε in 2.0 in.[g]	E_t/S_{ty}
Trapped rubber, shrinking		x		E_c/S_{cy} and $1/S_{cy}$
Roll forming		x		E_t/S_{ty}[h] and E_c/S_{cy}[i]
Spinning		x		E_c/S_{cy} and E_t/S_u
Deep drawing		x		E_c/S_{cy} and S_{ty}/S_{cy}

(a) The parameters can be determined in tensile and compressive tests.

(b) ε indicates natural or logarithmic strain: the dimensions indicate the distance over which it should be measured.

(c) E_c = modulus in compression; E_t = modulus in tension; S_{cy} = compressive yield strength: S_{ty} = tensile yield strength; S_u = ultimate tensile strength.

(d) Corrected for lateral contraction.

(e) For a standard 40-degree dimple.

(f) The correlation varies with sheet thickness.

(g) The correlation is independent of sheet thickness.

(h) For roll forming heel-in sections.

(i) For roll forming heel-out sections.

specific forming operations. As information of this kind is collected and systematized it will become easier to predict the response of materials to deformation processing.

The forming limits set by necking or splitting correlate with ductility measurements in tensile tests. Deformation limits set by buckling failures correlate with the ratios of elastic modulus to the yield strength of the material. Since changes in temperature affect all of these mechanical properties formability varies with deformation temperature. Stainless steels are generally formed at room temperature. The exceptions to this rule are some of the martensitic stainless steels which may be warm formed at 200-300 F to increase ductility.

BRAKE BENDING

Introduction. Brake bendingis a simple, versatile operation widely used for forming flat sheets into sections such as angles, channels, and hats. The process uses inexpensive, simple tooling that can be quickly adapted to different part shapes. Brake forming is used mostly for making parts to wide tolerances and for preforming operations on close-tolerance parts. Heavy-wall welded pipe and tubing also are made by brake-forming techniques, using specially shaped dies, and then welded. Hand-working or sizing operations are usually required to produce parts with closer dimensional tolerances.

Greater allowance for springback must be made when bending the stainless steels than when bending the carbon steels. This is because of the higher yield strengths and higher work hardening rates of the stainless steels. The increased springback is especially evident in the 300 series,

Although brake presses often are used to make simple bends, they also find extensive use in forming more complicated sections. Figure 23 illustrates the use of a 500-ton hydraulic brake press having a 30-foot-long bed, in producing corrugations in long sheets of stainless steel. The more complex die designs are illustrated producing three bends per stroke. The covering on the bottom dies minimizes scratching of the sheet during handling.

Principles of Bending. In bending, the metal on the inside of the bend is compressed, or shrunk, while that on the outside of the bend is stretched. This is shown in Figure 24 for two typical brake-forming setups. In air bending, the workpiece is supported only at its outer edges so that the length of the ram stroke determines the bend angle, α, of the part. The radius of the punch controls the inside radius of the workpiece.

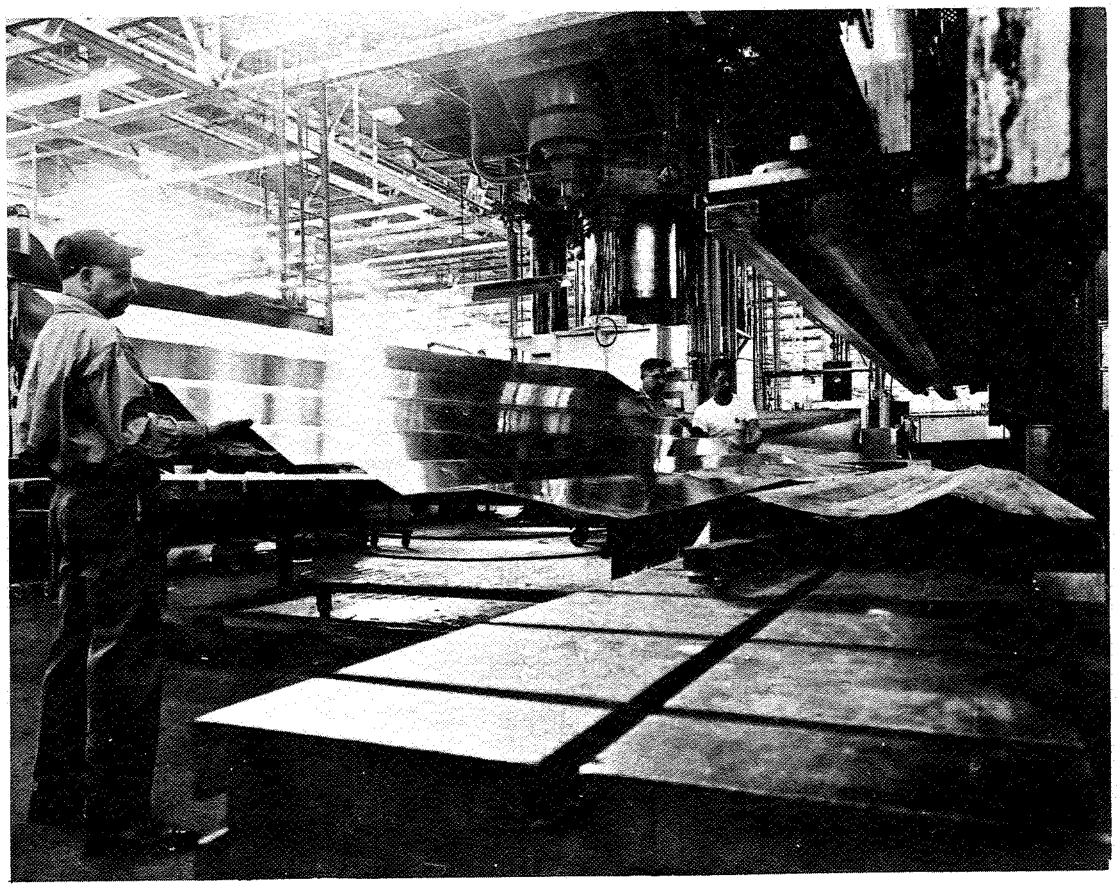


FIGURE 23. CORRUGATION OF LONG SHEETS OF TYPE 301 STAINLESS PRODUCED ON A 500-TON HYDRAULIC BRAKE PRESS WITH A 30-FOOT LONG BED

Courtesy of Columbus Division, North American Aviation, Inc.

In die bending, the sheet is forced into a female-die cavity of the required part angle, α.

The limiting span width, S, in Figure *36* depends on the sheet thickness, T, and the punch radius, R. According to Wood (Ref. 69), the practical limits for brake bending lie between:

$$S = 3R + 2T \text{ and } S = 2.1R + 2T \quad . \qquad (3)$$

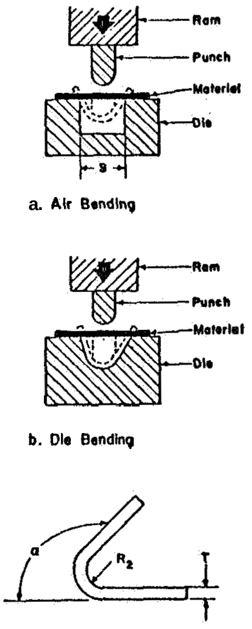


FIGURE 24. TYPICAL BRAKE-FORMING SETUPS AND PARAMETERS

Those variables and the bend angle control success or failure in bending. Larger radii are needed for thicker sheet and the ratio of R/T should also be increased for larger bend angles. The limiting bend angle and bend radius depend on the ability of the metal to stretch. If the operation is too severe, the metal cracks on the outer surface of the bend.

Presses Used for Brake Forming. A press brake is a single-action press with a very long and narrow bed. Its chief purpose is to form long, straight bends in pieces such as channels and corrugated sheets.

Brake presses are commercially available having capacities ranging from about 8 to 2000 tons. Figure 25 shows a large brake press having a capacity of 1500 tons and a bed 30 feet long. For bending relatively thin sheet metal, the press capacity can be relatively small.

Table X lists the capacities and other pertinent information on brake presses available from one manufacturer. As a general rule and subject to confirmation by equipment manufacturers on specific jobs, press ratings should be increased from 50 to 60 percent when bending stainless steels over those used for carbon steels (Ref. 3). This is especially true when bending the harder tempers since the stainless steels work harden more rapidly than the carbon steels and develop higher yield strengths than the carbon steels.

Tooling. Figure 26 shows a group of typical press-brake bending and forming dies (Ref. 70). The dies pictured include 90-degree and acute-angle forming dies (a and b), gooseneck dies (c), offset dies (d), hemming dies (e and F), seaming dies (g), radius dies (h), beading dies (i), curling dies (j), tube- and pipe-forming dies (k and 1), four-way die blocks (m), channel-forming dies (n), U-bend dies (o), box-forming dies (p), corrugating dies (q), multiple-bend dies (r), and rocker-type dies (s).

Materials used as dies and punches for brake-press forming the stainless steels are generally the same as those used for the carbon steels. As a basic principle, the larger the differential in hardness between the tooling and the workpiece, the greater the resistance to galling (Ref. 71, 72).

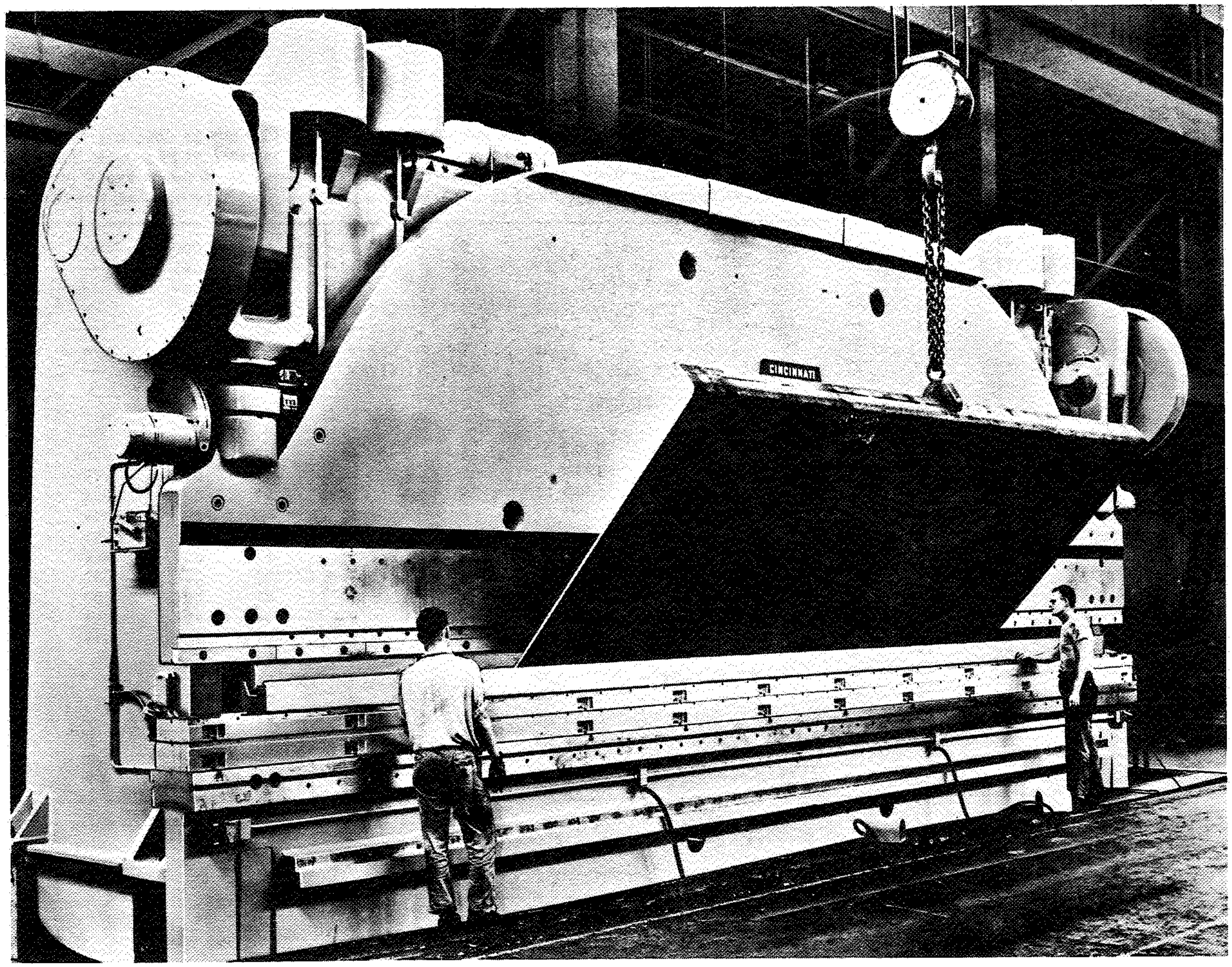


FIGURE 25. 1500-TON MECHANICAL PRESS BRAKE HAVING A 30-FOOT-LONG BED
Courtesy of the Cincinnati Shaper Company, Cincinnati, Ohio

TABLE X. CAPACITIES AND OTHER TYPICAL INFORMATION ON BRAKE PRESSES[a]

Model	Capacity, tons: Mid-Stroke	Capacity, tons: Near Bottom of Stroke	Range of Bed Lengths, feet: Longest	Range of Bed Lengths, feet: Shortest	Stroke: Standard Length, in.	Stroke: Speed, surface feet/minute	Bending Capacity, feet, Mild Steel With Standard Stroke for Thicknesses: 16 Gage	3/16 In.	1/4 In.	1/2 In.	3/4 In.	1 In.	Motor Horsepower	Range of Shipping Weight, pounds: Largest	Range of Shipping Weight, pounds: Smallest
Mechanical Press Brakes															
1B-15	--	15	10	4	2	20-50	4 4	3/4	--	--	--	--	3/4-1	3,800	2,500
1B-25	--	25	12	6	2	20-50	6-1/2	1-1/2	--	--	--	--	1-1/2	5,200	4,500
1B-36	36	55	12	6	2-1/2	40	12	3	--	--	--	--	3	8,300	6,900
1B-60	60	90	14	6	3	40	18	6	--	--	--	--	5	17,800	10,923
N-90	90	135	14	6	3	36 and 12	--	11	6	--	--	--	7-1/2	25,350	12,500
N-115	115	175	14	6	3	36 and 12	--	15	10	--	--	--	10	30,000	15,400
N-150	150	225	16	6	3	33 and 11	--	19	13	--	--	--	15	50,000	24,800
N-200	200	300	18	8	4	30 and 10	--	23	18	6	--	--	20	53,000	32,000
N-260	260	400	18-2/3	8-2/3	4	30 and 10	--	--	24	8	--	--	20	67,500	37,000
N-335	335	500	18-2/3	8-2/3	4	30 and 10	--	--	25	10	5	--	25	90,000	60,000
N-400	400	600	24	10	4	30 and 10	--	--	30	12	5	--	30	120,000	64,000
N-520	520	750	24	10	4	23 and 7	--	--	--	18	10	--	40	157,000	79,500
N-650	650	1000	24	10	5	23 and 7	--	--	--	24	12	6	40	180,000	92,000
N-825	825	1250	22	14	6	20 and 6	--	--	--	30	17	10	50	194,000	133,000
N-1000	1000	1500	24	14	6	20 and 6	--	--	--	--	21	12	50	230,000	141,000
Hydraulic Press Brakes															
HD-200	--	200	18-2/3	8-2/3	12	21 and 34(b)	--	14	12	--	--	--	25	50,000	26,500
HD-300	--	300	18-2/3	8-2/3	12	25(b)	--	--	16	8	--	--	30	52,600	29,000
HD-400	--	400	18-2/3	8-2/3	12	26(b)	--	--	--	12	6	--	40	67,000	33,000
HD-500	--	500	18-2/3	8-2/3	12	25(b)	--	--	--	14	9	--	40	85,500	50,000
HD-600	--	600	24	10	12	25(b)	--	--	--	16	10	--	50	119,000	59,800
HD-750	--	750	24	14	12	21(b)	--	--	--	22	14	10	60	120,000	79,500
HD-1000	--	1000	24	14	18	21(b)	--	--	--	--	18	14	75	204,000	102,000

(a) Data taken from Booklet 203C and Bulletins 89F and 91 from Niagara Machine and Tool Works, Buffalo, New York.
(b) Normal press speed gives rated capacity. High press speeds along with press tonnage ratings are as follows: HD-200, 57 and 65 in./min at 70 tons; HD-300, 44 and 62 in./min at 120 tons; HD-400, 51 and 62 in./min at 160 tons; HD-500, 54 and 58 in./min at 200 tons; HD-600, 56 and 51 in./min at 240 tons; HD-750, 48 and 47 in./min at 300 tons; and HD-1000, 58 and 44 in./min at 400 tons

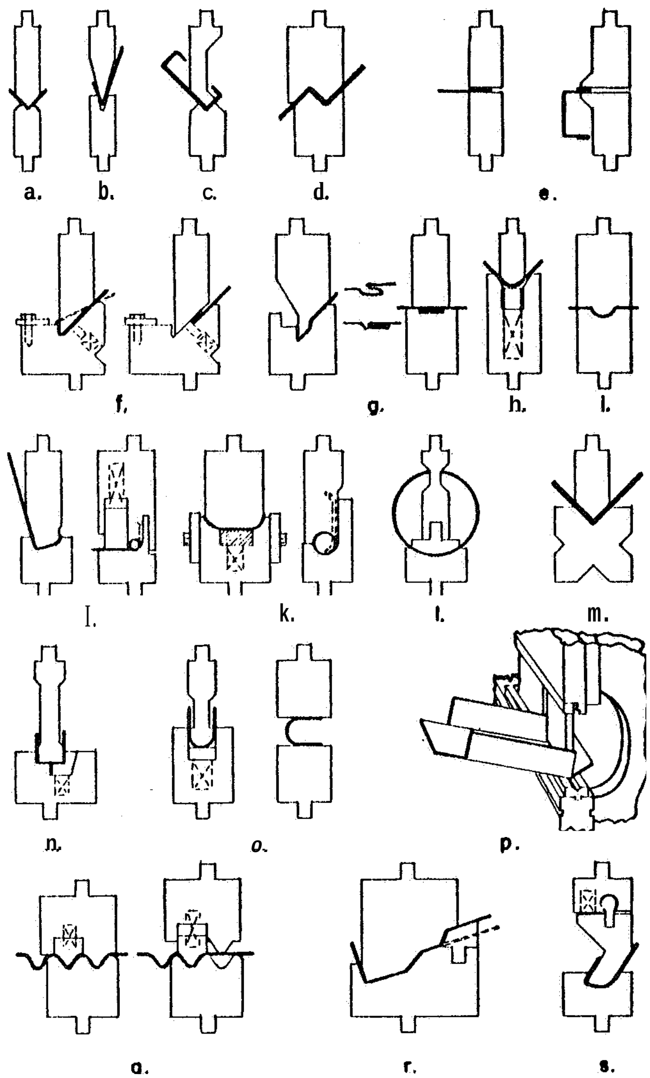


FIGURE 26. TYPICAL PRESS-BRAKE-BENDING AND FORMING DIES (Ref. 70)

Derived or adapted from the Verson Allsteel Press Company, Chicago, Illinois (a, f, g, h, i, k, 1, n, o, q, r, s); The Cincinnati Shaper Company, Cincinnati, Ohio (b, d, m, p); and Dreis and Krump Manufacturing Company, Chicago, Illinois (e, j). Courtesy of American Society of Tool and Manufacturing Engineers.

Brake-press tooling is made from a variety of materials and the choice of tooling for a specific application depends on the size of the part, the number of parts to be formed, and the complexity of the required bends. When only a small number (250 to 1000) parts are required, cold-rolled steel often is used as a die material. Zinc-alloy (Kirksite) tooling also may be used to produce small quantities of parts (usually less than 50). Meehanite cast iron is used for punches and dies at temperatures up to 1400 F.

When the quantity of parts to be produced is large (1,000 to 10,000), punches and dies made of hardened 1080 carbon steel or low-alloy steels such as SAE 3140 and 4340, tool steels such as H-11, and aluminum bronze are used extensively. In this connection, laboratory tests indicate that hardened 17-4 PH stainless steel has excellent resistance to galling when used against solution-treated 17-4 PH stainless steel, and should prove to be an excellent die material also for the regular grades of stainless steel (Ref. 71). Chromium plating on steel punches and dies and aluminum-bronze dies are often used to minimize galling. For the production of very large quantities of parts (over about 10,000), the extra cost involved in using cemented carbide punches and dies may be warranted. However, cemented carbides should not generally be used in conjunction with lubricants containing sulfur and chlorine because the nickel- or cobalt-alloy binder may be embrittled, thus, causing the tool to crumble.

Sometimes beryllium copper is used for forming dies, especially for relatively short-production runs. This material can be precisely cast to shape and, for many applications, requires no further machining. Thus, economy in die costs can be achieved over other methods and materials.

Punches are made to the desired bend radii. The female die may be a V die or a channel die. For brake forming at room temperature, a hard-rubber insert sometimes is placed in the channel die to avoid scratching the formed parts. The surface of the punch must be free of defects such as nicks where it contacts the blank,

In recent years, urethane pads also have been used as universal female dies for some brake-forming applications. Figure 27 shows some press-brake dies in which urethane has been used. These dies are most useful where set-up time, flexibility, and prevention of scratching and marring of parts are important factors. Only the punch needs to be machined for the specific application since the urethane behaves like a liquid under the confined conditions.

Figure 27 shows the following press-brake applications of urethane dies: V- and U-forming applications (a, b, and c); radius-forming applications (d); forming with gooseneck punches (e and f), forming reverse bends (g), and contour forming with concave areas (h). For these latter applications, the lighter the sheet thickness, the sharper the definition.

Bending Procedures. Blanks of stainless steel sheets are prepared for bending on a press brake by methods described in the section on blank preparation. Whenever possible, the stainless steels are bent in the soft annealed condition but, sometimes, it is necessary to bend them in the work-hardened condition. Data in Table XI give minimum bend radii for the austenitic stainless steels (Ref. 73). Bend radii used for design purposes usually are larger than the minimum bend radii. The values of bend radii given in Table XII are those used for some grades of austenitic stainless steels by one aircraft company.

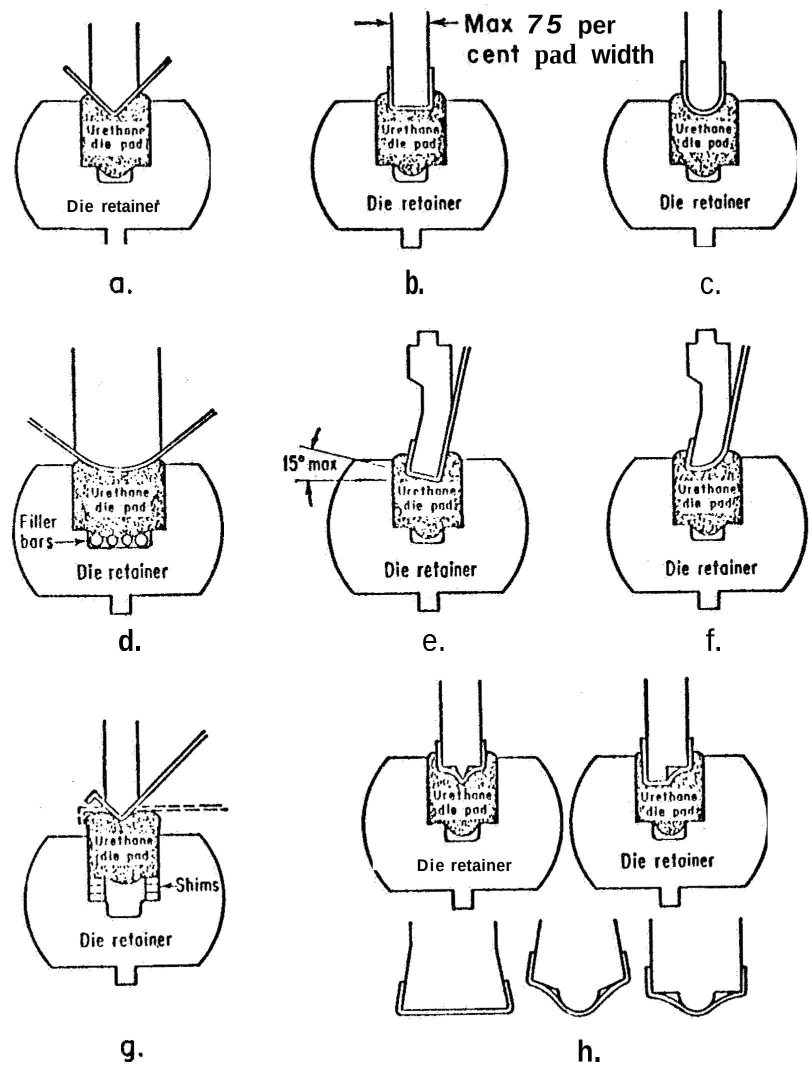


FIGURE 27. PRESS–BRAKE DIES USING URETHANE AS THE LOWER DIE (Ref. 70)

Courtesy of the American Society of Tool and Manufacturing Engineers.

TABLE XI. RANGES OF MINIMUM BEND RADII FOR VARIOUS TEMPERS OF AUSTENITIC STAINLESS STEELS **(Ref. 73)**

Temper	Approximate Strength Levels, psi Yield	Tensile	Minimum Bend Radii, R, as a Function of Thickness, T
Annealed	30,000	75,000 to 100,000	1/2 to 1-1/2
1/4 hard	75,000	125,000	1 to 2
1/2 hard	110,000	150,000	2-1/2 to 4
Full hard	140,000	185,000	4 to 6

The surfaces of sheets as well as the surfaces of the punches and dies are often covered with paper or other materials to minimize scratching and marring during handling or bending. Adhesive tape also may be used on the surfaces of the tools to maintain good surface appearance. Sheets of stainless steel that have pronounced directional properties, such as Type 430, are more easily bent in the direction perpendicular to the rolling direction (Ref. 3). Warming the straight chromium grades such as Types 430, 442, and 446 to temperatures in the range of 250 to 400 F improves their bendability. Conversely, it is good practice not to bend these types of stainless steel at subnormal temperatures. Also, a reduction in the speed of bending combined with a little warming is particularly beneficial with the higher chromium grades such as Type 446 (Ref. 3).

Lubricants normally are not used when bending the stainless steels. When used, the lubricant serves more to protect the sheet or part from marking and abrasion than to provide any actual lubricating action. Such lubricants are usually light oils or soap solutions (Ref. 55). When lubricants

TABLE XII. DESIGN STANDARD BEND RADII FOR SELECTED[a] STAINLESS STEELS

Material 'hickness, inch	Standard Bend Radii, inch[b] Types 301, 302, 316, 321 Annealed	Types 301 and 316 1/4 H	Types 301 1/2 H
0.012	0.03	0.06	0.06
0.016	0.03	0.06	0.06
0.020	0.03	0.06	0.06
0.025	0.03	0.06	0.09
0.032	0.03	0.06	0.09
0.036	0.06	0.09	0.13
0.040	0.06	0.09	0.13
0.045	0.06	0.09	0.13
0.050	0.06	0.13	0.16
0.056	0.06	0.13	0.19
0.063	0.06	0.13	0.19
0.071	0.09	0.16	0.22
0.080	0.09	0.16	0.25
0.090	0.09	0.19	0.31
0.100	0.13	0.22	0.31
0.112	0.13	0.22	0.34
0.125	0.13	0.25	0.38
0.140	0.16	0.28	0.44
0.160	0.16	0.31	0.50
0.180	0.19	0.38	0.56
0.190	0.19	0.38	0.63
0.200	0.22	0.41	0.63
0.224	0.22	0.44	0.69
0.250	0.25	0.50	0.70
0.313	0.31	--	--
0.375	0.38	--	--
0.500	0.50	--	--

:a) Data taken from McDonnell Aircraft Company, St. Louis, Missouri, Design Handbook Section on "Standard Bend Radii", Code No. 76301, 6M39 (June, 1963).

(b) Bend radii measured on the inside surface of the bend.

are used, care must be exercised to completely remove any oil residues or other contamination prior to subsequent heat treatments. Cleaning may be accomplished with suitable solvents, or, more thoroughly, with a vapor degreaser or alkaline cleanser after forming.

Bending Limits, Failures in bending always occur by splitting in the outer fibers. Through the years, minimum bend radii have usually been determined by trial and error using the experience gained from similar materials as guidelines. More recently, a number of engineering methods have been developed for predicting the minimum radius to which a material may be bent without fracture (Ref. 74,79). These methods usually are based on the assumption that the material is bent in plane strain and that the strain at which a workpiece splits in bending is equal to that strain at fracture in a tensile specimen. The natural or logarithmic strain in the outer fiber of a bent structure is

$$E = \ln \left(\sqrt{1 + T/R}\right) \quad , \qquad (4)$$

where

T = thickness, inches

R = inner bend radius, inches.

In tensile tests

$$E = \ln \frac{100}{100 A_R} \quad , \qquad (5)$$

where

A_R = reduction in area expressed in percent.

Datsko and Yang (Ref. 74) showed that the minimum bend radii for various materials could be predicted fairly accurately by the following relationships:

$$\frac{R_{min}}{T} = \frac{50}{A_R} - 1 \text{ (for } A_R < 20) \qquad (6)$$

$$\frac{R_{min}}{T} = \frac{(100 - A_R)^2}{200 - A_R^2} \text{ (for } A_R > 20) \quad . \tag{7}$$

The differences between Equations (6) and (7) arose from taking into account a displacement of the neutral axis during bending. Datsko (Ref. 74) considered the displacement to be significant in materials exhibiting large reduction-in-area values. The equations may be used to estimate minimum safe bending radii from tensile-property data found in handbooks. It is safer, of course, to determine the values on materials of interest on flat specimens.

Wood and his associates (Ref. 69) determined the limiting tensile strain by measuring the elongation in a gage length of 0.25 inch and correcting it for width strain. This is equivalent to the strain based on reduction-in-area values for biaxial stress, but is affected by specimen geometry. To use their approach, tension tests are made on specimens marked with a grid of 1/4-inch squares as shown in Figure 28. Then the data are used for the equations given in Table XIII to construct a formability diagram like that shown in Figure 29. Their analysis takes bend angle as well as critical bend radius into account. Figure 29 is based on a material with a corrected limiting plane-strain value of $E = 0.4$. The curve would move to the right for materials exhibiting better ductility in plane-strain tensile tests.

The experimental work of Wood and his associates (Ref. 69) did not include any of the 200-, 300-, 400-, or 500-series of stainless steels. The required elongation values, E (0.25 inch gage length) to construct a splitting limit curve and apply the theory developed by Wood can be obtained using a gridded specimen as shown in Figure 28, together with the suitable equations from Table XIII for any or all of the stainless steels.

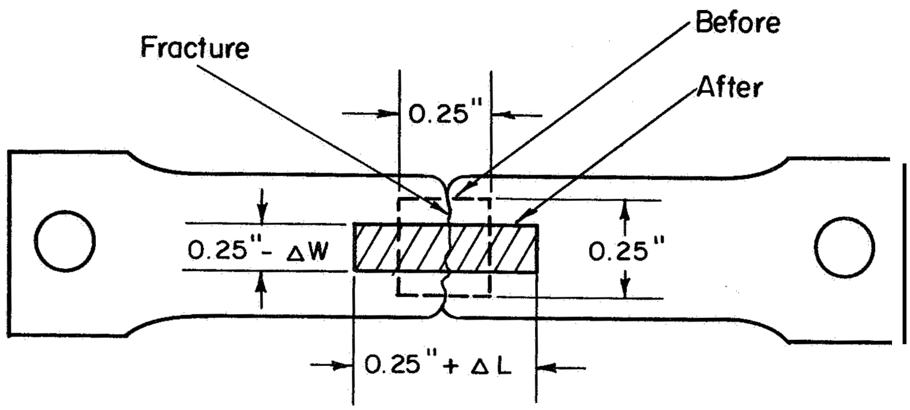


FIGURE 28. TYPICAL GRIDDED TENSION SPECIMEN (Ref. 69)

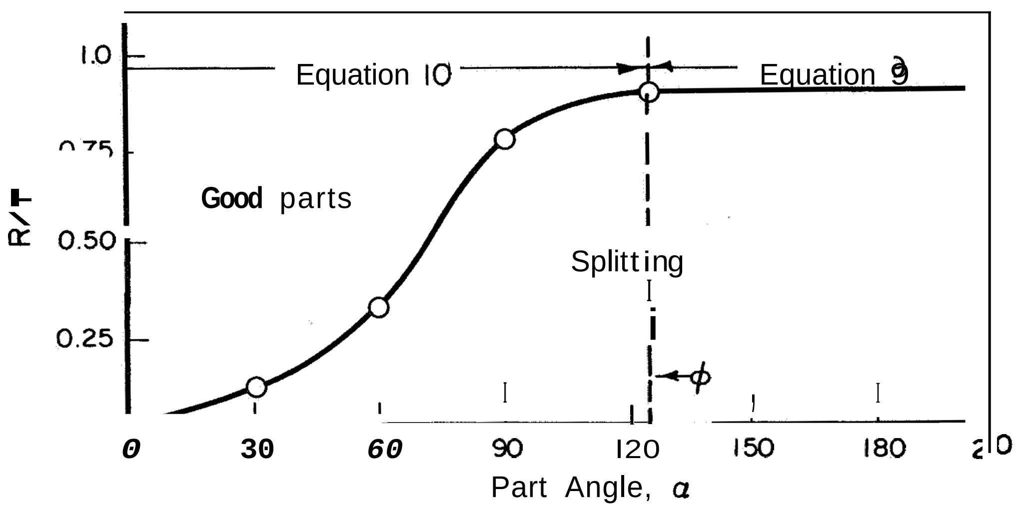


FIGURE 29. SPLITTING–LIMIT CURVE FOR BRAKE FORMING (Ref. 69)

TABLE XIII. EQUATIONS FOR CONSTRUCTING SPLITTING-LIMIT DIAGRAMS FOR BRAKE FORMING (Ref. 69)

Terms:

R = radius of punch on inside of bend

T = thickness of workpiece

e = base of natural logarithms, or 2.718

α = part angle

E = corrected value of maximum strain based on 0.25-inch gage length.

Equations:

where $\alpha > \varphi$,

$$R/T = 1/(2.718)^{2E} - 1 \qquad (8)$$

where $\alpha < \varphi$,

$$R/T = 0.5[R/T \text{ from Equation (8)}]\,[1 + \sin(\varphi - 90\text{ deg})] \qquad (9)$$

$$\varphi = \frac{11.4 - R/T \text{ from Equation (8)}}{0.0845} \qquad (10)$$

$$\alpha = \theta\,\frac{\varphi}{180\text{ deg}} \qquad (11)$$

$$R/T = 0.5\left[2.718^{2E} - 1\right]^{-1}\left[1 + \sin\left(\frac{15.21\,\alpha}{(11.4 - 2.718^{2E} - 1)^{-1}} - 90\text{ deg}\right)\right]. \qquad (13)$$

Springback. Springback is affected by the design of the part and the yield strength of the metal. Thus, metals with higher strength, such as the stainless steels, exhibit more springback than carbon steels or other lower strength metals. For this reason, stainless steels generally cannot be bent on bottoming dies designed for bending carbon steels. Stainless steels in the soft annealed condition will show less springback than the same alloys in the work-hardened condition. The most common, and perhaps least expensive, way of correcting for springback is by overbending. Thus, if it is desired, for example, to produce a 90-degree bend in annealed stainless, it may be necessary, in air bending, to have a male die with an 80-degree angle; in work-hardened stainless, the angle on the die may be reduced to about 60 degrees to correct for the increased springback.

When only a few bends are involved, hand operations are sometimes used to correct for springback. When many bends are involved, sizing in dies at room or elevated temperatures may be used to compensate for the springback resulting from brake bending. Sizing operations insure parts with more accurate bends than are possible with other means employed to compensate for springback.

Post-Forming Operations. The requirements for post-forming operations may include deburring; thorough cleaning by vapor degreasing, and alkaline-cleaning methods; visual or penetrant inspection for cracks; shearing length or width when required; and pickling, washing, protective wrapping, and identifying. Often the parts also are annealed after the final bending operation.

Sometimes when complicated procedures are involved in forming parts from the stainless steels, intermediate anneals may be necessary especially if the final part shape requires extensive bending. These anneals are accomplished by heating in air at the solution-treating temperature to restore full ductility to the part. Such anneals must usually be followed by a pickling treatment to remove the scale that formed during the anneal.

If the dimensions and accuracy of the finished piece make the final anneal impractical, the following alternative procedure may be used:

(1) Form to as near completion as possible, preferably a minimum of 90 percent of the finished shape

(2) Anneal at the solution-treating temperature

(3) Pickle

(4) Perform final sizing operations.

Sometimes severely formed austenitic stainless steels are stress relieved to prevent stress corrosion cracking. Stress relieving of these steels is normally carried out in the temperature range of 500 to 800 F for 1/2 to 2 hours followed by air cooling. Martensitic alloys are always stress relieved or tempered after quench hardening; stress relieving is carried out between 300 and 850 F while tempering requires temperatures in the 1000 to 1400 F range (Ref. 75).

DEEP DRAWING

Introduction. Deep drawing is a process used to produce cylindrical or prismatic cups with or without a flange on the open end from sheet metal. Cups or tubes can be sunk or redrawn to increase their length and to reduce their lateral dimensions. The drawing stresses result principally from the action of the punch on the central section of the blank. If the ratios of the blank diameters to sheet thickness and punch diameter are sufficiently small, the metal will draw in around the punch without buckling. Under such conditions, and by using other expedients, sheet metals can be deep drawn in single-action presses. Double-action presses, however, are used more commonly. They apply pressure on a blank holder to prevent buckling of the flange.

The deep-drawing process is well-suited to producing large numbers of identical, deeply recessed parts. Precise tooling and carefully controlled forming conditions must be used to insure successful operations. Drawing speeds from 12 to 200 inches per minute may be used on stainless steels (Ref. 76). The expense of setting up suitable equipment and procedures usually limits economical operations to rather large lots, over 500 pieces.

Type 300 stainless steels normally are drawn at room temperature. The Type 200 stainless steels may be deep drawn at temperatures of 200 F, which reduces the tendency of the material to work harden (Ref. 76). The Type 400 stainless steels may be deep drawn at room temperature or at a temperature from 200 to 300 F. Cups, domes, cones, and boxes are produced by deep drawing. A good example of commercial deep-drawing operations is the forming of fountain pen caps or the forming of percolator cups. These are both high-production-type applications.

Presses for Deep Drawing. Both mechanical and hydraulic presses are used for deep drawing. Punch speed and the force available on a mechanical press ordinarily varies during the stroke. Furthermore, it is more difficult to provide a controlled blank holder pressure on mechanical presses than on hydraulic presses. For these reasons, the use of mechanical presses is normally restricted to shallow parts where the depth of draw is 5 inches or less.

The use of hydraulic presses is normally preferred in drawing of stainless steels. Hydraulic presses operate at lower punch speeds than mechanical presses. This is generally an advantage in deep drawing stainless steels since the material should be drawn slowly. Hydraulic presses for drawing operations are generally equipped with a die cushion that is operated hydraulically. The hold-down pressure on the blank holder is usually preset to remain constant during the drawing operation, although auxiliary pumps may be used to vary the pressure during the stroke. The hold-down pressure can be applied to the blank holder by air or hydraulic cushions or springs. Devices for this purpose can be added to single-action presses.

The blank holder must be rigidly constructed and adjusted to allow the metal to thicken as the edge of the blank moves radially toward the punch. The pressure needed to prevent wrinkling in the flange is of the order of 1-1/4 percent of the ultimate strength of the workpiece material. This pressure, ranging from 500 to 2500 psi for the Type 300 and 400 stainless steels in the annealed condition, is exerted on the area of the blank holder in contact with the blank, and normally raises the drawing load by about 20 percent. Hold-down pressures for the Type 200 stainless steels will be slightly higher due to the higher strength of these materials (Ref. 77).

Presses are available in various sizes for deep-drawing parts as small as cooking utensils and as large as automobile roofs. The characteristics of a few commercial presses used for typical operations are indicated in Table XIV. Figure 30 shows an 800-ton hydraulic press equipped with a 600-ton die cushion used in forming sinks from stainless steel.

The maximum load in drawing a blank is normally reached when the flange is decreased in diameter by about 15 percent, or when the punch travel is about one-third complete. The maximum drawing load can be estimated from the following formula (Ref. 78):

$$P = d\ TS\ \pi\ (C - 1 + \frac{D}{d}) \qquad (13)$$

where

P = punch load, pounds

D = blank diameter, inch

d = punch diameter, inch

T = blank thickness, inch

S = maximum stress of material, psi (average yield strength)

C = empirical constant to take bending and blank-holding loads into account, approximately 0.35 €or stainless steel.

Tooling for Deep Drawing. The design of the tooling used in deep drawing depends on the type of press to be used. Some of the typical tooling arrangements for drawing or redrawing are shown in Figure 31. In the simplest terms, the tooling consists of three parts: die, punch, and hold-down ring. The punch may be attached to the ram or in inverted drawing operations to the base platen. The die will be attached to the press member opposite to the punch. The hold-down ring would be attached to the die cushion in an inverted operation by means of push rods or might be connected

TABLE XIV. CHARACTERISTICS OF TYPICAL DEEP-DRAWING PRESSES

Notes:

(1) Most draw presses are single action with a die cushion. Some may require the use of an ejector for part removal.

(2) Increased platen area is generally coincident with increased press tonnage.

(3) Mechanical presses are more adaptable to high-speed and automated operation. They are also more difficult to control and tool up.

(4) Additional sizes and tonnages of presses are available, and the manufacturers should be consulted for specific requirements.

directly to a die cushion that can pull down instead of push. In single-action presses an air-operated die cushion might be used or the hold-down ring could be attached to the ram and spring-loaded. When the ratio of the depth of draw to the blank diameter is small, it is sometimes possible to form without a hold-down ring.

Although not widely used in production operations, there are two alternative methods for preventing wrinkling without supplying control

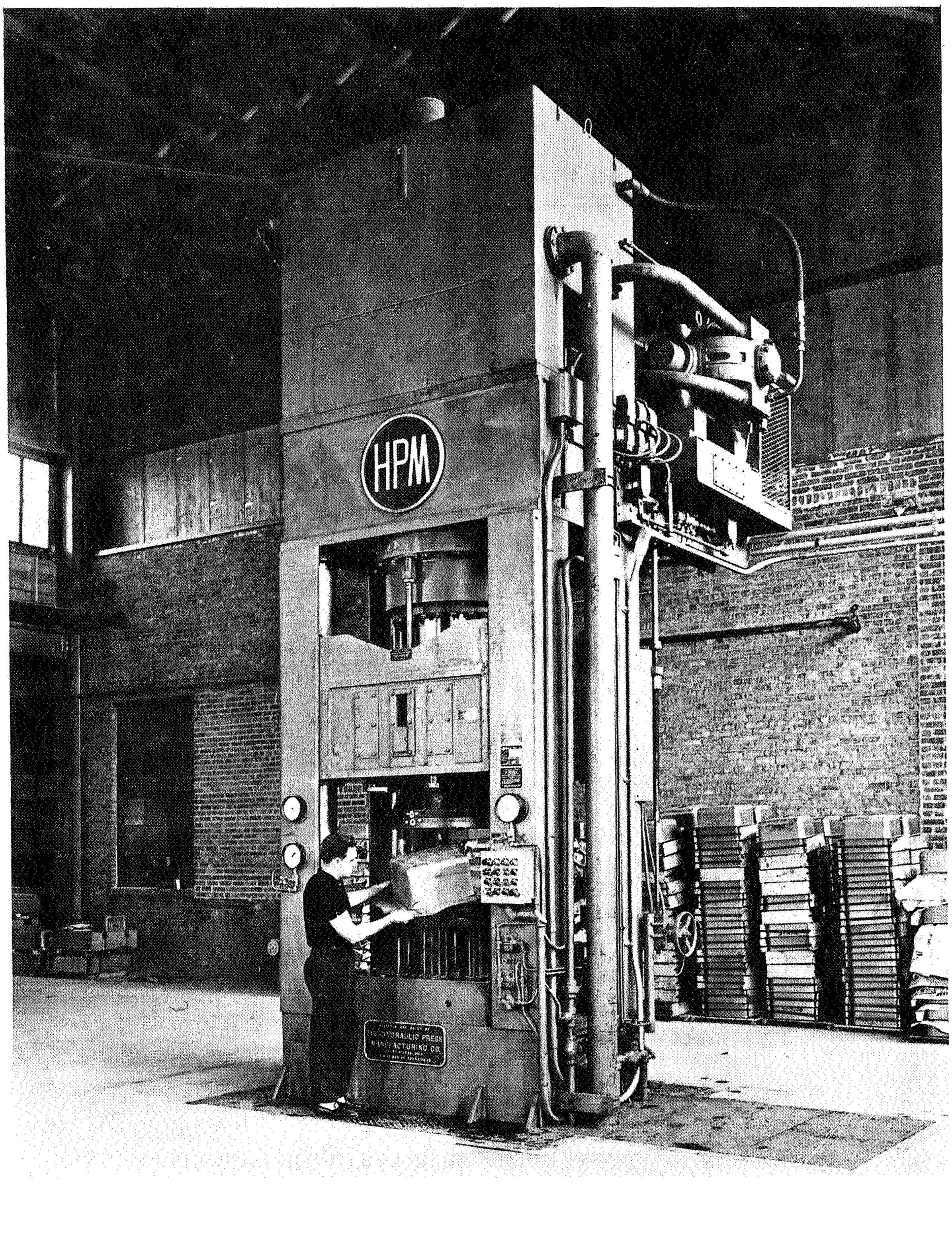
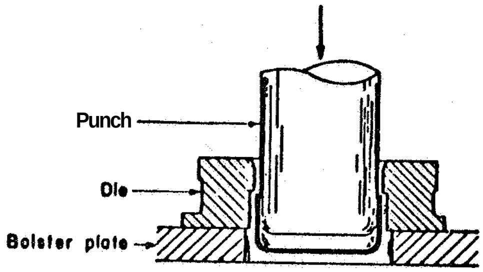
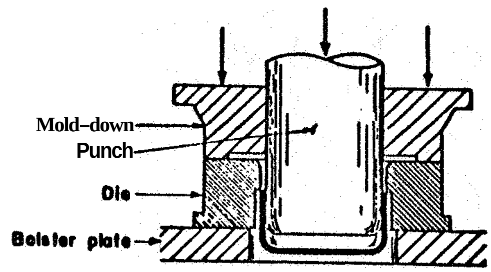


FIGURE **30.** 800-TON PRESS EQUIPPED WITH A 600-TON DIE CUSHION USED FOR DRAWING STAINLESS STEEL SINKS

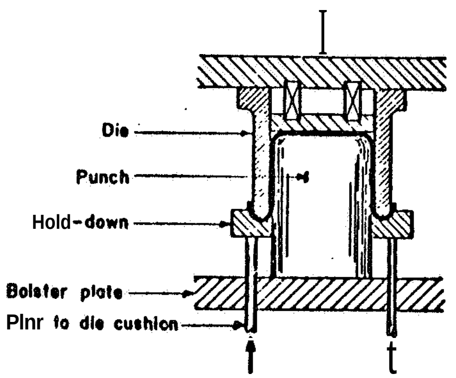
Courtesy of the Hydraulic Press Manufacturing Company, Mt. Gilead, Ohio



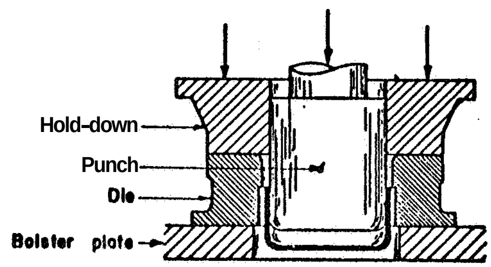
a. Single Aclbn Without Hold–Down



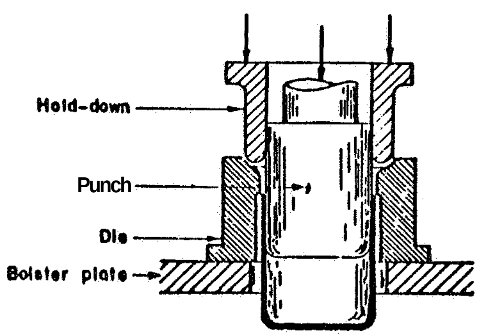
b. Double Action With Recessed Hold–Down



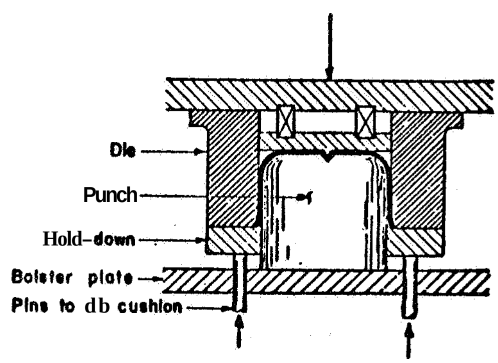
c. Single Action Inverted With Die Curhbn Hold-Down Reverse Redraw



d. Double Action With Flat Hold–Down Push-Through Type



e. Double-Action Redraw Push-Through Type



f. Single-Action Redraw With Die–Cushion Hold–Down

FIGURE 31. TYPES OF DEEP–DRAWING OPERATIONS (Ref. 79)

pressures to the hold-down ring. A rigid blank holder with a flat surface is the simplest type of hold-down ring. It requires careful adjustment of the gap between the die and the hold-down surface to allow for thickening as the blank is drawn and to prevent wrinkling. The drawing load is increased when the gap is either too small or too large. According to Sachs (Ref. 80), the gap should be 25 to 50 percent smaller than the thickness developed as the edge of the flange moves from its origin to final position. This amount of thickening is given by the equation

$$\frac{T}{T_1} = \frac{D}{D_1} \qquad (14)$$

where

T = blank thickness

T_1 = thickness of the flange during drawing

D = blank diameter

D_1 = diameter at the edge of flange, or the mean diameter of cups drawn without a flange.

The difficulty of adjusting rigid blank holders can be avoided by tapering the hold-down surface. The taper which is not very critical can be estimated from the above equation. Experiments indicate that conical blank holders result in lower drawing loads than other types (Ref. 80).

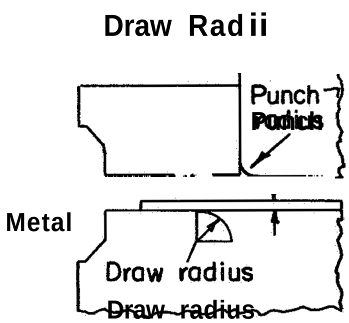
A number of tooling materials have been used for deep drawing stainless steels. Dies made from nondeforming type, high-carbon, high-chromium die steel treated to R_c 60 to 62 are most satisfactory. Cast-iron dies may be used for small production runs, while cemented carbide dies may be used for large production quantities. Alloy cast iron containing chromium and nickel gives excellent results (Ref. 3).

Clearances between the punch and die must be controlled t‹ ›ʟ⌣ᵥent galling, rupture, or buckling in the cup wall. The selectic ′ the clearance between the punch and draw ring depends, to some extent, on the dimensional requirements of the part. If the clearance is larger than the amount of thickening predicted by the preceding equation, the cup part will not be in contact with both the punch and the die. This results in minimum drawing loads but the parts will have variable wall thicknesses. If the clearance is smaller than necessary to accommodate the thickening in the upper part of the cup, some ironing or wall thinning will occur. Severe ironing increases drawing loads. Clearances for deep drawing stainless steels should be equal to the material thickness of the blank plus 40 to 45 percent of this thickness, as shown in Figure 32. These alloys generally possess higher mechanical properties than carbon steel and have greater resistance to wall thinning.

The radii on the draw ring and nose of the punch are important in severe drawing operations, because they affect the stress required for bending. If the punch radius is too small the metal will thin, neck, and rupture near the bottom of the cup. Typical die radii for stainless steels are given in Figure 32. Radii slightly larger than the minimum allowed for bending will permit shallow draws. Larger radii permit parts to be formed with larger flanges or to deeper depths. In general, the radius on the draw ring should be 4 to 8 times the thickness of the metal (Ref. 3). Excessively large radii, more than about 10 T, may cause the parts to pucker. For severe operations, the punch radius should exceed 4 times the sheet thickness. When more than one stage drawing is to be performed, large-draw ring radii should be used on the initial die stages. The radius can be reduced on succeeding stages until the desired radius is obtained.

	Draw Radius	Punch Radius
Chromium-nickel stainless (type 304)	5 to 8t	4t min.
Chromium stainless type (430)	7 to 15t	5t min.
Carbon steel type (1008)	4 to 8t	2t min.

	Draw Clearance
Chromium-nickel stainless (type 304)	t plus 20 to 40 %
Chromium stainless type (430)	t plus 15 to 20 %
Carbon steel type (1008)	t plus 5 to 15%



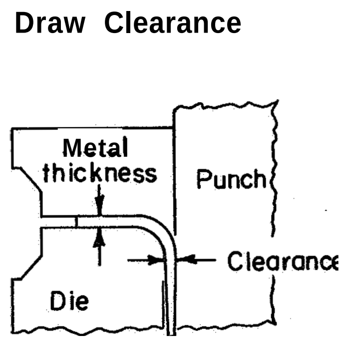


FIGURE 32. DRAW RADIUS AND DRAW CLEARANCES FOR STAINLESS STEELS (Ref. 77)

Techniques for Deep Drawing. The techniques used in deep drawing depend on the type of equipment available and the shape of the part to be produced. Shallow parts of cylindrical shape are the easiest to produce. As the complexity of the shape and depth of drawing increases, so does the difficulty in setting up and producing the parts. In most drawing operations, compressive stresses in the circumferential direction tend to buckle or wrinkle the rim of the blank. Shallow wrinkles should be prevented from forming by adjusting the force on the hold-down ring; attempts to iron out wrinkles should be avoided. For large production runs on a single-action press, the clamping force may be applied by means of springs. Where production runs are smaller or a number of different size parts are to be made on the same equipment, it is better to have a readily adjustable hold-down force. This is a desirable feature when variations in thickness and properties of sheet material might be expected. The operator can readjust the machine settings to accommodate the gage variations and reduce the amount of scrap. Double-action presses are more versatile with respect to adjustment of operating conditions but are generally more expensive.

Some parts may be deep drawn in one stroke of the press. Others require a number. of operations in different dies. There is a limit, even with intermediate anneals, on how far a part can be reduced in one set of dies. The general practice is to take a smaller reduction in redrawing operations than that used for the previous operation. Although a 35 to 40 percent diameter reduction is reasonable for cupping, it should be reduced to 15 to 25 percent in redrawing. A typical drawing sequence for Type 347 stainless steel is shown in Figure 33. This part was annealed after the second and each successive draw. Another example is the Type 316 stainless steel part shown in Figure 34. This part was annealed after each forming stage; castor oil was used as the drawing lubricant.

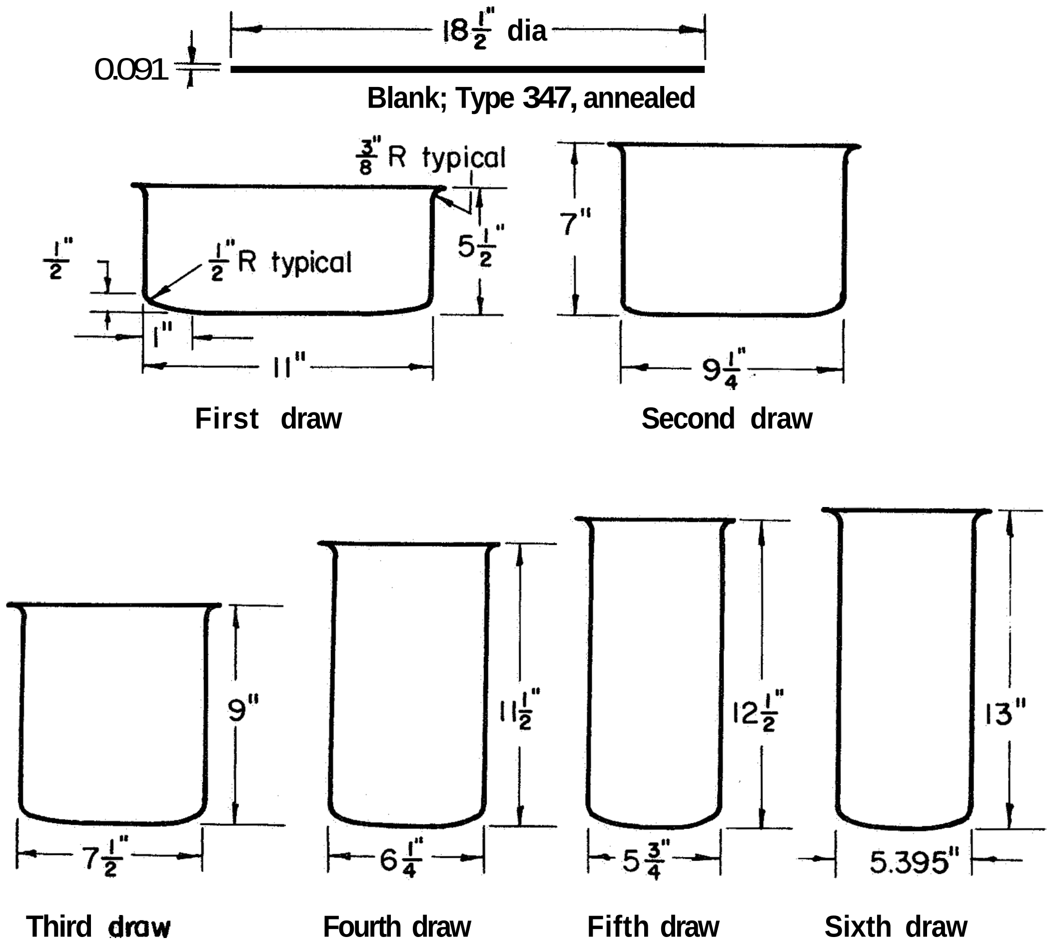


FIGURE 33. DRAW REDUCTIONS FOR A DEEP STAINLESS STEEL SHELL (Ref. 79)

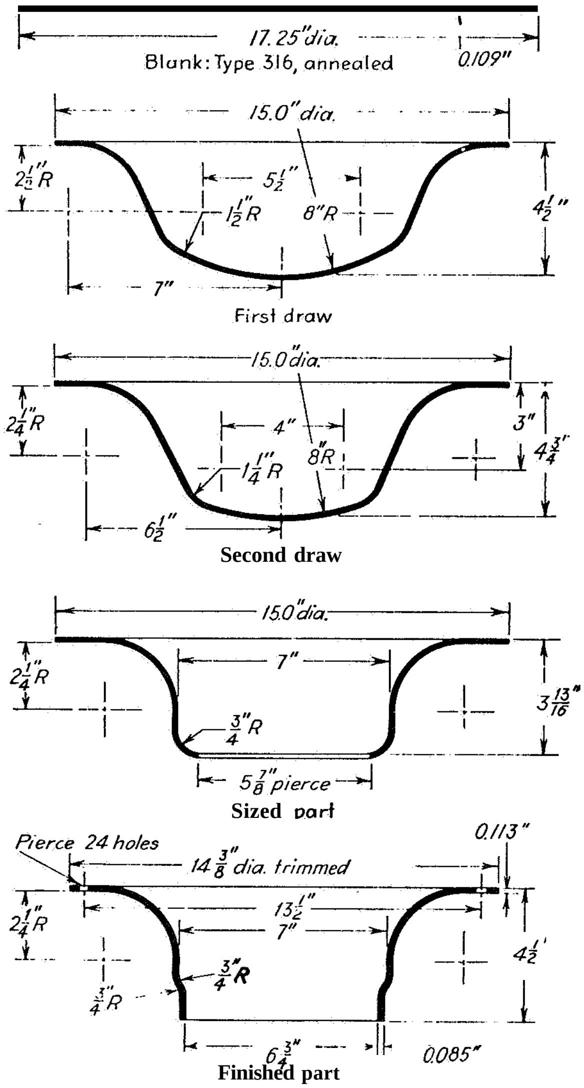


FIGURE **34.** AN EXAMPLE OF A DRAW USING A HIGH BLANKHOLDING PRESSURE (Ref. 79)

The depth to which stainless steels can be drawn to rectangular shapes in one press stroke is a function of the corner radius and part dimensions. The corner radius should exceed 10 percent of the minimum part dimension (Ref. 3). The depth of draw should be limited to 2 to 5 times the corner radius. Such factors as the shape of the part, whether it has straight or tapered sides, and the thickness of the material can affect the limiting depth of draw. As the sheet thickness decreases below 0.050 inch the permissible depth also decreases. The forming limits for drawing rectangular boxes in the 300 series stainless steels are given in Figure 35. The effect of prior deformation (temper) on the depth of draw is illustrated by Figure 36 for a rectangular part.

The draw ring radius should be more generous for drawing rectangular shapes than for cylindrical shapes. A factor of 5 to 7 times the thickness of the material should be used.

Rectangular shapes can be redrawn to sharpen the corners or to stretch out wrinkles along the sides. When the depth of draw is greater than that possible in one operation, it is sometimes necessary to draw about two-thirds of the depth in the first stage and complete the part in a second stage in the same die. This practice is also used to avoid wrinkling.

Speeds from 10 to 20 ft/min are satisfactory for drawing the Type 300 and 400 stainless steels. The optimum speed may be lower or higher for the other stainless steels depending on their rate of work hardening and sensitivity to strain. According to Giordano the Type 200 stainless steels work harden rapidly at first and can then be formed at a constant stress level (Ref. 76).

<u>Lubricants</u>. Lubrication of the blanks is necessary to obtain maximum drawability. Lubricants reduce the energy required to overcome

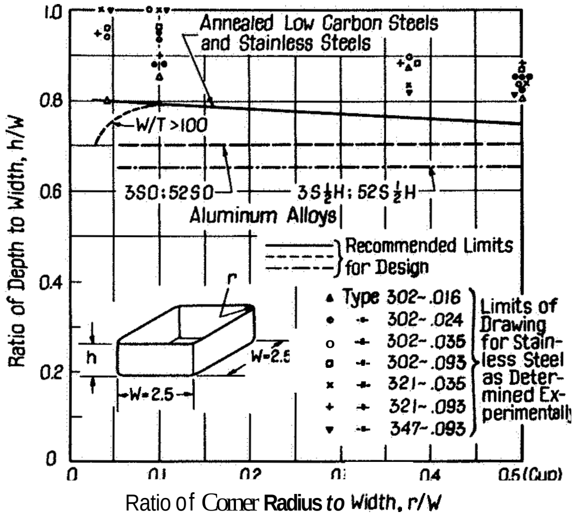


FIGURE 35. LIMITS OF SQUARE-BOX DEPTH (Ref. 79)

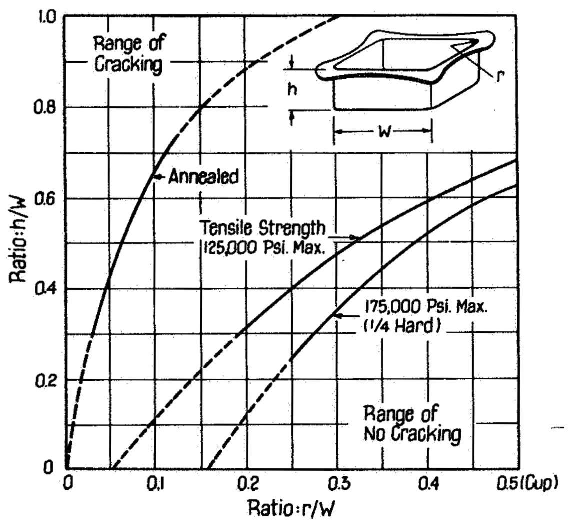


FIGURE **36.** STRESS CRACKING IN BOXES OF TYPE 301 STAINLESS STEEL (Ref. **79)** friction between the blank and the tooling and reduce the possibility of galling or seizing.

A heavy-bodied mineral oil of the chlorinated or sulfurized type should be used for heavy press work (Ref. 81, 82). For mild deformations, light oils and soap solutions may be used. The lubricants are applied to the blanks by dipping, spraying, or swabbing. The various manufacturers of lubricants should be contacted for specific recommendations for a given alloy and type of drawing. All lubricants should be thoroughly removed before any thermal treatment of stainless steels to prevent surface contamination.

In some cases, applying the lubricant to only certain portions of the blank or tooling may assist in obtaining maximum formability. Friction at the radius and bottom of the punch is desirable. Higher friction on the punch side of the blank reduces the tensile stresses that cause stretching and sometimes rupture at those locations. Therefore, benefits are sometimes obtained from rough or unlubricated punches (Ref. 83). For instance, a lubricant between the blank and the die and the blank holder and between the part and the die is desirable. Friction in those locations raises the drawing load and may lead to galling or nonuniform movement of material over the tooling.

Developments of Blanks. The blank diameter for making a given size cup can be determined from Figure 37. When the final cup diameter and height are known, the blank diameter can be determined from the graph.

Principles of Deep Drawing. Unlike the situation in some other forming operations, failures in deep drawing are controlled by the general changes in shape rather than by the strain requirement in certain locations.

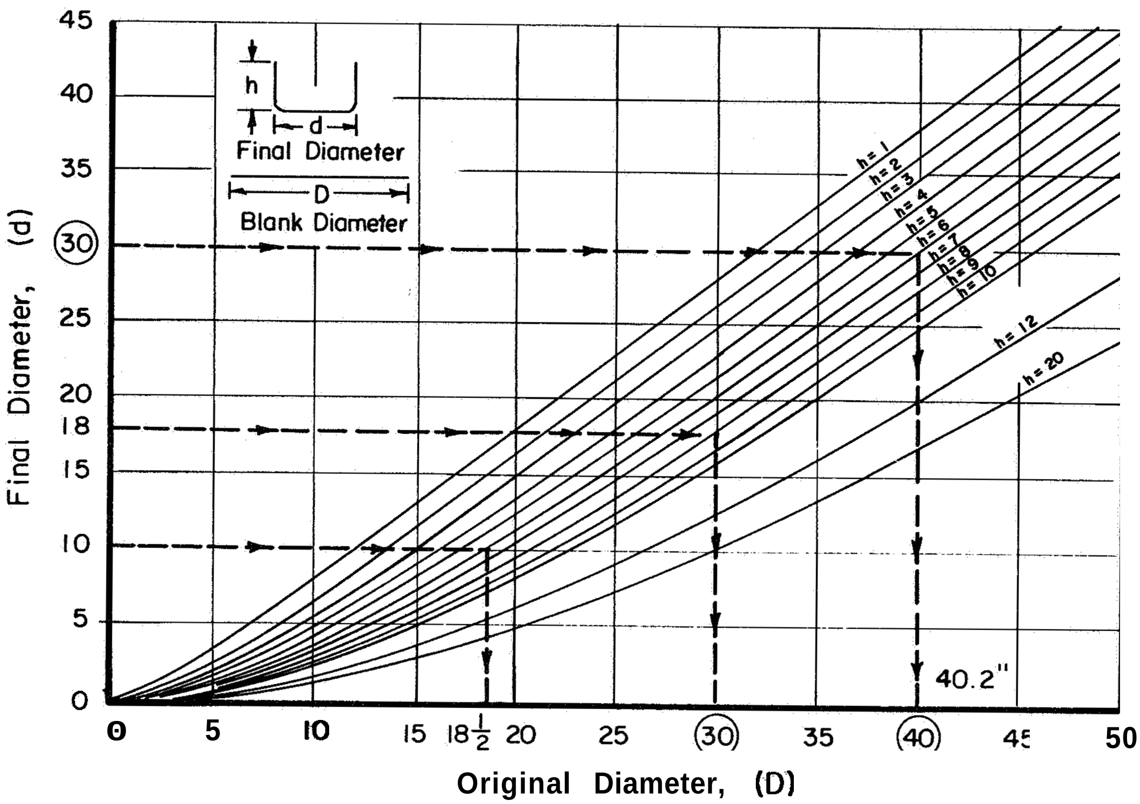


FIGURE 37. EXAMPLE OF DETERMINING BLANK SIZE BY EQUIVALENT AREA CALCULATION (Ref. 3)

Example of Method of Use

The blank diameter required to produce the above 10" diameter by 6" deep vessel is determined by finding the intersection of the 10" diameter line with the h=6" line and reading the point D=18-1/2" blank size.

To obtain a cylindrical shell 30" in diameter and 6" high, the blank diameter is found by intersecting the horizontal 30" line and the h=6 line and then identifying the vertical line passing through that intersection, which is 40.2" to which would be added sufficient metal to take care of a flange and to compensate for thickening.

In like manner to obtain a shell of diameter 18" and height 8", a blank of approximately 30" would be required and would call for a 40% draw.

It is on the basis of these formulae that the above curves have been prepared:

$$100\left(\frac{D-d}{D}\right) = \%\ \text{Draw} \qquad (15)$$

$$D = \sqrt{d^2 + 4\,dh} \qquad (16)$$

Example: For d = 10" and h = 6"

$$D = \sqrt{100 + 4 \times 10 \times 6}$$

$$= 18\text{-}1/2" \text{ (approx.)}$$

Neglecting (1) thinning and thickening, (2) knuckle and flange radius, (3) top flange.

The forces developed at the punch originate from:

(1) Stress required to bend the sheet around the nose of the punch,

(2) Stress necessary for circumferentially compressing and radially stretching metal in the flange,

(3) Stress required to bend the metal around the draw ring and unbend it as it moves from the flange into the wall of the part,

(4) Stress used to overcome friction at the die radius and under the blank holder, and

(5) Stress developed by ironing the wall.

For these reasons, it is difficult to predict success or failure in a particular deep-drawing operation from ordinary tensile data for the workpiece material.

Considerable background of information is available about the influence of characteristics determined in true-stress-true-strain tensile tests on the performance of steel in deep-drawing operations. Although the principles would be expected to hold for stainless steels, pertinent data are scanty. Studies on steel indicate that better performance in drawing operations correlates with higher values of work-hardening coefficients and uniform elongation and more severe, normal anisotropy. The relative importance of these characteristics varies with the geometry of the drawing operation.

Uniform elongation is particularly important in drawing operations characterized by significant amounts of stretch-forming. For example, it is more important in controlling forming limits for cups with hemispherical rather than flat bottoms. Even when stretching is not of major importance, the workpiece must be ductile in order to withstand bending. Materials with higher work-hardening coefficients are more resistant to thinning and permit deeper draws without tearing.

The concept that pronounced normal anisotropy is desirable for deep drawing is a little more complicated. For maximum drawability in ductile materials, it is desirable for the material to be resistant to thinning from radial stretching but weak in upsetting from circumferential compression. This results in a high strength in the wall of the cup compared with the stresses needed to upset material in the flange. This condition is better satisfied by materials exhibiting higher ratios of width to thickness strains in tensile tests. This type of anisotropy termed "normal" in contrast to directional variations in properties in the plane of the sheet is expressed by the following relationship:

$$R = \frac{\ln \frac{W_0}{W}}{\ln \frac{T_0}{T}} \tag{17}$$

where

R = anisotropy

W_0 = original width of specimen

W = width after straining

T_0 = original thickness

T = final thickness.

The anisotropic parameter of sheet material can be determined by measuring strain ratios of specimens oriented at 0, 45, and 90 degrees from the rolling direction. The components of normal anisotropy can be defined as:

$$R = 1/4 \ (R0 + 2 R_{45} + R_{90}) \quad . \tag{18}$$

The degree of normal anisotropy in terms of relative flow stress in the thickness, Z, and planer, X, directions of sheet, is given by the expression:

$$\frac{Z}{X} = \sqrt{\frac{1 + R}{2}} \quad (19)$$

A completely isotropic material would have an R value of 1 for tests in all directions and uniform strength in the thickness and plane of the sheet.

The severity of a deep-drawing operation can be described by defining the geometry of the cup and blank. The important geometric variables are indicated in Figure 38. The deep-drawing properties of materials are often compared on the basis of the maximum reductions they will withstand under standardized conditions. The ratings may be expressed on the basis of the

$$\text{Maximum Drawability Percentage} = 100\left(\frac{D - d}{D}\right) \quad (15)$$

or the

$$\text{Limiting Drawing Ratio} = D/d \quad (20)$$

where D and d are the diameters of the blank and punch, respectively.

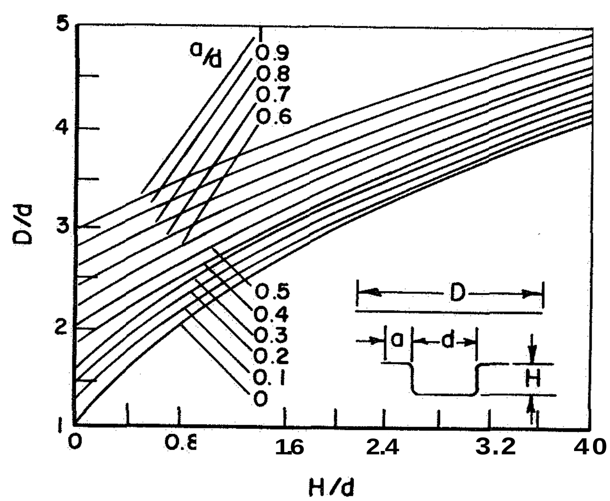


FIGURE 38. THEORETICAL RELATIONS BETWEEN DIMENSIONS OF A SHARP-RADIUSED CYLINDRICAL PART AND BLANK DIAMETER (Ref. 80)

The ratio of the blank radius to the height of the cup is also used to indicate the severity of a drawing operation. If no stretching or ironing occurs the height, H, of flat-bottomed cups with sharp radii can be calculated from the relationship,

$$\frac{H}{d} = 1/4 \left[(D/d)^2 - 1 \right] \qquad (21)$$

When there is a flange on the cup, the relationship changes since the restraining force caused by shrinking the flange must be considered. The use of a flange although wasteful in material may eliminate wall splitting in a part. The ratio of the diameter to the thickness of the blank may also affect success in deep drawing. In any case, the friction resulting from the hold-down pressure becomes an appreciable part of the load in drawing comparatively thin blanks.

Deep-Drawing Limits. Success in deep-drawing operations is influenced by mechanical properties and, hence, by prior processing history. A comparison of drawing qualities of some Type 300 and Type *400* stainless steel is given in Table XV.

Wood and associates (Ref. 69) have shown the drawability of material can be predicted from the following forming index:

$$\frac{E}{Y_c} \times \frac{Y_c}{Y_t} = \text{Deep-Drawing Formability Index} , \qquad (22)$$

where

E = Young's elastic modulus, psi

Y_c = compressive yield strength, psi

Y_t = tensile yield strength, psi.

A higher index indicates better formability in deep drawing. Using this index for a particular material and material condition, a relationship

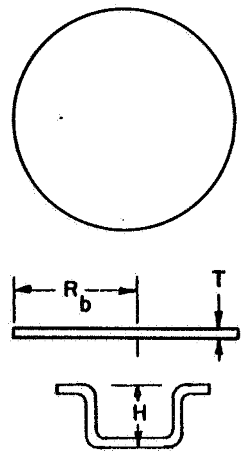
TABLE XV. COMPARISON OF DRAWING QUALITIES OF TYPES 410, 430, AND 442 WITH TYPES 302 AND 304 (Ref. 3)

	Types 410, 430, and 442	Types 302 and 304
Drawing characteristics similar to mild steel	Yes, to an extent depending upon analysis	No
Work hardening behavior during drawing	Harden up to a certain point, then continue to deform with little additional hardening	Continuous during drawing
Power required to start plastic flow	Higher, on account of higher yield strength	Lower. Yield strength about the same or slightly higher than plain steel
Ability to stretch	Less. Therefore may require slightly larger blank and looser hold-down than Types 302 and 304	Greater
Tendency to show stretcher strain patterns when in annealed condition	Yes	No
Most usual maximum first reductions	25-35 percent	40-45 percent
Preheating to 200 F approximately	Helpful	Never employed

between the ratio of the flange width to the part radius and the ratio of the flance width to the material thickness for deep drawn cups can be determined and the forming-limits envelope can be constructed, as shown in Figure 39. Since the required property tests have not yet been conducted on the conventional stainless steel, the curve shown is only an estimate.

Before deep drawing any of the stainless steels, they should be in the most ductile condition. Since the material purchased in the annealed condition may work harden during transportation and storage, the material should be annealed prior to forming as a precaution. For best formability, the stainless steels should have a hardness of R_b 90 or less before forming (Ref. 84).

Care should be taken to assure that the tooling is clean and free of defects. The surface of the blanks should also be clean to prevent abrasion of the tooling. Surface scratches should be prevented or removed and the edges of the blanks should be deburred and free of any cracks. Sometimes additional precautions are required to maintain a bright finish on stainless steels. These might include covering of the surface with a plastic or greased paper.



Part shape and dimensions

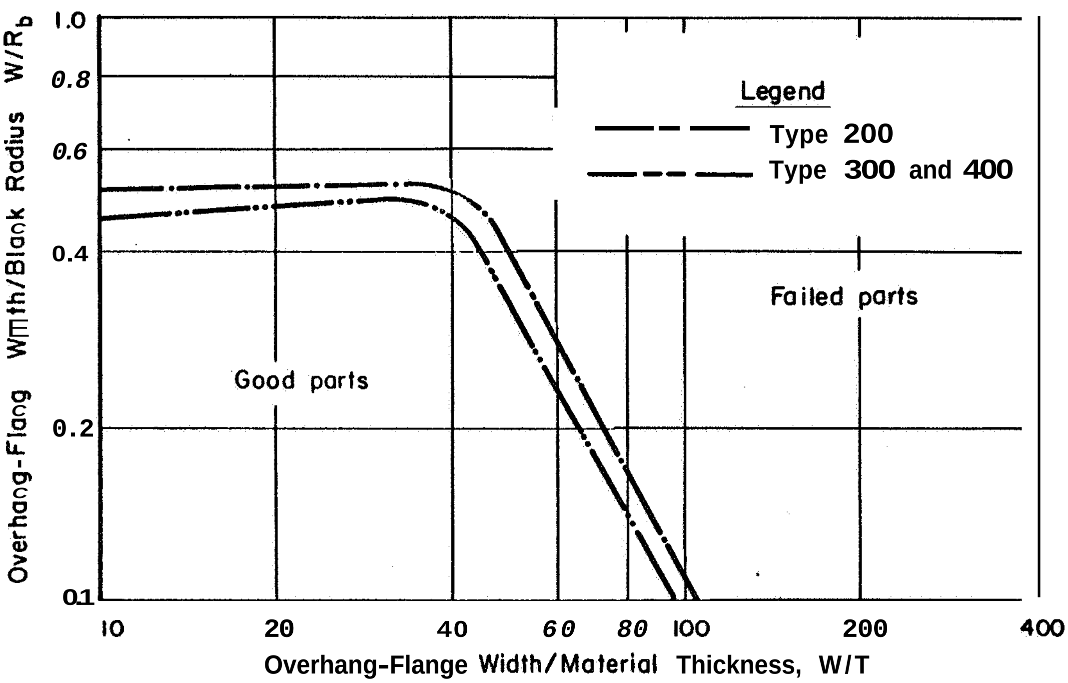


FIGURE 39. ESTIMATED DEEP-DRAWING-LIMIT CURVE FOR STAINLESS STEELS CUPS

SPINNING

Introduction. Spinning is a process for shaping seamless, dished sheet-metal parts by the combined forces of rotation and pressure. Only minor changes in material thicknesses occur during spinning. Spinning has been used to make some of the largest hemispherical and elliptical tank ends made to date.

Principles of Spinning. Spinning is classified as manual or power spinning, depending on the manner of applying the force to the blank. Manual spinning, illustrated in Figure 40, is limited to thin workpieces, less than 1/8 inch thick for annealed stainless steel. Power spinning uses mechanical or hydraulic devices to apply greater tool forces to the blank and can, consequently, be used to form thicker and stronger material.

Spinning differs from most metalworking processes in that the material is deformed at a point rather than over a broad area, and a large portion of the blank is unsupported during processing. These characteristics are advantageous because simple tooling can be used to make complex shapes. The application of internal spinning is shown in Figure 41.

During spinning the metal blank is subjected to bending forces along the axis of spinning and compression forces tangential to the part. Difficulties are encountered with elastic buckling when the ratio of the depth of the part to the thickness of the material becomes too great. The limits are related to the ratio of compressive modulus of the material to the compressive yield (Ref. 69). Elastic buckling occurs in the unspun flange of the part as shown in Figure 42.

The ratio of depth to diameter of parts that can be produced by spinning is limited by plastic buckling. Buckling limits are related to the ratio of

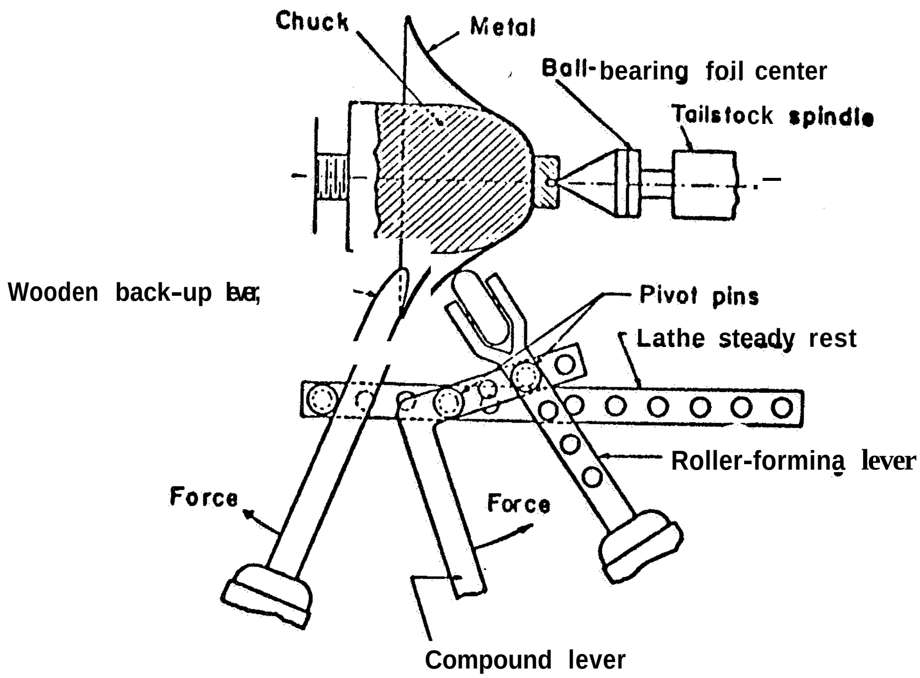


FIGURE 40. MANUAL SPINNING (Ref. 80)

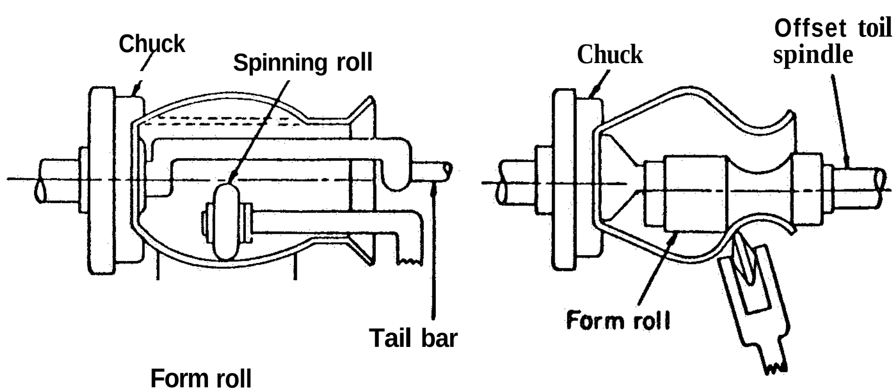


FIGURE 41. INTERNAL SPINNING TECHNIQUES (Ref. 85)

tensile modulus to the tensile ultimate strength of the workpiece material (Ref. 69). Since plastic buckles are very difficult to remove they should be prevented by limiting the amount of deformation in one operation to that permitted by the characteristics of the material. The Type 300 stainless steels may be spun at room temperature. Type 305 is the best stainless steel material for spinning since it has a slow rate of work hardening and low yield strength. The Type 405, 410, and 430 stainless steels have properties resembling carbon steels with higher yield strengths. Although these materials can be spun at room temperature, warming to 200 F helps improve ductility. Type 446 stainless steel should be spun at 200 F (Ref. 3).

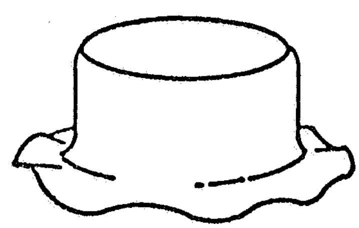


FIGURE 42. ELASTIC BUCKLING IN A SPIN PART (Ref. 69)

Exceeding the formability limits causes shear splitting or circumferential splitting, as shown in Figure 43. Shear splitting is a result of exceeding the ultimate tensile strength of the material in the tangential direction, while circumferential splitting is caused by exceeding the strength of the material in the axial direction.

Spinning to the final shape desired may require a number of steps and intermediate anneals between them. The amount of reduction taken in each successive step should be reduced for a successful operation. For example, a part that receives 50 percent reduction on the first step might be reduced 40 percent on the next step, and 30 percent on the final step. The amount of reduction that can be taken in each step is a function of the work-hardening characteristics of the material. Since the stainless steels work harden very rapidly only a single tooling pass should be made between anneals.

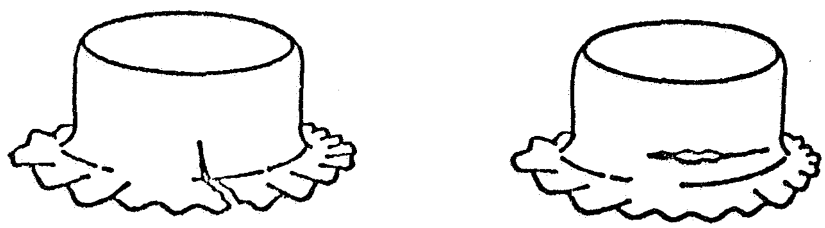


FIGURE 43. SHEAR SPLITTING AND CIRCUMFERENTIAL SPLITTING (Ref. 69)

Equipment. Most lathe manufacturers will make equipment for spinning manually operated machines are being replaced by mechanically or hydraulically operated equipment. The latest equipment incorporates numerical control for automatic programming of the spinning operation. The largest spinning equipment is capable of spinning parts with a diameter of 25 feet. Most of the work with this size part is performed at elevated temperatures (Ref. 86, 87).

Tooling. Mechanical or hydraulic actuated spinning rollers of hardened tool steel heat treated to a hardness of R_c 60 to 62, sometimes with a hard chromium plate, are used for spinning stainless steels. The surface of the rollers should be highly polished. The diameter of the rollers should be approximately one-half the smallest diameter of the part.

Mandrels for spinning can be made of tempered masonite for production runs of 25 parts or less and for intermediate operations where tolerances are liberal. For larger production quantities the mandrels may be made of ductile cast iron or tool steel. A hardened, smooth surface on the mandrel permits removal of tool marks from previous forming stages and gives a closer tolerance on the finished parts.

For forming very large parts, when the cost of a mandrel would be prohibitive, a stake is often used. A stake has the approximate shape of the part to be formed and operates directly underneath the roller. By altering the position of the stake the contour of the part can be changed. A small number of stakes with slightly different contours can be used to spin a large variety of shapes at a very reasonable cost compared with fabrication of a complete mandrel for each part.

Lubricants. Very little has been published on lubricants specifically for spinning. Due to the localized forming forces the requirements for a lubricant are somewhat more stringent than for other forming operations. In general, the lubricant used should be a high-pressure, colloidal zinc or molybdenum disulfide paste to prevent galling. For room-temperature spinning, yellow laundry soap, beeswax, tallow, or mixtures of the latter two may be used. Heavy-bodied oils are desirable for the extremely severe operations (Ref. 85).

Blank Preparation. Spinning requires a circular blank with sufficient material to complete the part and, generally, some allowance for trimming after forming. The radius for the blank can be determined by examining the section through the completed part and measuring the total length of material required to make the shape starting from the center of the part to one edge. To this, the allowance for trim stock, a minimum of 1 inch, is added. The maximum allowance is dictated by the scrap allowed and the swing of the machine.

Spinning Limits. The information available on spinning of stainless steel is meager, but some estimates of relative ratings are given in Table XVI. Relative spinnability factors are based on Type 305 stainless steel, the most spinnable of the stainless steel alloys, which was assigned a rating of 1. All other members of the stainless steel family have poorer spinnability and ratings less than 1. It should be noted that the spinnability factors can be used to estimate the approximate cost of spinning.

The speed at which stainless steels can be spun depends on the size of the blank; lower speeds are used on larger blanks. Speeds one-third to one-half the rate used to form carbon steel should give satisfactory results. Spinning lathes with speeds from 250 to 1000 rpm have been satisfactory for small parts. Parts of up to 6 feet in diameter require much lower speeds from 30 to 60 rpm. Speeds for spinning stainless steels of varying thicknesses and blank diameters can be estimated from Figure 44.

Examples of Spun Parts. Figure 45 indicates some design considerations affecting the difficulty of spinning different shapes. As the difficulty increases, so does the cost for producing the part. A variety of typical shapes produced commercially by spinning are shown in Figure 46. The dimensions of parts that have been made commercially by spinning are given in Table XVII. Parts up to 25 feet in diameter have been spun (Ref. 86). Tolerances for spun parts of various diameters are given in Figure 47. Figure 48 shows the use of spinning to close the end on a Type 321 stainless steel tube.

TABLE XVI. RELATIVE SPINNABILITY OF STAINLESS STEELS AT ROOM TEMPERATURE (Ref. 88)

Material AISI Type	Shallow Spinning	Deep Spinning
302	0.98	0.60
304	0.98	0.90
305	1.00	1.00
309S	0.80	0.45
316	0.90	0.60
321	0.85	0.50
347	0.90	0.50
430	0.90	0.50

Note: The base rating of 1.00 was given to the most spinnable of the stainless steels, Type 305. The lower the rating, the higher the cost of spinning.

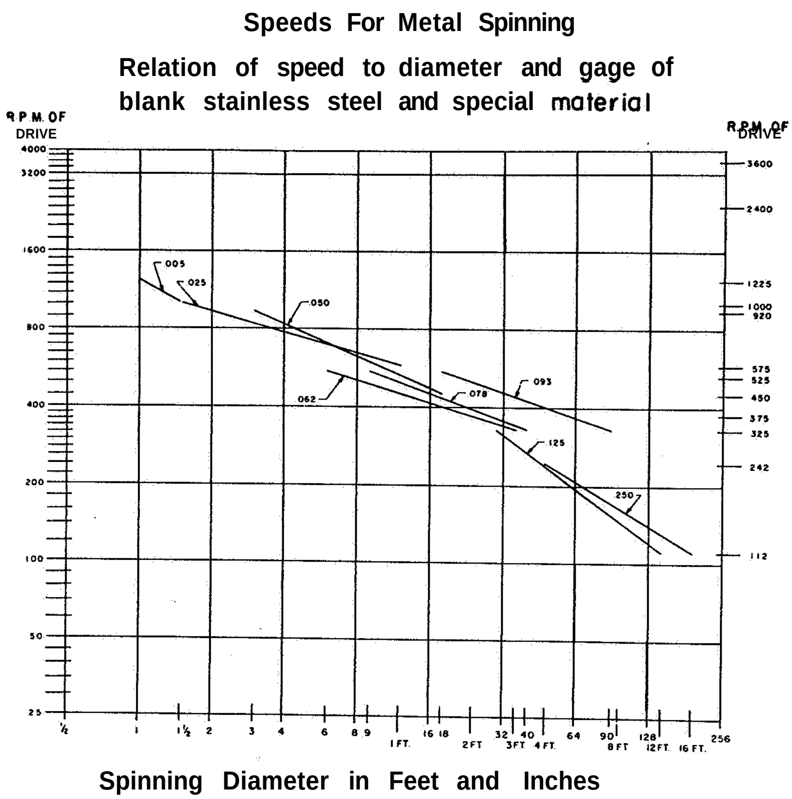


FIGURE 44. SPEEDS RECOMMENDED FOR SPINNING STAINLESS STEEL BLANKS OF DIFFERENT GAGES AND DIAMETERS (Ref. 89)

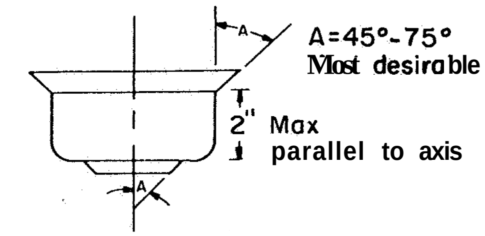
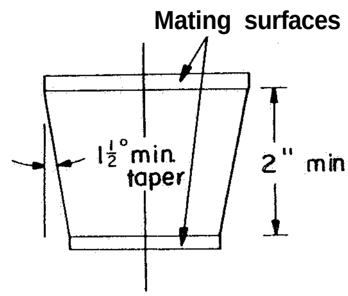
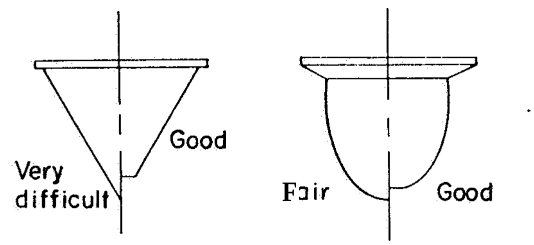
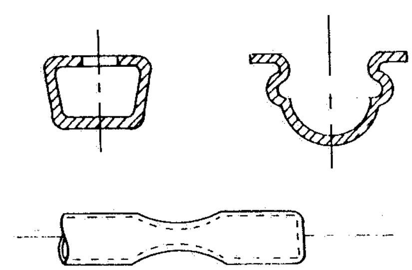
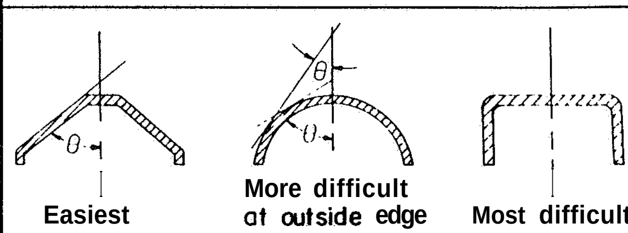
Minimize number of surfaces parallel to part axis.	
Use $1\frac{1}{2}$° minimum taper on parts deeper than 2 inches, except for mating surfaces.	
Maintaining a small flat at bottom of part is desirable when possible: diameter should be at least 10 % of overall diameter.	
Avoid reentrant contours.	
Spinning difficulty increases as angle between surface and axis decreases.	

FIGURE 45. SPINNING SHAPE CONSIDERATIONS (Ref. 88)

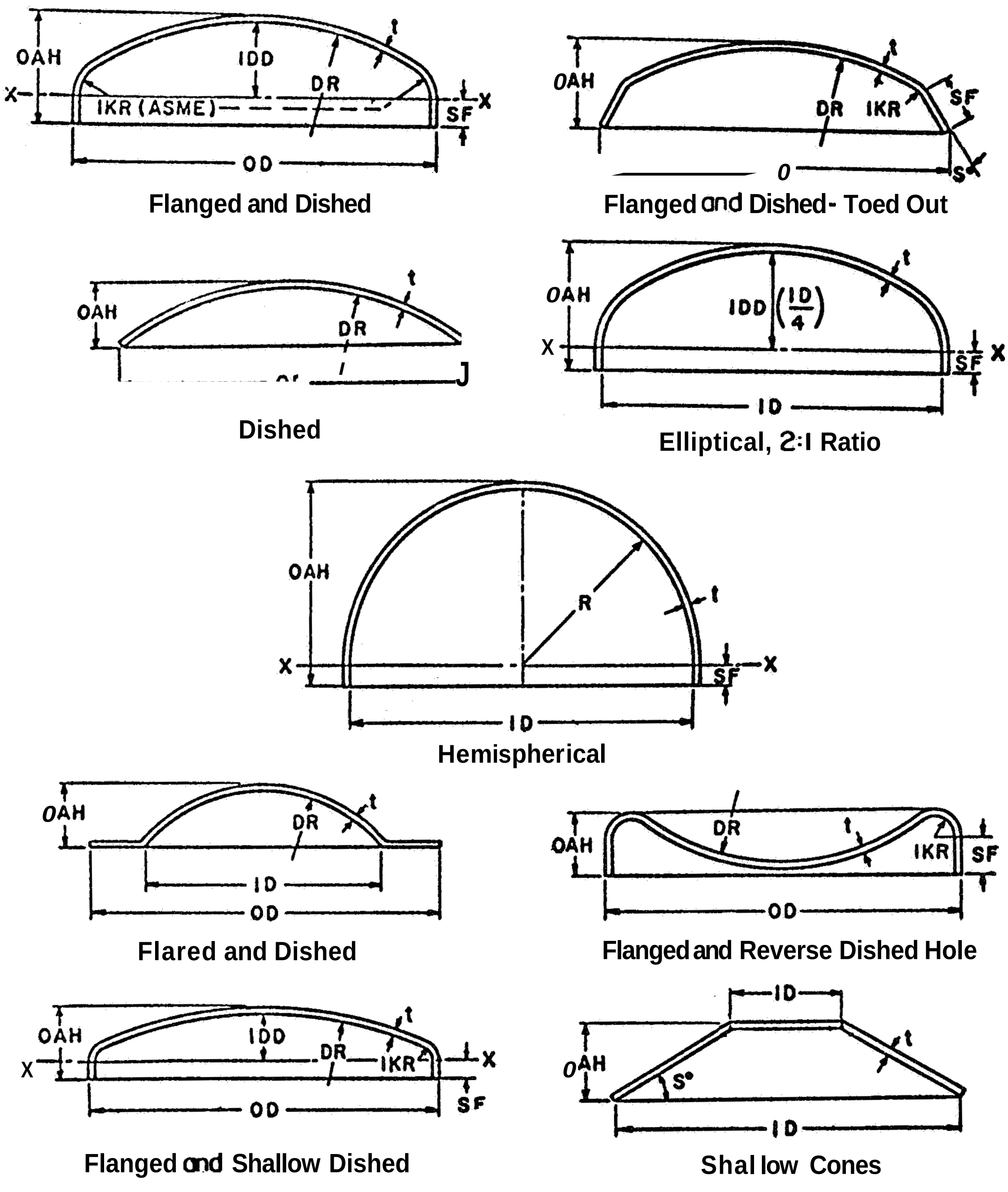
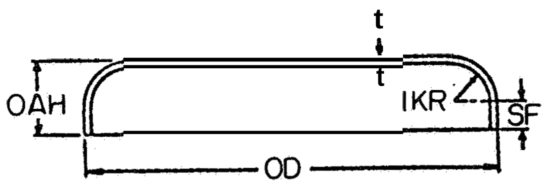
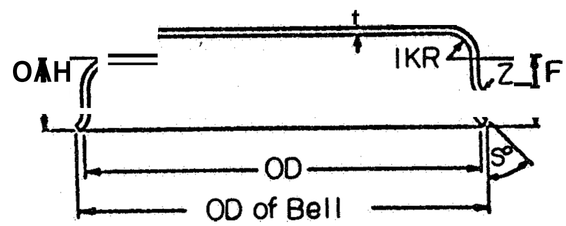


FIGURE 46. SHAPES AND IMPORTANT DIMENSIONS OF COMMERCIAL FORMED HEADS

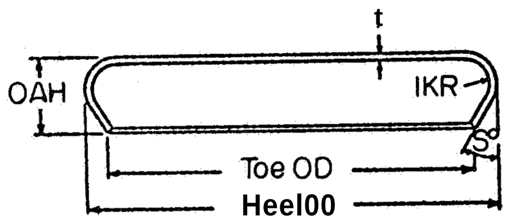
Courtesy of Bethlehem Steel Corporation.



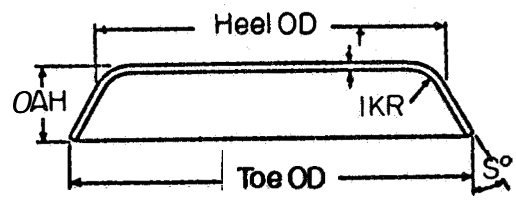
Flanged



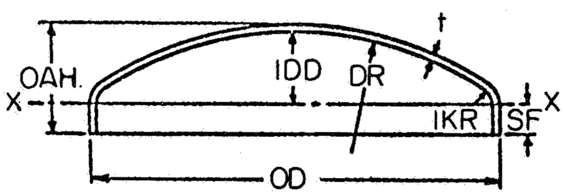
Flanged - Belled



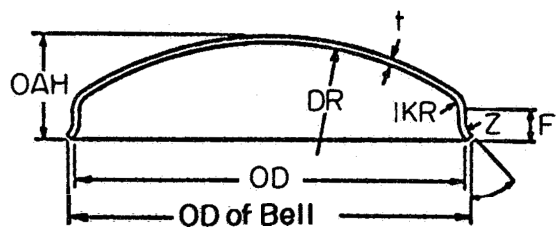
Flanged - Toed In



Flanged - Toed Out



Standard Flanged and Dished



Flanged and Dished - Belled

FIGURE 46. (Continued)

LEGEND DIMENSIONS

OD - Outside diameter
ID - Inside diameter
OAH - Overall height
IKR - Inside knuckle radius
DR - Dish radius
t - Thickness gage
IDD - Inside dish diameter
SF - Skirt length
S° - Flange angle
Z - External radius
F - Flange length

TABLE XVII. RANGE OF COMMERCIAL STEEL DISHED-HEAD SIZES PRODUCED BY SPINNING ONE-PIECE BLANKS (Ref. 86, 87)

Shape	OD* Range, inches	Gage, t,* Range, inches	IKR* Range, inches	SF* Range, inches	DR* Range, inches	IDD* Range, inches	ID* Range, inches	Included Angle, degrees
Flanged	12 - 246	3/16 - 2	9/16 - 6	1-1/2 - 8	--	--	--	--
Dished	12 - 192	3/16 - 3	--	--	12 - 28[illegible]	--	--	--
Flanged and dished	12 - 246	3/16 - 3	9/16 - 9	1-1/2 - 8	12 - 170	1-13/16 - 49-7/16	--	--
Flanged and dished ASME code type	12 - 246	3/16 - 3	3/4 14-3/4	1-1/2 - 8	12 - 180	1-15/16 - 34-7/8	--	--
ASME elliptical, dished, ratio 2 1	--	1/4 - 6	--	2 - 10	--	3 - 54	[illegible] - 2[illegible]	--
Hemispherical	-	3/[illegible] - 6	-	0 - 4	-	--	[illegible] - [illegible]	--
Flared and dished	18 - 150	3/16 - 2	--	--	12 - 168	--	12 - 144	--
Flanged and reverse dished	18 - 144	3/16 - 1-1/2	9/16 - 4-1/2	1-1/2 - 7	18 - 144	--	--	--
Flanged and shallow dish [illegible]	[illegible] - 144	1/4 - [illegible]2	3[illegible] - 1-[illegible]2	1-[illegible]2 - 3-[illegible]2	1[illegible]6 - 300	3-[illegible] - 14-7[illegible]	--	--
Flanged and conical dished	66 - 108	3/8 - 2	--	1-1/2 - 5	--	--	--	140
	28 - 144	5/16 - 2	--	1-1/2 - 5	--	--	--	120
	42 - 102	5/16 - 2	--	1-1/2 - 5	--	--	--	114
	30 - 120	3/8 - 2	--	1-1/2 - 4	--	--	--	90

Note: Maximum-diameter dish may not be formable with maximum thickness [illegible] at [illegible] se of weight of part.

* Shape dimensions given in Figure 46.

Nominal Diameter of Part (inches)	Minimum Tolerance		
	D (inches)	L (inches)	θ (degrees)
Under 1.5	±0.010	±0.015	±1
1.5 to 5.0	20.015	±0.030	±3
5.0 to 20.0	±0.030	±0.030	±3
20.0 to 36.0	20.060	±0.045	±5
36.0 to 72.0	20.120	±0.060	±5

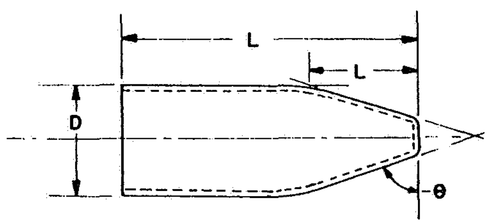


FIGURE 47. TYPICAL SPINNING TOLERANCES (Ref. 88)

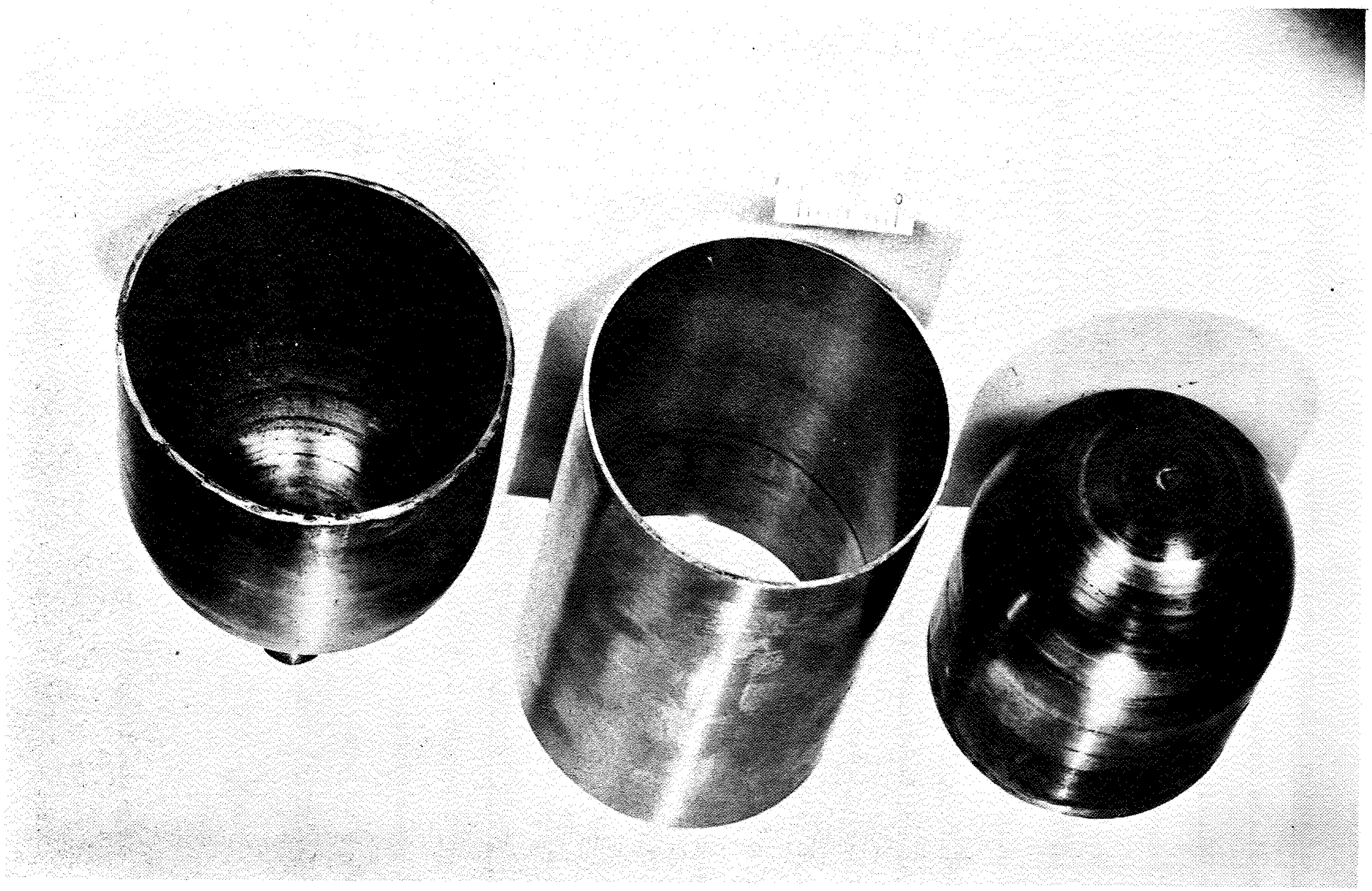


FIGURE 48. SPHERICAL END TUBE - SPUN DOWN MATERIAL 321 STAINLESS STEEL 0.090 INCH WALL, 3.875-INCH-INSIDE DIAMETER

Courtesy of Marquardt Corporation, Ogden, Utah

SHEAR FORMING

Introduction. Shear forming differs from spinning principally because it produces reductions in thickness. A number of trade names have been used to describe the shear forming process since its development. Some of the nonproprietary names used in the past are rotary extrusion, shear spinning, flow turning, and power spinning. Throughout this report the term "shear forming" will be used because it appears to be emerging as the most accepted name for the process.

Principles of Shear Forming. Shear-forming processes can be broken down into cone and tube shear forming. Other shapes can be considered modifications of cones. Examples of such modifications are shown in Figure 49.

A typical example of shear forming is shown in Figure 50. The blank, a circular disk, is clamped to the rotating mandrel by the tail stock. Two rollers located at opposite sides of the mandrel apply a force along the axis of the mandrel and force the blank to take the shape of the mandrel. The rolls are not driven but rotate due to contact with the rotating blank. Tube shear forming may be either forward or backward.

Cone Shear Forming. The percentage reduction of material thickness during cone shear forming is a function of the part shape. Figure 51 shows the geometric measurements that are important for shear forming a cone. The final thickness is related to the initial thickness of the blank by the sine of a half angle of the cone.

$$T = T_b \left(\sin \frac{a}{2}\right) \qquad (23)$$

where

T = the final thickness, inches

T_b = the initial blank thickness, inches

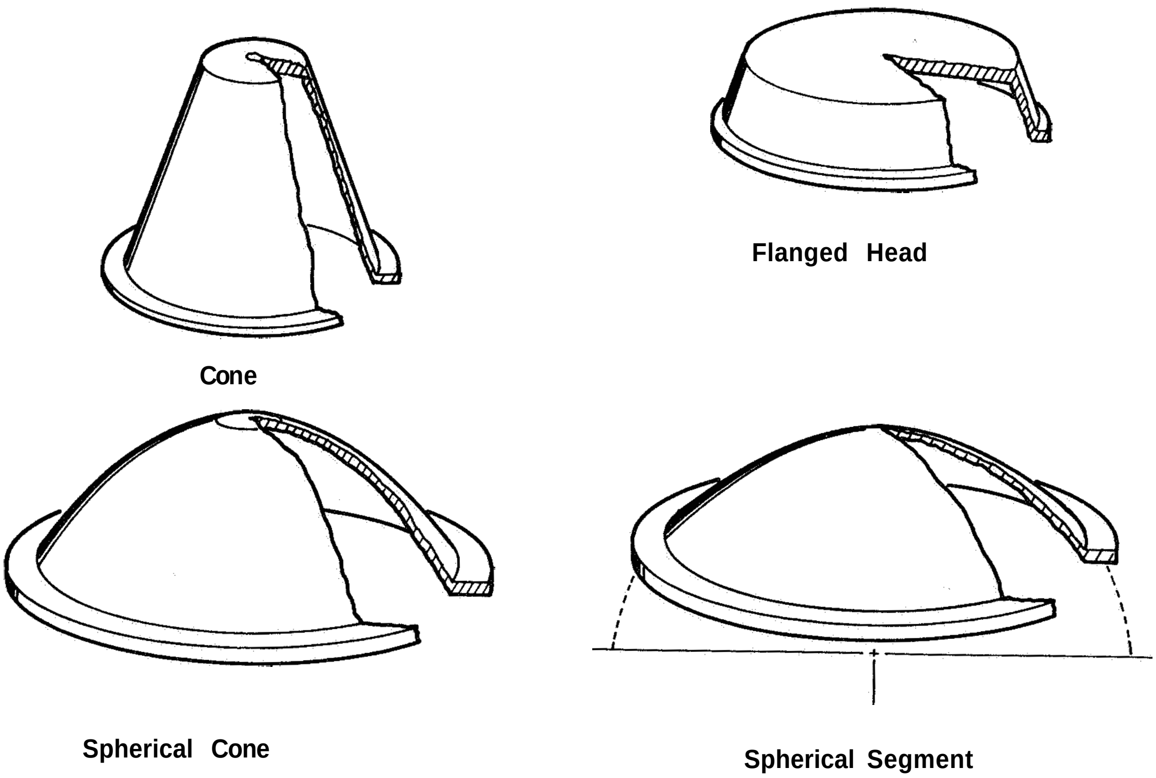
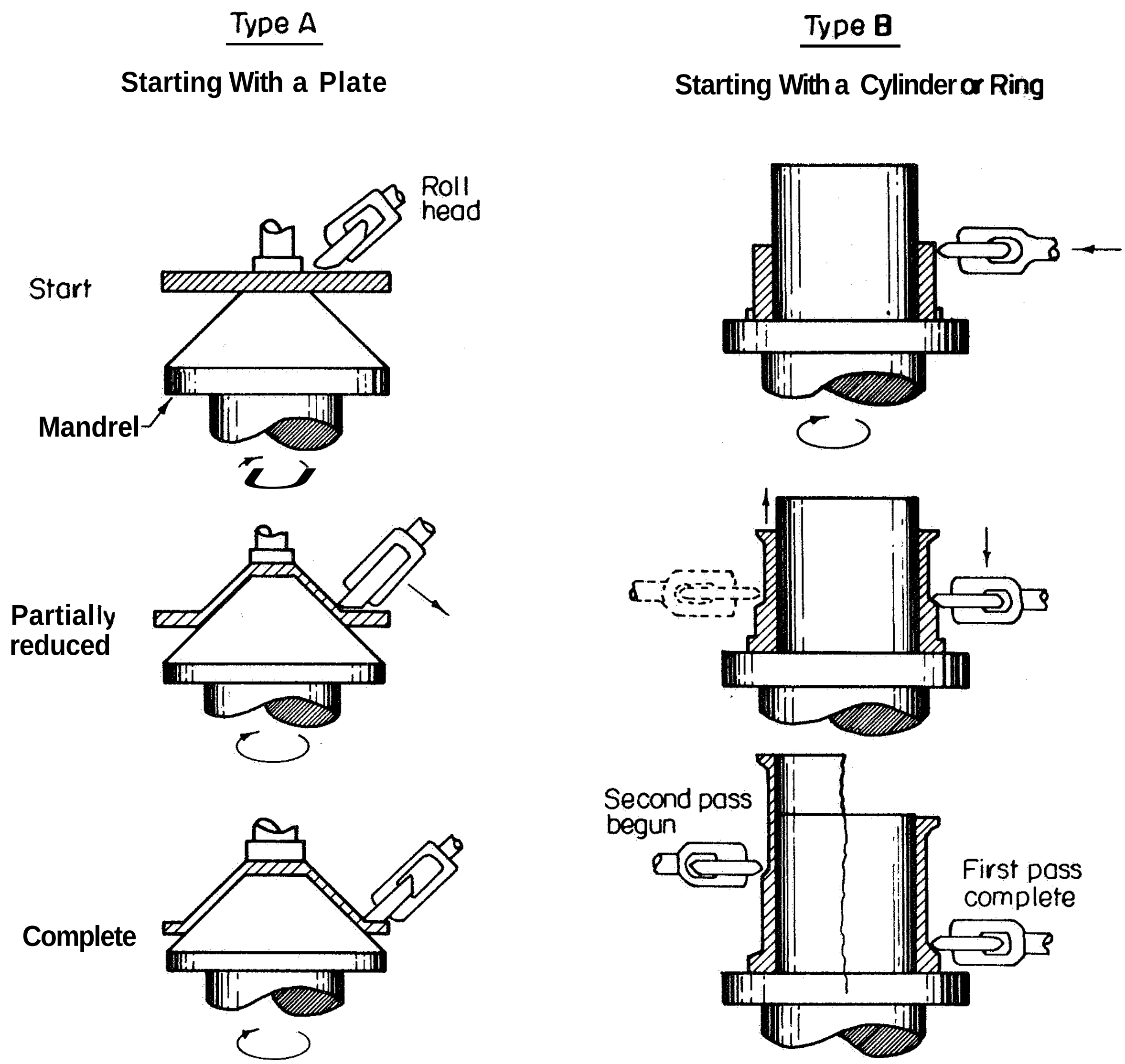


FIGURE 49. SHAPE CAPABILITY BY SHEAR FORMING FROM PLATE (**Ref.** 90)



Type **A.** Part thickness is a function of "sine law" and starting-blank thickness. *(See* Figure 51)
Requires programed roll-head movement, and multiple passes require mandrel changes.

Type B. Part thickness is optional and controlled by roll-head position.
Opposed roll heads are preferred, and multiple passes are frequently used.

FIGURE 50. TWO BASIC TYPES OF SHEAR FORMING (Ref. 90)

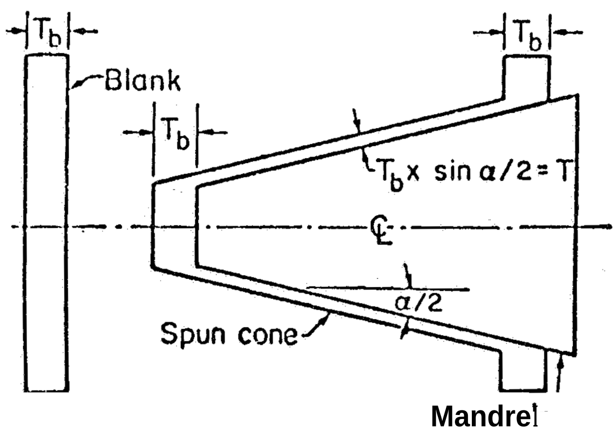


FIGURE 51. GEOMETRIC RELATIONS IN CONE SHEAR FORMING (Ref. 91)

a = the included angle of the cone, degrees.

The percentage reduction is, therefore, related to the sine of the cone half angle

$$R = 100\ (1 - \sin \frac{a}{2}) \tag{24}$$

where

R = the percent reduction.

The same rule applies to shapes other than a cone; the final thickness at any given point along the part is determined by the angle the part makes with the axis at that point. For instance, forming a hemisphere results in a variation of thickness with the bottom of the hemisphere having the same thickness as the blank and the edge being the thinnest section as shown in Figure 52.

Tube Shear Forming. Shear forming of tubes can be of two basic types: forward and backward. In forward tube shear forming the material flows in the same direction as the tool motion, usually toward the head stock. In backward shear forming the material flow is opposite to the forward travel usually toward the tail stock (Ref. 92).

Backward tube shear forming simplifies blank holding and permits higher production rates because the tool travels only 50 percent of the total part length. The process can produce parts that are beyond the normal length capacity of a specific machine. There are difficulties in backward shear forming with respect to holding axial tolerances. Since the first section of the formed material must travel the greatest distance, it is most likely to be out of plane.

Forward tube shear forming is preferred when longitudinal accuracy of sculptured sections is required. Since each deformed increment of material remains stationary, errors in concentricity are swept away from

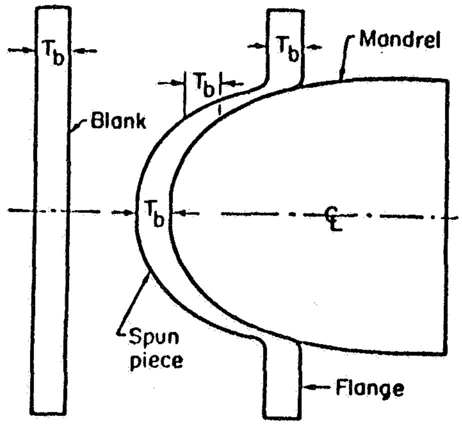


FIGURE 52. THICKNESS OF A MATERIAL IN A SHEAR-FORMED HEMISPHERE (Ref. 92)

the finished part and are left in the trim stock. Tolerances of ± 0.002 inch can be held on wall thickness with this technique (Ref. 93).

In shear forming of tubing, the basic sine law for shear forming cannot be applied. The maximum permissible reduction for ductile materials depends on the state of stress in the deforming area and the material properties. The maximum reduction can be predicted from the tensile reduction in area both for cone and tube shear forming (Ref. 94). The experimental data shown in Figure 53 indicate that a maximum shear-forming reduction of about 80 percent can be taken on materials with a tensile reduction in area value of about 50 percent. Beyond this level of tensile ductility there is no further increase in formability. Among materials with the reduction in area value less than 50 percent ductility determines formability.

Some of the process parameters affecting the limiting reductions are the feed rate, corner radius of the tool, the depth setting of the tool, and the angle of the tool. Kitchin found a number' of factors that affected shear forming of Type 321 stainless steel (Ref. 95).

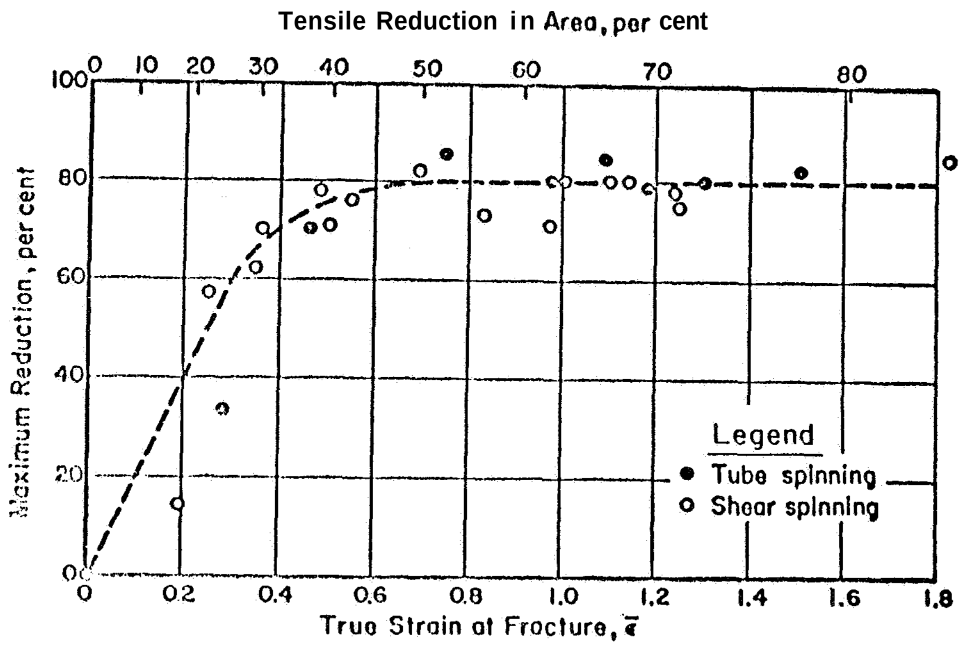


FIGURE 53. MAXIMUM SPINNING REDUCTION IN TUBE AND SHEAR SPINNING OF VARIOUS MATERIALS AS A FUNCTION OF TENSILE REDUCTION IN AREA (Ref. 94)

(1) Wall thickness variation on as-spun cylinders is generally minimum when:

(a) The mandrel run-out is small, preferably 0.001 inch maximum

(b) The percent reduction for a single shear-forming pass is below 30 to 40 percent

(c) The ratio of spindle speed/longitudinal roller feed is high

(d) The ratio of the axial roller bite/roller step approaches 1.0

(e) Backward shear spinning is used rather than forward shear spinning

(f) The preform wall thickness is small

(g) Shear spinning is done at room temperature.

(2) The variations in internal diameter and wall thickness of shear-formed tubes are minimized when:

(a) The mandrel run-out is small, preferably 0.001 inch maximum

(b) The percent reduction for a single shear-forming pass is below 30 to 40 percent

(c) The ratio of spindle speed/longitudinal roller feed is high

(d) The ratio of the axial roller bite/roller step approaches 1.0

(e) Backward shear spinning is used rather than forward shear spinning

(f) The preform wall thickness is small

(g) Shear spinning is done at room temperature.

(3) Following the recommendations in "b", "c", "d", and "f" (above) minimizes the growth in internal diameter which sometimes occurs in shear forming. From that standpoint, it is also desirable to use a minimum number of passes and rollers with 30-degree contact angles and a radius of intermediate size.

(4) High spindle speeds may cause a decrease in internal diameter, instead of growth, but are likely to give better surface finishes.

(5) Rollers with wider bands improve surface finish and minimize variations in wall thickness.

Equipment. Shear-forming machines are heavier and have considerably more power than spinning lathes. Spinning can, however, be conducted on shear-forming machines for producing cones. A shear-forming machine is capable of shear forming a 60-inch-diameter, 321 stainless steel blank 1/2 inch thick is shown in Figure 54.

Until recently the shear-forming equipment being used for the Minuteman missile cases, 65 inches in diameter, was the largest in the industry. Now,

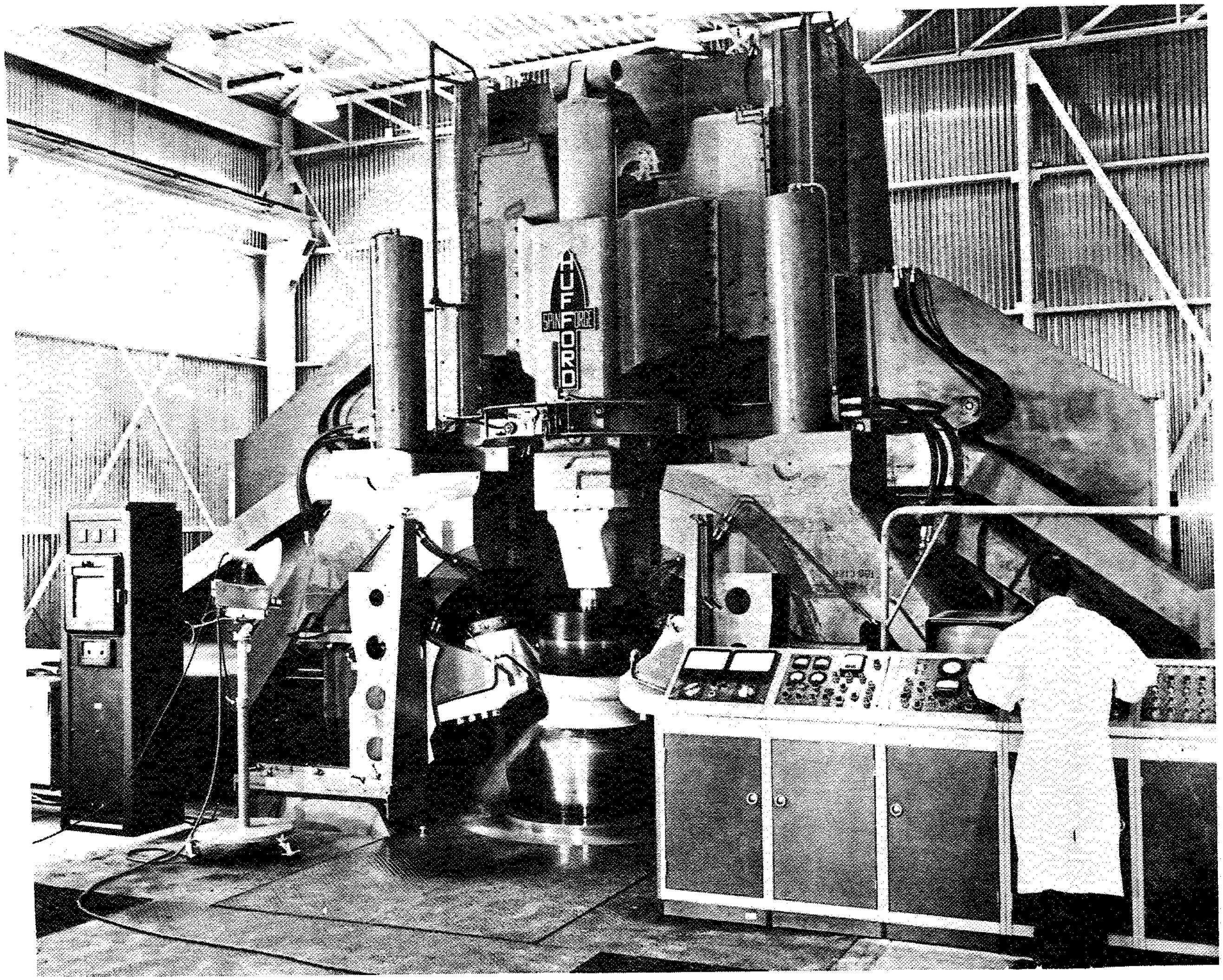


FIGURE 54. 60-INCH SHEAR-FORMING MACHINE FORMING A TYPE 321 STAINLESS STEEL EXIT NOZZLE

Courtesy of Marquardt Corporation, Ogden, Utah

equipment capable of shear forming of 13-foot-diameter cylinders more than 15 feet long is available at NTW Missile Engineering, Inc., and at the Ladish Company (Ref. 90).

The NTW machine operates vertically but instead of using a mandrel, the shear-forming action is developed between a large-diameter container ring and three inside rollers. The metal flow is axial and since the starting ring is placed within a container, internal roll extrusion is quite descriptive of this shear-forming technique. The machine is equipped with an adjustable orifice ring to prevent minor corrections in diameter. Major changes from the present 120-inch diameter capability requires additional container rings.

The Ladish process can also shear form large-diameter rings with stiffeners on both the inside diameter and the outside diameter. This is a feature not typical of other shear-forming processes. Shear-formed parts are now under evaluation for applications in solid-propellant booster programs. Although this equipment has not been used for forming stainless steels, it does have the capability for working them. In the present practice motor-case segments are made from rolled and welded plate of high-strength steels and from stainless rolled rings, both of which require substantial machining to obtain the final dimensions. Shear forming to the final wall thickness would provide a substantial saving in both material and machining time. The Ladish machine is capable of producing cylinders up to 160 inches in diameter and 15 to 20 foot long. Future size expansion is controlled mainly by the other facilities available for handling such large items (Ref. 90).

Some of the specifications for specific machines now available are given in Table XVIII. These machines are manufactured by Lodge & Shipley,

TABLE XVIII. TYPICAL AVAILABLE SPINNING AND SHEAR-FORMING-MACHINE SIZES (Ref. 93, 96, 97, 98)

Manufacturer	Part Port- Diameter, in.	Part Port- Length, in.	Spindle, hp	Forces: Roller, lb	Forces: Carriage, lb	Forces: Tailstock, lb	Production Rate, piece/hr	Machine Weight, lb	Number of Rolls	Type
Lodge & Shipley	12	15	15	4,000	5,000	2,000	75-100	8,750	1	Horizontal
(Floturn)	12	15	40	14,000	12,000	3,000	90-125	26,000	2	Vertical
	24	30	75	32,000	54,000	8,000	30-80	52,000	2	Vertical
	40	50	20	15,000	--	7,300	8-30	41,000	1	Horizontal
	60	70	90	40,000	--	15,000	1-15	100,000	1	Horizontal
	70	84	150	70,000	70,000	35,000	1-15	195,000	2	Horizontal
Cincinnati Milling	42	50	20	50,000	50,000	35,000	--	53,970	1	Horizontal
Machine Company	42	50	20	50,000	50,000	35,000	--	78,970	2	Horizontal
(Hydrospin)	62	50	20	50,000	50,000	35,000	--	145,500	2	Horizontal
	70	72	30	70,000	70,000	50,000	--	235,000	2	Vertical
Hufford Manufacturing	60	60	200	225,000	225,000	200,000	--	--	2	Vertical
Company	60	120	200	225,000	225,000	200,000	--	425,000	2	Vertical
(Spin forge)	96	120	600	[illegible]	[illegible]	—	—	[illegible]	2	Vertical

Cincinnati Milling Machine Company, and Hufford Manufacturing Company. Additional sizes in machines may be available so that the manufacturer should be informed of specific requirements.

Tooling. Shear forming requires stronger tooling than spinning because greater forces are characteristic of the process. Rollers are used for applying the forming force to the blank. The diameter of the rolls is generally kept to a minimum consistent with the force that it is required to transmit. The shape of the roller depends on the amount of reduction to be taken with each pass. A typical roller configuration is shown in Figure 55 and the more important surfaces are indicated. The contact angle determines the length of contact surface for any given reduction; the greater the contact length, the greater the frictional forces between the roller and material. The approach surface and contact angle are required to prevent material from burring ahead of the roller. Since the roller step controls the amount of reduction, a different roller is required for each reduction. The burnishing angle and land tend to smooth out the ring marks left on the part due to the axial travel of the tool. Rollers for shear forming are generally made of high-speed tool steel, heat treated to R_c 60. The surface is polished and can be hard chromium plated for a good surface finish on the part.

The mandrels for shear forming are made of heat-treated steel because of the high forces involved. A softer material would be locally deformed by the roller pressure. Large mandrels are generally made as shells with supporting internal structures while smaller mandrels are solid.

Lubricants. Very little has been published on lubricants specifically for shear-forming operations on stainless steels. In general, the lubricant should be a high-pressure colloidal zinc or moly-disulfide paste to prevent

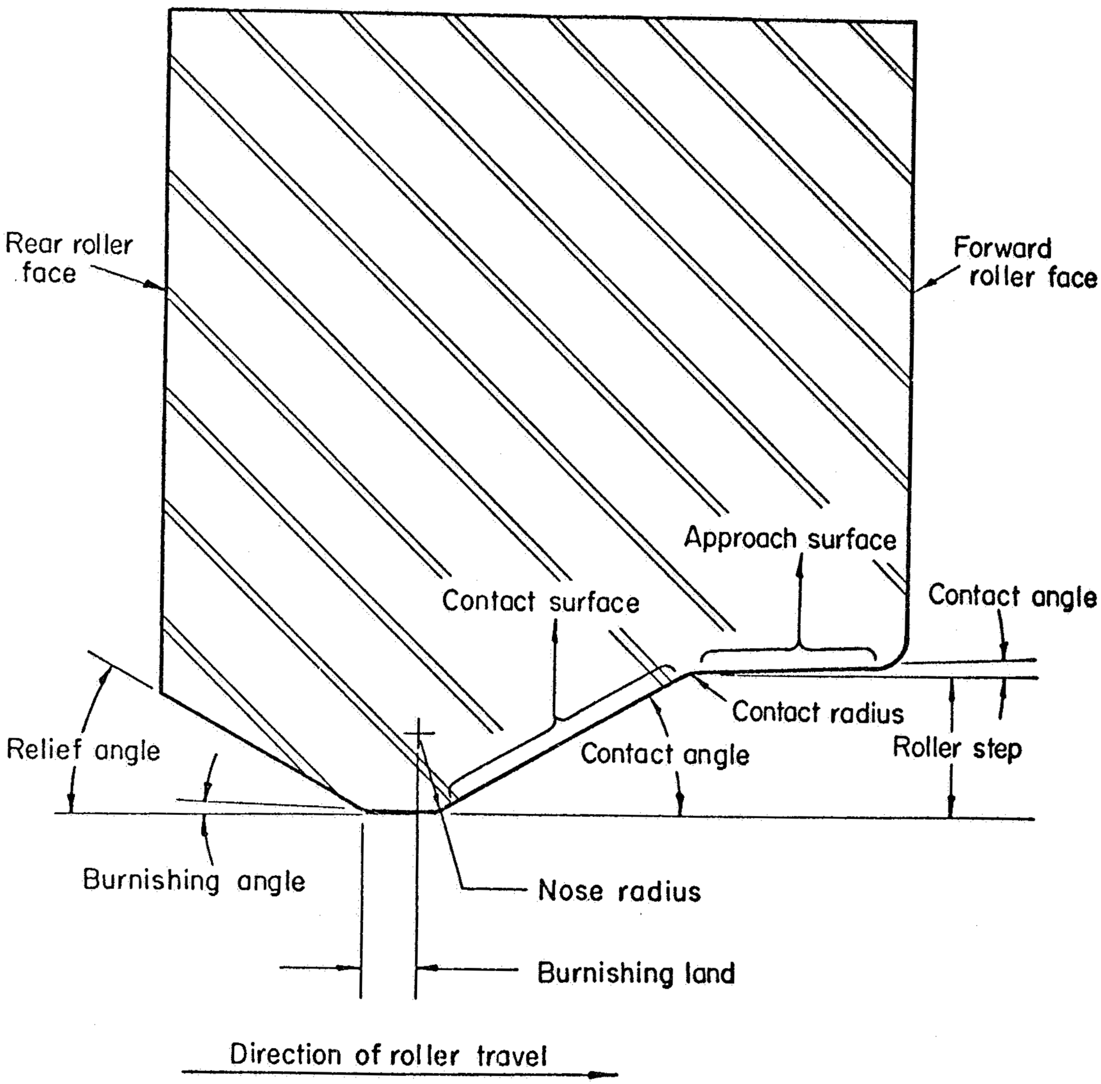


FIGURE 55. ROLLER CONFIGURATION FOR SHEAR FORMING (Ref. 95)

galling at roller pressures up to *400,000* psi on stainless steels (Ref. 95). For room-temperature shear forming, heavy-bodied oils are desirable for the extremely severe work (Ref. 98) of shear forming.

Blank Preparation. Blanks for cone shear forming require a diameter the same as that of the finished part. Some additional allowance for trimming is desirable to reduce the possibility of cracking. This is likely to occur when shear forming is carried to the edge of the blank. The trim allowance should be at least equal to the original blank thickness.

Forward tube shear forming requires a blank with an inside diameter equal to the diameter of the finished part. The length of the tube blank is determined by the length of the finished part desired and the reduction to be accomplished. For a part shear formed to a 50 percent reduction, the length of the blank would be one-half of the finished part length. Some allowance for trim should be made in forward shear forming; an allowance of 1 inch for each 10 inches of finished length is normal practice.

Backward tube shear forming requires the same considerations in blank development as forward shear forming. The same reasoning is used in selection of the blank length. The blank inside diameter is the same as the finished tube diameter.

Blank Development. It is sometimes desirable to shear form a configuration other than a cone to a uniform thickness. The proper thickness of the preform can be determined by calculation or by trial-and-error technique. To calculate the appropriate blank thickness, it is necessary to know the desired finished material thickness, the shape of the part, and the percentage reduction desired. For example, consider the production of the hemispherical part shown in Figure 56 in which a maximum reduction of

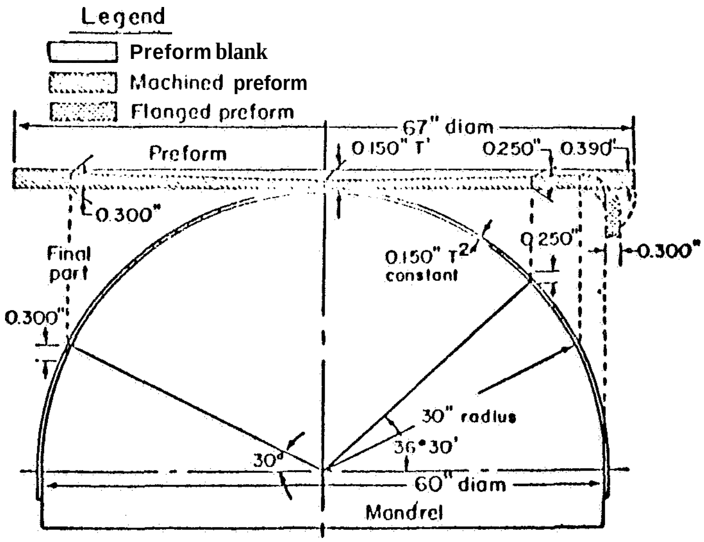


FIGURE 56. TYPICAL DEVELOPMENT OF A BLANK FOR CONSTANT SHEAR-FORMED THICKNESS (Ref. 92)

50 percent is expected to produce a constant wall thickness of 0.150 inch. Using the sine law to determine the vertical height of an element in the shell at increments of about 1/2 degree gives a continuous plot of the blank thickness. Since only a 50 percent reduction is permitted, however, the angle at which this occurs must be determined. In this case, 0.150/ 0.300 equals 0.500 which is the sine of 30 degrees. Consequently, the edge of the blank cannot exceed 0.300 inch in thickness. Preforming the edge from the 30-degree intersection to the lip of the hemisphere is therefore necessary as shown in Figure 56. The time involved in calculating the shape of the preform may not be warranted since some deviation from the sine law often occurs. Trial-and-error methods can be used by the operator to obtain the same results often more accurately. With this approach the operator shear forms a trial blank of a constant maximum thickness of 0.300 inch. After forming the part, thickness is measured at

various locations and the data are used for correcting the thickness of the next trial blank. This process may have to be repeated several times but the final refinement should give a very accurate part thickness. This technique may be necessary even when the thickness of the blank is precalculated.

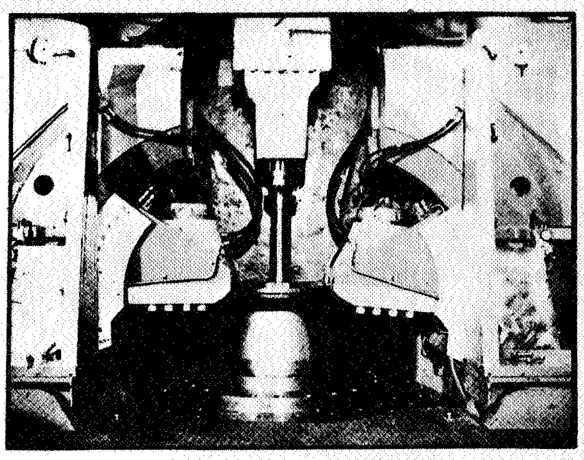
Shear Forming Limits. Shear forming is generally used to reduce machining time on parts with shapes that cannot be made by conventional forming methods. The limiting reductions in a single shear-forming pass at room temperature for a number of stainless steels are given in Table XIX.

The part shown in Figure 57 is representative of parts that can be made of stainless steel by shear forming. This part is a simple cone with straight sides as shown made from a 2-1/2-inch-long, 0.093-inch-thick Type 310 stainless steel welded blank. Depending on the shape and the material, parts are made from flat blanks or from preforms. An example of a shear-forming procedure using welded preform parts is shown in Figure 58. In these cases the preforms were made by rolling and welding a tube. Thickness control obtainable with several of the parts shown in Figure 58 are given in Figures 59 and 60. The final shape of these parts was obtained by explosive forming after the desired wall thickness had been obtained by shear forming.

Properties After Shear Forming. Like other cold-working processes, increasing the amount of deformation in shear forming usually. increases the strength and reduces the ductility of the workpiece in a regular manner. Some typical properties for several stainless steel alloys after shear forming are given in Table XX. These data indicate that reductions as low as 20 percent, more than double the yield strength and increase the

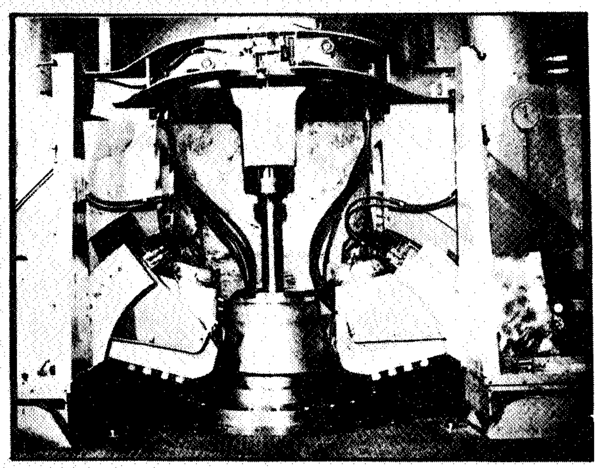
TABLE XIX. MAXIMUM REDUCTIONS IN SHEAR-FORMING CONES FROM STAINLESS STEELS AT ROOM TEMPERATURE (Ref. 99)

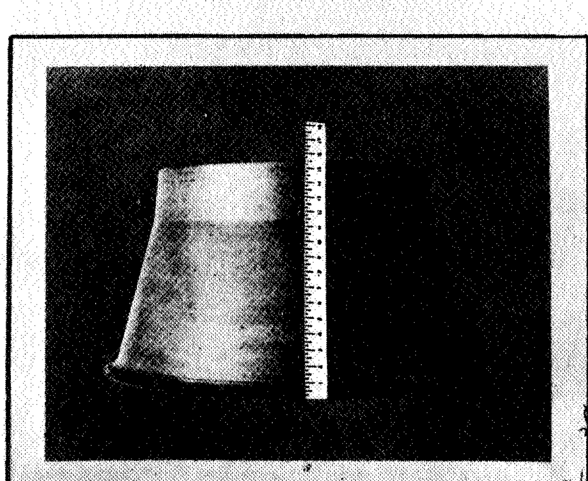
Materia1 AISI Type	Percent Reduction
301	70
302	70
310	70
321	70
347	70
19-9 DL	60
410	60
430	70



Spin forge machine setup for forming a 310 stainless steel structural skin from a $2\frac{1}{2}$ inch long .093 inch wall thickness preform.

A one-pass operation produces a skin .025 inch thick and 15 inches long. Material thickness is reduced approximately 73 percent in less than four minutes.





The part is finished net with no subsequent machine operations required except for finish trimming.

FIGURE **57.** **SHEAR** FORMING OF A ROLLED AND WELDED TYPE 310 STAINLESS STEEL PREFORM

Courtesy of Marquardt Corporation, Ogden, Utah

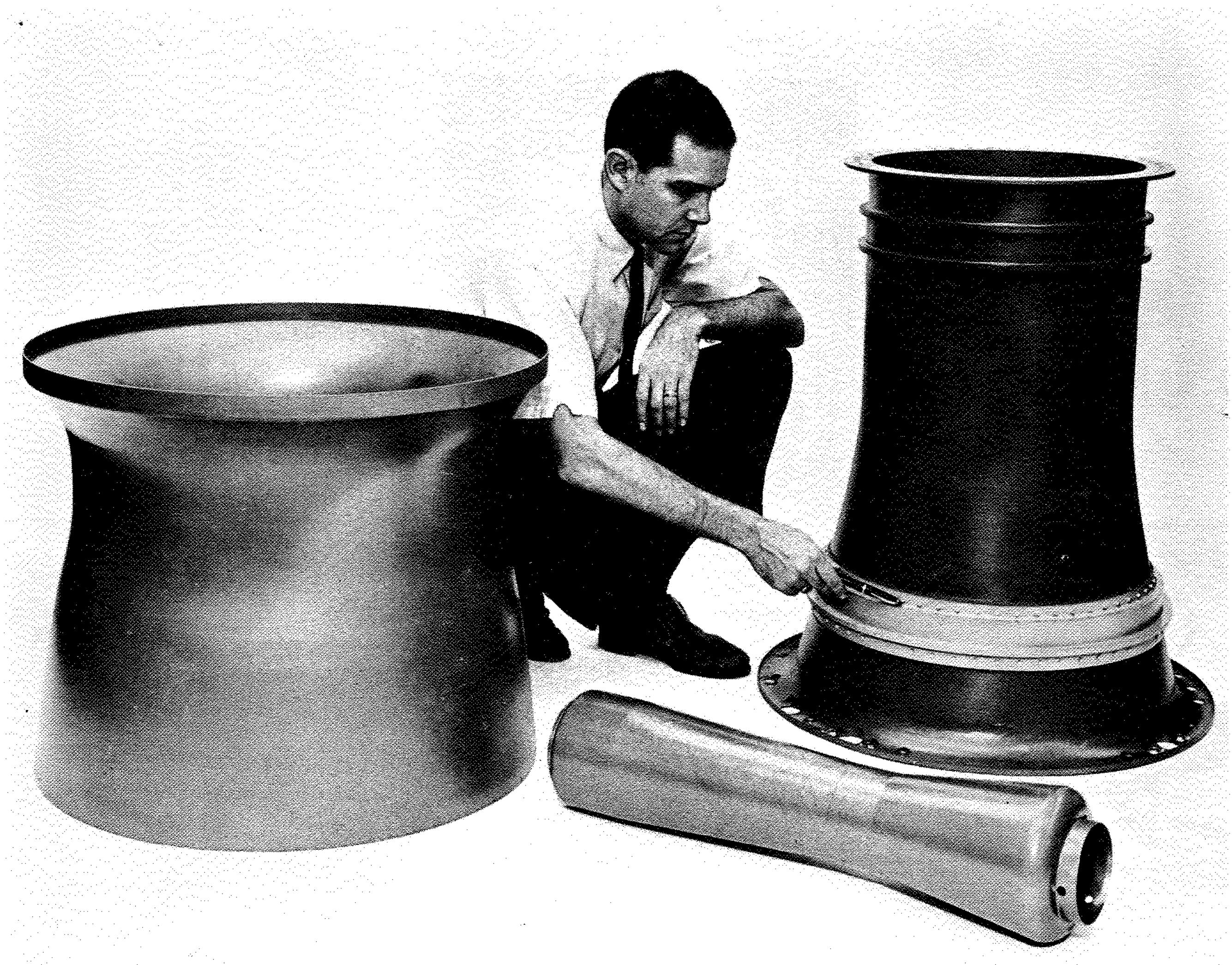


FIGURE 58. SHEAR-FORMED TYPE 321 STAINLESS STEEL PARTS

Courtesy of Marquardt Corporation, Ogden, Utah

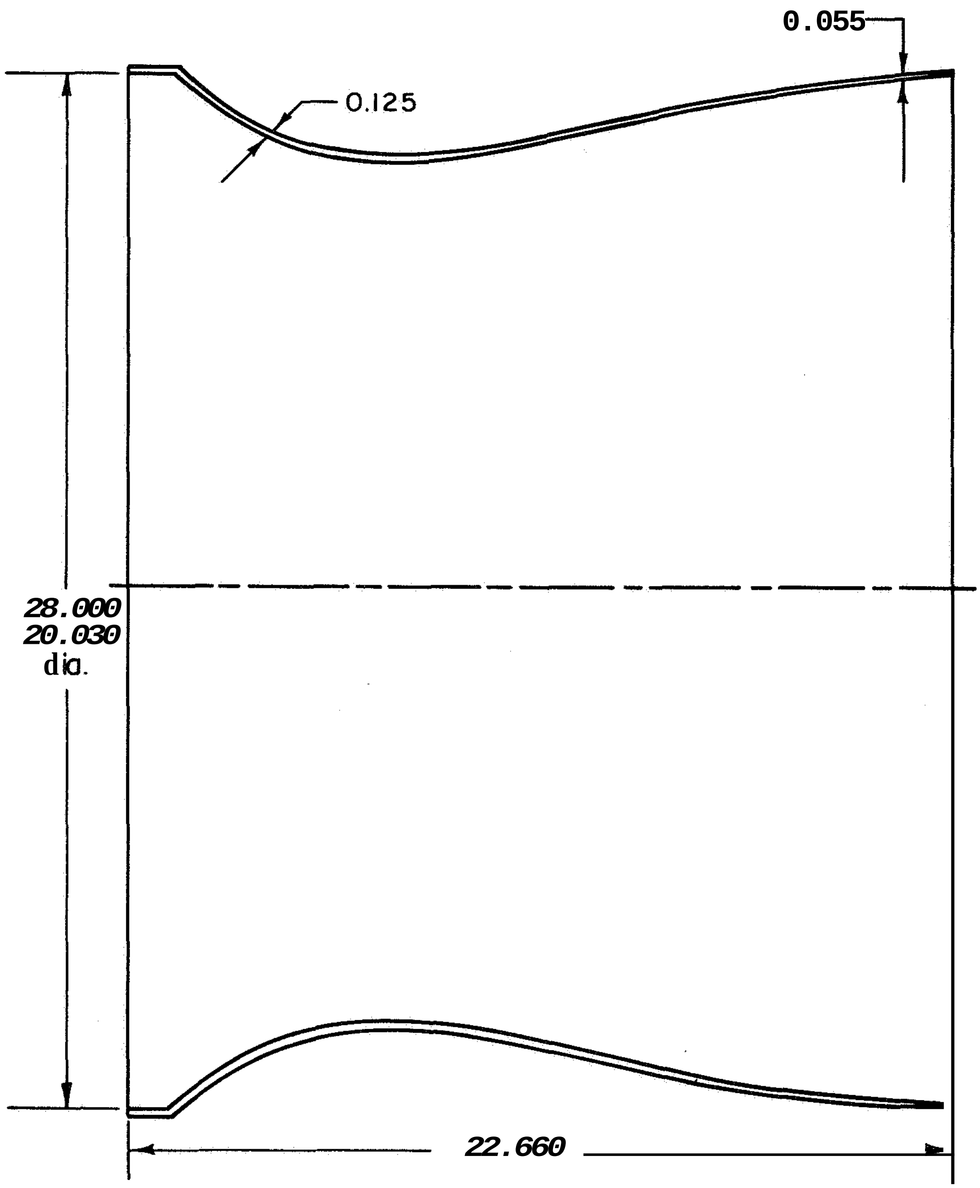


FIGURE 59. FINISHED 321 STAINLESS STEEL PART DIMENSIONS TO WHICH THE COMBUSTION CHAMBER EXIT NOZZLE IS SHEAR FORMED (Ref. 93)

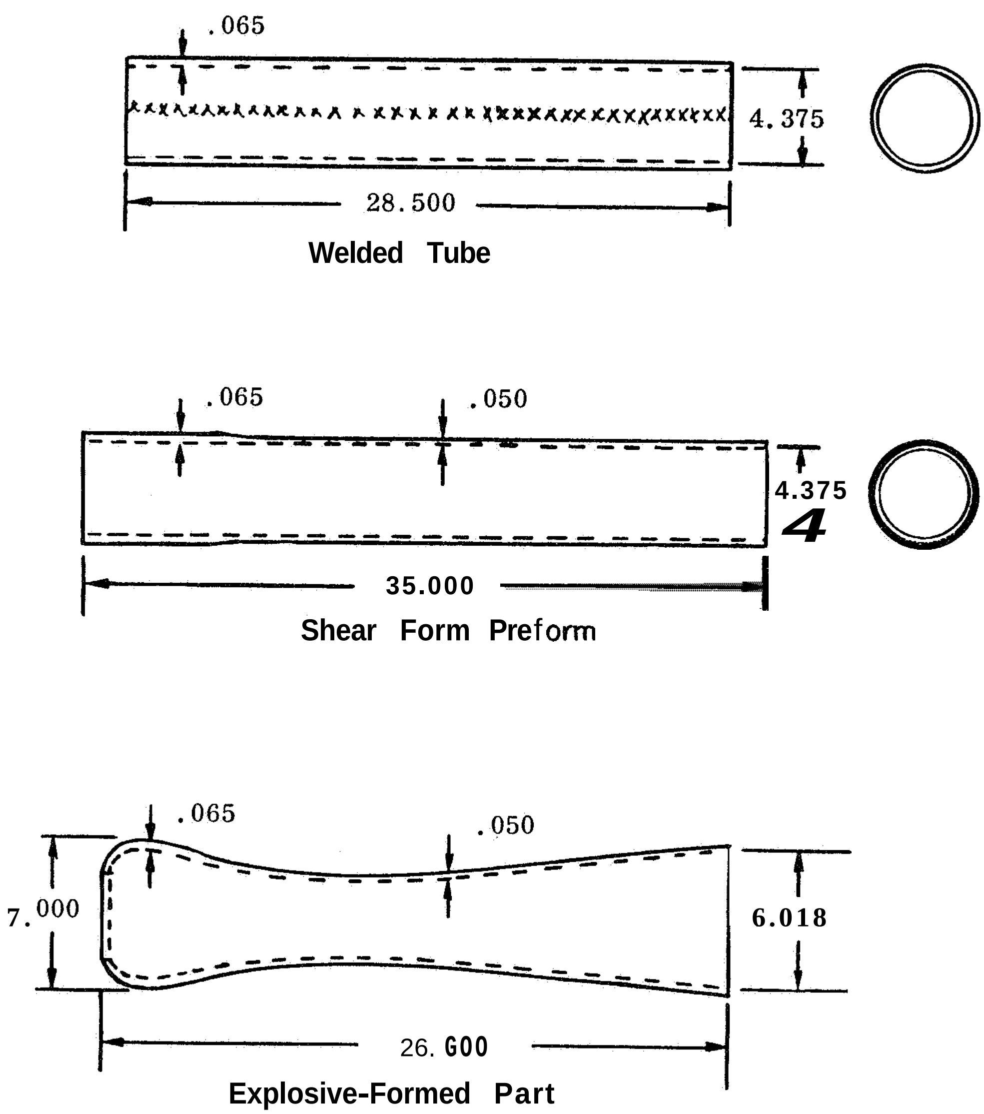


FIGURE 60. DIMENSIONAL REQUIREMENTS OF A PILOT CAN SHELL MADE OF 321 STAINLESS STEEL DURING THE THREE STAGES OF FABRICATION (Ref. 93)

TABLE XX. TENSILE PROPERTIES OF STAINLESS STEELS BEFORE AND AFTER SHEAR FORMING (Ref. 100)

aterial ISI Type	Condition	Orientation	Elongation in 2 Inches, percent	Tensile Yield Strength, 1000 psi	Tensile Ultimate Strength, 1000 psi	Hardness, Rockwell
301	Annealed	L	56.2	50.5	106.5	B 88.8
	"	T	48.0	54.6	107.3	B 90.5
	20% reduction	Radial	21.2	125.4	143.6	C 33.8
	30% "	"	18.3	144.7	157.2	C 36.5
	40% "	"	9.2	155.2	169.1	C 38.4
	50% "	"	11.0	156.7	169.6	C 41.9
	60% "	"	3.5	207.4	220.1	C 45.5
	70% "	"	2.8	223.6	230.1	C 46.4
302	Annealed	L	53.7	56.1	87.6	B 86.9
	"	T	54.2	58.2	89.7	B 86.3
	20% reduction	Radial	15.2	124.7	131.8	C 29.5
	30% "	"	11.8	129.3	140.4	C 31.5
	40% "	"	8.0	135.1	148.5	C 34.2
	50% "	"	6.5	143.5	153.8	C 34.7
	60% "	"	6.3	160.5	174.6	C 38.0
	70% "	"	3.0	186.5	200.3	C 40.6
310	Annealed	L	50.3	38.4	86.7	B 80.3
	"	T	46.8	38.7	86.9	B 81.7
	20% reduction	Radial	10.7	114.9	125.3	C 25.1
	30% "	"	9.0	124.1	134.2	C 27.8
	40% "	"	5.3	138.4	151.1	C 31.0
	50% "	"	2.7	127.4	135.3	C 31.0
	60% "	"	3.8	145.3	158.9	C 33.8
	70% "	"	4.2	171.3	182.3	C 36.7
321	Annealed	L	48.3	50.5	85.4	B 85.4
	"	T	50.2	50.4	84.8	B 86.2
	20% reduction	Radial	10.3	106.2	124.7	C 26.9
	30% "	"	8.2	128.5	139.5	C 30.0
	40% "	"	6.0	137.1	151.6	C 33.3
	50% "	"	6.2	134.9	149.6	C 33.5
	60% "	"	3.8	160.0	174.3	C 37.8
	70% "	"	3.5	159.5	179.3	C 37.8
347	Annealed	L	47.2	45.4	89.1	B 84.0
	"	T	47.5	37.5	88.7	B 82.3
	20% reduction	Radial	9.7	121.8	132.2	C 29.8
	30% "	"	6.8	137.5	150.7	C 32.4
	40% "	"	--	--	--	--
	50% "	"	4.3	139.2	155.1	C 35.5
	60% "	"	3.7	157.0	172.7	C 37.4
	70% "	"	2.7	163.0	186.5	C 39.5

TABLE XX. (Continued)

Material AISI Type	Condition	Orientation	Elongation in 2 Inches, percent	Tensile Yield Strength, 1000 psi	Tensile Ultimate Strength, 1000 psi	Hardness, Rockwell
430	Annealed	L	23.3	48.7	71.1	B 83.0
	"	T	23.0	51.7	76.0	B 83.3
	20% reduction	Radial	5.7	95.2	101.2	C 15.0
	30% "	"	6.5	100.4	104.0	C 17.2
	40% "	"	4.8	98.9	102.9	C 18.4
	50% "	"	4.3	107.0	112.2	C 20.8
	60% "	"	4.0	114.7	118.9	C 22.5
	70% "	"	2.5	121.6	122.9	C 21.7

Note: All values are averages for three determinations.
All shear forming was at room temperature.
All tensile specimens were removed from a shear-formed cone.

ultimate strength by 25 percent. Ductility can be restored to the part by annealing but the strength will be reduced. Normally a stainless steel part which has been shear formed at room temperature will have very high residual stresses. Consequently, machining the part may be expected to cause distortion. It is advisable, therefore, to anneal shear-formed parts before machining operations.

FLEXIBLE DIE FORMING

Introduction. In flexible die forming, a rubber pad, hydraulic bladder, or hydraulic fluid is used as part of the tooling. The fluid or rubber is confined or trapped in a retainer. Various trade names such as "Marforming", "Hydroforming", or the "Wheelon Process" are used to describe the types of equipment used in forming materials by the flexible die techniques. In the Marforming or Guerin Process, as shown in Figure 61, closing the upper and lower platens causes the rubber to fill the space between the retainer and the part and forces the blank to assume the shape of the punch. In the Hydroform Process, shown in Figure 62, a rubber bladder filled with fluid is compressed by the motion of a press, which moves both the punch and bladder. In the similar Wheelon process a rubber bladder is inflated by a pressurized fluid to deform the blank around a fixed punch. In hydraulic bulge forming, the metal blank is forced against a die directly by the hydraulic fluid.

Among other advantages, flexible die forming requires only half the die set normally used in press forming. The process is best suited for making small quantities of parts with shallow recesses although some deeply recessed parts have been made successfully by bulge forming. All of the processes can be adapted to form several small parts simultaneously depending on the capacity and platen area of the press available for mounting punches.

The hydraulic bulging process can also be used to form blanks into female dies. An example of a hydraulic bulging operation is shown in Figure 63. The Type 320 stainless steel preform was a flanged, flat-bottom cone. Hydraulic pressure supplied through the hose shown at the bottom forced the

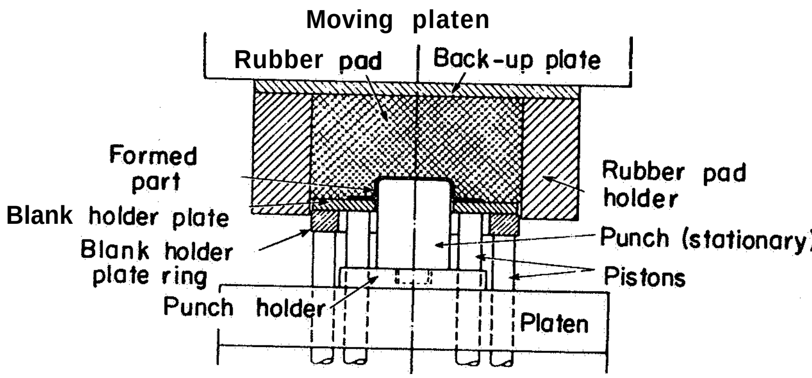


FIGURE 61. MARFORMING PROCESS (Ref. 3)

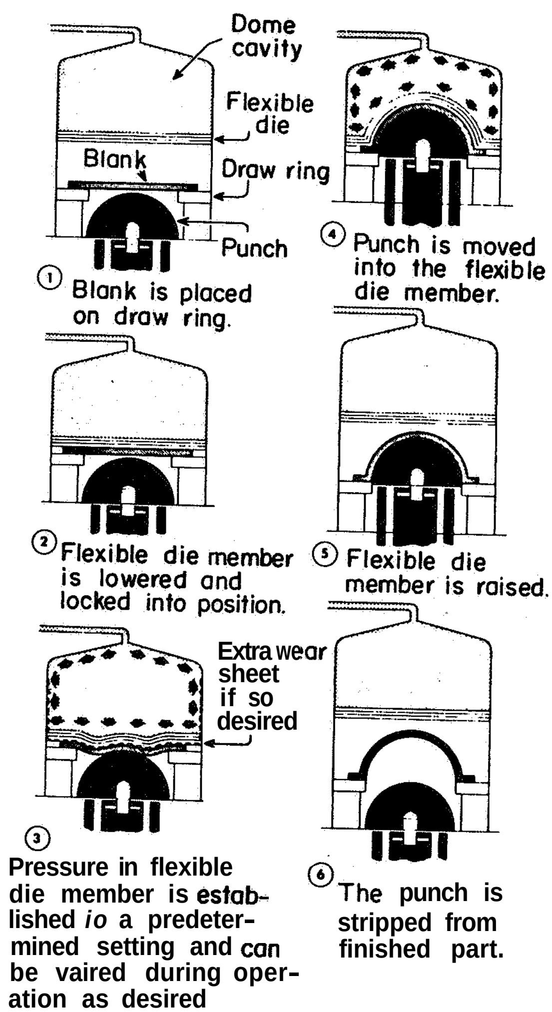


FIGURE 62. THE OPERATING CYCLE OF THE HYDROFORM PROCESS (Ref. 3)

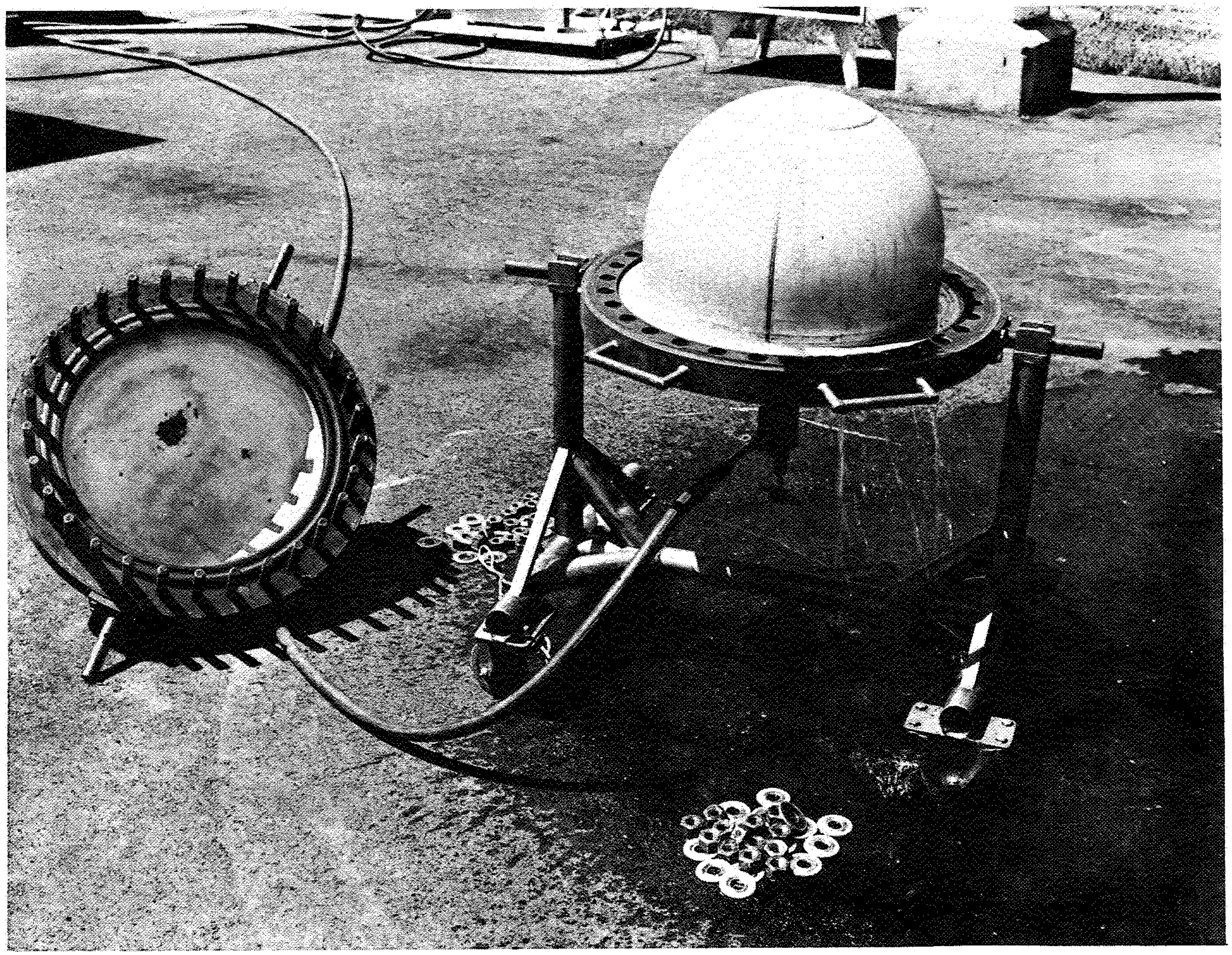


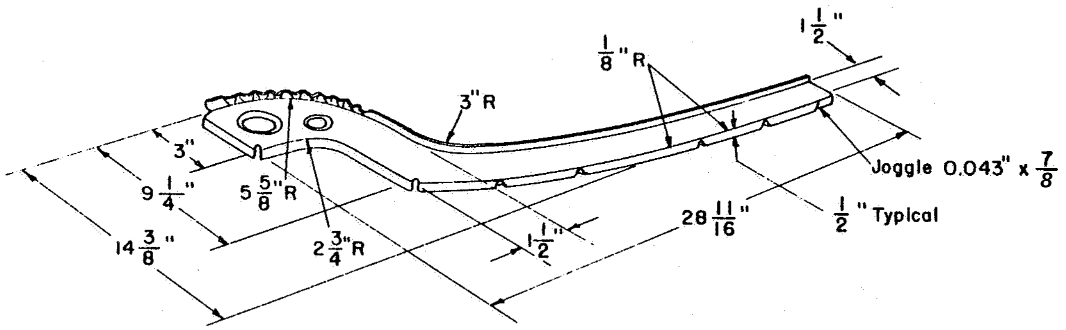
FIGURE 63. BULGE FORMING TOOLING AND 321 STAINLESS STEEL PART
(Courtesy of General Dynamics Convair Division, San Diego, California)

metal to take the shape of the plastic female die shown at the left. This method has the advantage of not requiring heavy press equipment, although the tooling must be strong enough to withstand the hydraulic pressure (Ref. 3).

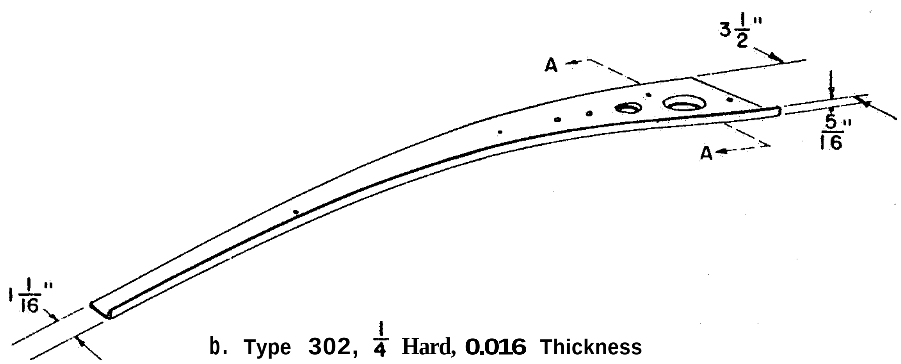
The maximum pressure developed in flexible die forming is ordinarily about 10,000 psi. However, some recent work with high-energy impact machines equipped with trapped rubber heads showed that pressures of 24,000 psi are obtained with a striking velocity of 800 inches per minute (Ref. 101). A feature of the parts made by the high-pressure methods is that substantially less springback occurs. In the case of a 321 stainless bulkhead, a tolerance of ±0.0032 inch was held. Parts formed by the other flexible die processes generally require some additional work to correct the springback.

The Guerin and Wheelon processes have been used extensively by the aircraft industry for forming parts with straight and curved flanges. The parts may be formed in one operation or in stages requiring several forming blocks depending on the shape of the part. Some typical Marformed or trapped rubber-formed aircraft parts are shown in Figure 64. The material thickness and condition of the stainless steel blanks are indicated on the drawings.

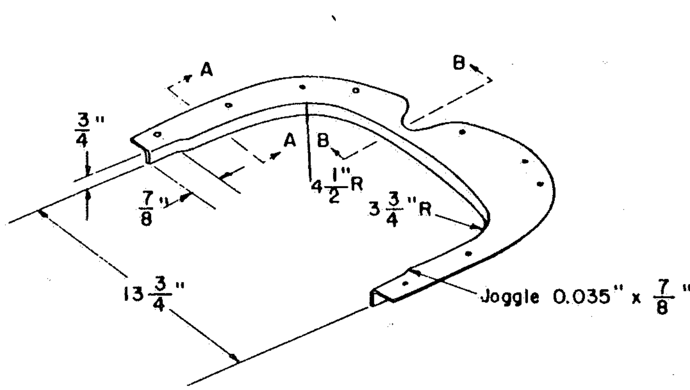
Presses. Generally, the smaller presses are single action while the larger presses are of the double-action type. Most of the standard single-action hydraulic presses can be adapted with a flexible die for forming operations. A typical press for trapped-rubber forming, for example, might have a loading capacity of 500 tons and a working area of 500 square inches. The limitations on equipment are generally set by the maximum pressures that can be generated in the rubber and the strength of the container surrounding the rubber pad.



a. Type 302, 1/4 Hard, 0.016 Thickness



b. Type 302, 1/4 Hard, 0.016 Thickness



c. Type 302, Annealed, 0.030 Thickness

FIGURE 64. TYPICAL TRAPPED–RUBBER–FORMED STAINLESS STEEL PARTS (Ref. 79)

The main objective of current development progress related to flexible die forming is to increase the pressure that can be applied to the workpiece. Heavier containers are being built and new synthetic rubber compositions which will withstand the higher pressures are being developed. A representative list of available trapped-rubber presses is given in Table XXI.

Tooling. The tooling for flexible die forming is made from a variety of materials depending on the tool life desired and the operating conditions. Cold-rolled steel is often used because it is inexpensive and fairly easy to machine. When a longer tool life is required, hardened carbon steel or alloy tool steel is used. Where the part shape is more complex and the punch is more difficult to machine, cast iron and ductile iron have been used. Kirksite has been used but the ductile alloy may give a very short life when working stainless steels.

Since there is very little rubbing action on the die during forming, very little wear occurs in normal operations. Most of the wear is attributed to the methods used for removing formed parts from the tools. The pressure exerted by the flexible pad is fairly uniform over the part and die. A good surface finish should be maintained on the die to permit easy movement of the blank as the metal is drawn in and to prevent scratching or marring of the surface during forming.

Sometimes a pressure plate is used over the punch to assist in keeping the surface of the part flat. The surface plate should have a good finish and be aligned on the punch by means of tooling pins. Pins also serve to keep the blank in proper position on the punch during forming.

Normally, the tooling is made to "blue-print" dimensions and the springback in the part removed by benching or hot-sizing operations. Benching of stainless steels is generally very limited since the alloys tend to harden

TABLE XXI. SIZES OF TYPICAL TRAPPED-RUBBER PRESSES

Manufacturer	**Work** Area, in.^{2}	Press Stroke, inches	Forming Pressure, 1000 psi	Strokes/Hr
Cincinnati Milling Machine Co.	50	5	5	1200
	113	7	10	1200
	177	7-9	Up to 15	1200
	314	10	Up to 15	1200
	490	12	10	1200
	53[illegible]	12	Up to 15	90
	804	12	10	90
The Hydraulic Press Manufacturing Company	up to 2200	15	up to 7	20

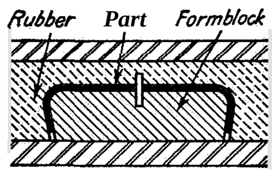
considerably during forming. Springback of flanges can be minimized by undercutting the angles by the amount of springback expected. This technique is not very successful when the flange angle reaches 90 degrees or more. Another technique that can be used to extend forming limits is to place strips of lead over the flange area. Additional pads of rubber may also be placed over those areas where more pressure is required. Several other methods of obtaining greater forces in the flange area are shown in Figure 65.

Increasing the rubber pressure usually has little effect on forming limits, but Wiegand and Lee report some benefits in the plastic buckling region for medium and heavy sheet materials (Ref. 102). Higher pressures had no effect in forming stretch flanges. On the other hand, there was some benefit from increased pressure when forming shrink flanges on medium and heavy sheet materials. A comparison of parts formed by high-pressure and high-velocity trapped-rubber forming indicated no significant difference in formability between the two processes.

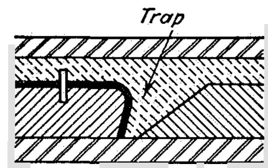
A high rubber pressure is expected to decrease springback but the effect is more noticeable for soft materials than it is for stainless steels.

Tooling for hydraulic bulge forming has been made from a number of materials. These include reinforced concrete lined with plastic, laminated plastics, Kirksite, engineering steels, and tool steels. The type of tooling used depends on the cost of tooling materials and the tolerances to be held. Metal tooling is preferred for precision close-tolerance forming.

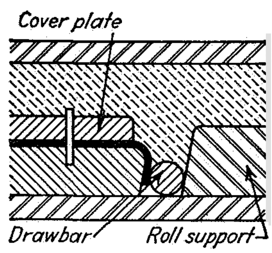
Techniques for Flexible Die Forming. The multidirectional pressure in flexible die forming produces more uniform stresses in the blank than does the uniaxial loading of conventional drawing. This permits the drawing of both deeper and more complex shapes than obtained by conventional



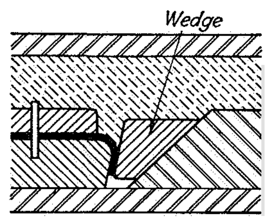
(A) Regular hydropress rubber forming



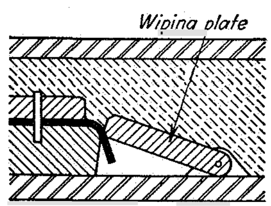
(B) Trap for increasing rubber **pressure** against the flange



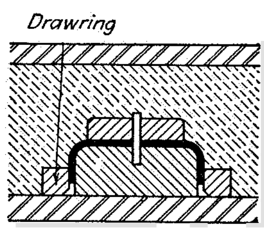
(C) Cylindrical **drawbar** or **roll**



(D) Wedge



(E) Hinged wiping plate



(F) Drawring

FIGURE 65. AUXILIARY RUBBER–FORMING TOOLS (Courtesy International Nickel Company)

drawing. In trapped-rubber forming, the die radius is variable and depends on the pressure applied. As the forming pressure is increased the radius of the part decreases until it touches the tool. The forming pressure can be adjusted during the forming operation with the trapped-rubber process. In practice, the pressure is maintained at a low level until the material has been stretched to the deepest part of the die, then the pressure is increased until the desired radii has been developed on the part.

With trapped-rubber forming there is no transmission of stress through the wall of the partially formed part. The material is supported across the die by uniform pressure while the material is unsupported at the forming radius. Since small increments of the blank are stretched into the void and against the punch at one time, there is no pronounced thinning of the partially formed section of the part. By proper adjustment of the forming pressure and the speed, stretching and thinning of the metal during forming can be made to compensate for the increase in flange thickness, This results in a part with fairly uniform wall thickness. Near the completion of the forming stroke the pad pressure, which controls the holding force, must be increased to prevent wrinkling of the flange. The smaller gripping area, thicker flange, and work hardening in the stretched regions necessitate an increase in pressure to complete the forming.

The use of a peripheral flange restrains trapped-rubber parts and assists in obtaining closer dimensional tolerances. The extra material can be removed after forming. When blanks are trimmed to final size before forming, lead strips are often used as a substitute for the flange to assist in forming since the lead acts like a mating die.

A number of techniques have been worked out for bulge forming, but most of them consist of restraining the edges of the blank and stretching the remainder to shape. In some cases, a small amount of draw is permitted; however, in most cases, the part is formed entirely by stretching. The pressure should be applied slowly and held at approximately the yield point of the material until the part contacts the die. Then the pressure can be increased to produce the desired elastic expansion of the die. When the pressure is released, springback brings the part back to the desired finished shape. Dies made from zinc-base alloys with plastic facings, permit the approach to compensate for springback. This technique cannot be employed for parts made by shrinking.

Many parts have been bulge formed by high-velocity techniques using chemical explosives and electrical discharges as energy sources. A number of uses have been found for such techniques but conventional processes are generally more economical. Some exceptions to that generalization are discussed in the Proceedings of the NATO Conference on High Energy Rate Working of Metals (Ref. 103). That publication gives a good summary of high-velocity studies throughout the world.

Blank Preparation. Blank preparation procedures for flexible die forming are the same as those used for other forming processes. Usually blanks for trapped-rubber forming must be provided with tooling holes to maintain part location on the punch during forming. They must be located accurately with 1/32 of an inch or difficulty will be experienced in loading the blanks and possibly from elongation of the holes during forming. The tooling hole should be deburred the same as the rest of the blank.

Lubricants are seldom used on blanks to be formed in flexible dies, since there is very little sliding-type friction involved in the process. If a lubricant is used, it should be a type that can be easily removed before any elevated-temperature treatment of the stainless steel.

Forming Limits. The trapped-rubber process is commonly used for producing contoured flange sections and stiffened panels from stainless steels. Finished parts can be made if the requirements for the bead radius, flange height, bead spacing, or the free-forming radius are not too severe. When the design requirements exceed the forming capabilities of the material, the process may be used to fabricate preforms that are subsequently formed to final size after the stainless steel has been annealed.

Ductility and stiffness are the principal properties influencing the performance of a material during trapped-rubber forming. Wood and Associates (Ref. 69) have shown the quantitative relationships between mechanical properties determined in tensile and compressive tests and formability limits. The conventional values for tensile elongation correlate with the maximum permissible amount of stretching without splitting. In stretch flanging, splitting limits are given by the maximum ratio of the flange height to the contour radius. Generally speaking, the contour radius on a forming block for annealed stainless steel parts should be 5 inches or larger for sheet thicknesses up to 0.080 inch. Buckling, which depends on the ratio of the elastic modulus to the yield strength of the material, affects the maximum height to which flanges can be formed. The tendency for buckling increases with the ratio of the flange height to the thickness of the workpiece material. In shrink flanging using higher forming pressure minimizes buckling or wrinkling. That expedient is not helpful in stretch flanging. The minimum permissible bend radii in rubber-pad forming of various stainless steels are the same as those given in the section on brake forming. Higher forming pressures are needed to produce smaller bend radii.

For tight bends, the minimum practical flange length increases with sheet thickness. For forming pressures of 5000 psi or more the ratio of stretch flange length to sheet thickness should fall in the range from 25 to 30, a ratio of 20 applies for shrink flanges. Flange angles can usually be formed at tolerances of about 5 degrees.

Some parts made by the trapped-rubber process include beads, shrink flanges, and stretch flanges. If so, failures may occur in various regions depending on the severity of the shape change required at those locations. Therefore, it is convenient to consider separately the different criteria limiting formability.

Figures 66 and 67 show the estimated limits for stretch and shrink flanges that can be produced from Type 300 stainless steels by the trapped-rubber process at room temperatures. Since the necessary mechanical-property data were not available for the stainless steels of interest, the limits were estimated.

Beading is another common operation in rubber forming. The bead radius is important because the stiffening effect decreases as the radius increases. The minimum radius that can be formed in a stainless steel sheet is the same as that for the brake-bending operation. How closely the minimum bend radius of either a bead or the die-bend radius of the forming block can be approached depends on the forming pressure. The minimum radius cannot exceed the minimum brake-bend radii or failure of the part will occur.

As in drop-hammer forming, failures in beading operations result from either splitting or buckling. Success or failure depends on the ratio of the bead radius to the thickness of the materials, R/T, or on the spacing of beads, R/L.

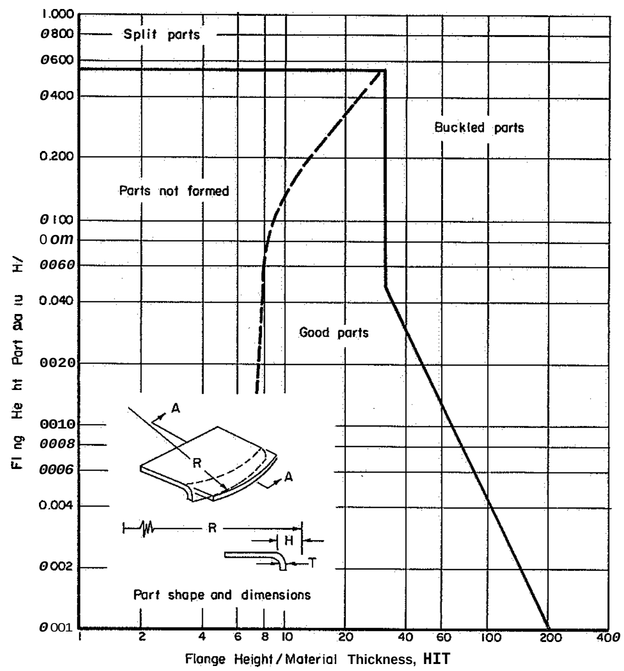


FIGURE 66. ESTIMATED FORMABILITY LIMITS FOR TYPE 300 STAINLESS STEELS IN RUBBER-STRETCH-FLANGE FORMING

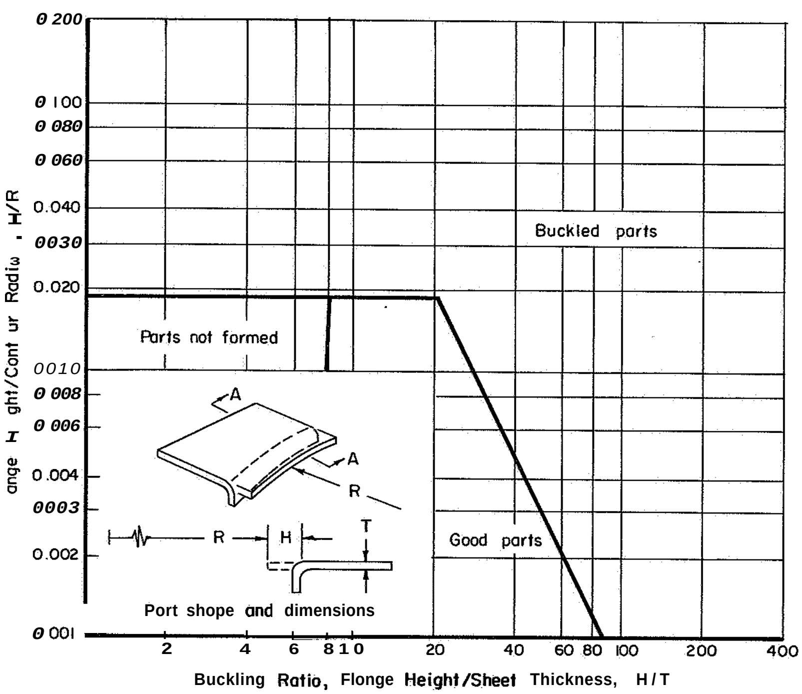


FIGURE 67. ESTIMATED FORMABILITY LIMITS FOR TYPE 300 STAINLESS STEELS IN RUBBER-COMPRESSION-FLANGE FORMING

Figure 68 gives the estimated forming limits for beaded panels made by the trapped-rubber process. These estimates of forming limits were made for relatively low forming pressure of 3000 psi.

The flange height obtainable, on a production basis, for Types 301 and Type 321 stainless steel in the annealed condition can be determined from Tables XXII and XXIII for stretch and shrink flanges respectively. The flange heights for stretch and shrink flanges of Type 301 stainless steel in the 1/4-hard condition are given in Tables XXIV and XXV. Tables XXVI and XXVII give the forming limits for Type 301 stainless steel in the 1/2-hard condition. The values given in these tables are for normal production in trapped-rubber forming.

Samples of Parts Formed in Flexible Dies. Typical trapped-rubber formed stainless steel parts are shown in Figure 69 both before and after benching, The material was 0.080 inch thick and had a stretch of 30 percent and a shrink of 22 percent. Springback was 2 degrees on the stretch flange and up to 15 degrees on the shrink flange. After benching, the springback was reduced to 1 degree on stretch flange and 2 degrees on the shrink flange.

Figure 70 shows a hemispherical dome made from a welded preform in Type 321 stainless steel. Some draw occurred in the forming of this part as evidenced by the wrinkling in the flange area. An example of explosive forming is the Type 301 stainless-steel wheelcover shown in Figure 71. The open die is shown to the left while the completed part is on the right. The material thickness was 0.032 inch. The use of explosive forming for prototype work has been a successful application of this process since only half of the die set need be made.

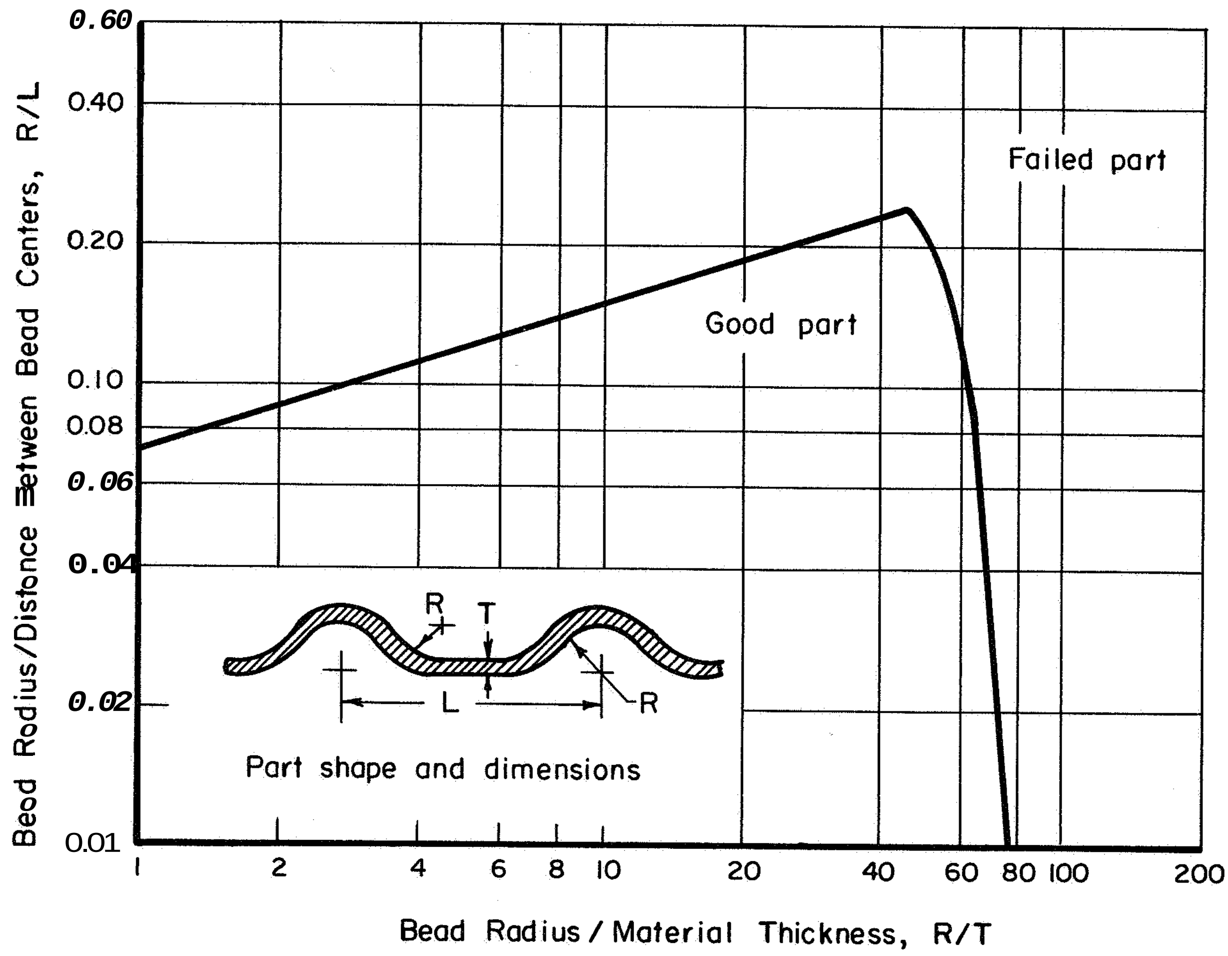


FIGURE 68. ESTIMATED FORMABILITY LIMITS FOR TYPE 300 STAINLESS STEELS IN TRAPPED–RUBBER–BEAD FORMING

TABLE XXII. STRETCH FLANGE LIMITS; 0° - 120° FLANGE; COLD FORMED ON RUBBER PRESS; TYPES 301 AND 321 ANNEALED STAINLESS STEEL (Ref. 104)

CONTOUR RADIUS (Rc)	MATERIAL THICKNESS (t)												
	.016	.020	.025	.032	.040	.045	.050	.063	.071	.080	.090	.100	.125
	FLANGE HEIGHT (h) LIMITS												
5	.06 .64	.09 .80	.12 1.00	.17 1.28	.25 1.60	.29 1.71	.35 1.71	.49 1.71	.59 1.71	.71 1.71	.85 1.71	1.00 1.71	1.40 1.71
10	.04 .72	.06 .85	.08 1.02	.12 1.28	.17 1.60	.20 1.80	.24 2.00	.34 2.52	.41 2.84	.49 3.20	.59 3.42	.69 3.42	.97 3.42
15	.03 .82	.05 .95	.07 1.12	.10 1.34	.14 1.62	.16 1.80	.19 2.00	.28 2.52	.33 2.84	.40 3.20	.47 3.60	.56 4.00	.78 5.00
20	.03 .91	.04 1.05	.06 1.22	.08 1.45	.12 1.70	.14 1.87	.17 2.04	.24 2.52	.28 2.84	.34 3.20	.41 3.60	.48 4.00	.67 5.00
25	.03 .98	.04 1.13	.05 1.31	.07 1.55	.10 1.81	.13 1.97	.15 2.12	.21 2.57	.25 2.85	.30 3.20	.36 3.60	.43 4.00	.60 5.00
30	.02 1.04	.03 1.20	.05 1.40	.07 1.64	.10 1.91	.11 2.07	.13 2.23	.19 2.64	.23 2.92	.27 3.23	.33 3.60	.39 4.00	.54 5.00
35	.02 1.09	.03 1.27	.04 1.47	.06 1.73	.09 2.01	.11 2.17	.12 2.33	.18 2.75	.21 3.00	.25 3.31	.30 3.66	.36 4.00	.50 5.00
40	.02 1.14	.03 1.33	.04 1.54	.06 1.81	.08 2.10	.10 2.27	.12 2.44	.16 2.86	.20 3.11	.24 3.39	.28 3.73	.33 4.08	.47 5.00
45	.02 1.19	.03 1.38	.04 1.60	.05 1.88	.08 2.19	.09 2.36	.11 2.53	.15 2.96	.18 3.22	.22 3.51	.27 3.81	.31 4.15	.44 5.02
50	.02 1.23	.03 1.43	.04 1.66	.05 1.95	.07 2.26	.09 2.45	.10 2.63	.15 3.06	.17 3.32	.21 3.61	.25 3.93	.30 4.24	.42 5.10
55	.02 1.27	.02 1.47	.03 1.71	.05 2.02	.07 2.34	.08 2.53	.10 2.71	.14 3.16	.17 3.42	.20 3.71	.24 4.04	.28 4.36	.39 5.17
60	.02 1.31	.02 1.52	.03 1.76	.05 2.08	.07 2.41	.08 2.60	.09 2.79	.13 3.25	.16 3.52	.19 3.81	.23 4.14	.27 4.46	.38 5.24
65	.02 1.35	.02 1.56	.03 1.81	.05 2.13	.06 2.47	.08 2.67	.09 2.87	.13 3.34	.15 3.62	.18 3.92	.22 4.24	.26 4.57	.36 5.36
70	.02 1.38	.02 1.60	.03 1.85	.04 2.19	.06 2.53	.07 2.74	.09 2.94	.12 3.43	.15 3.71	.18 4.02	.21 4.34	.25 4.67	.35 5.47

TABLE XXIII. SHRINK FLANGE LIMITS; 0° - 120° FLANGE; COLD FORMED ON RUBBER PRESS; TYPES 301 AND 321 ANNEALED STAINLESS STEEL (Ref. 104)

CONTOUR RADIUS (Rc)	MATERIAL THICKNESS (t)												
	.016	.020	.025	.032	.040	.045	.050	.063	.071	.080	.090	.100	.125
	FLANGE HEIGHT (h) LIMITS												
5	.06 .22	.09 .22	.15 .22										
10	.04 .33	.06 .33	.10 .33	.16 .33	.25 .33								
15	.03 .41	.05 .43	.07 .44	.12 .44	.19 .44	.24 .44	.30 .44						
20	.02 .48	.04 .52	.06 .54	.10 .55	.15 .55	.19 .55	.24 .55	.38 .55	.48 .55				
25	.02 .54	.03 .59	.05 .63	.08 .65	.13 .66	.16 .66	.20 .66	.31 .66	.40 .66	.50 .66			
30	.02 .58	.03 .64	.04 .70	.07 .75	.11 .77	.14 .77	.17 .77	.27 .77	.34 .77	.43 .77	.55 .77	.67 .77	
35	.02 .62	.02 .70	.04 .76	.06 .83	.10 .86	.12 .88	.15 .88	.24 .88	.30 .88	.38 .88	.48 .88	.59 .88	
40	.01 .65	.02 .73	.03 .82	.05 .90	.08 .95	.11 .97	.13 .98	.21 .99	.27 .99	.34 .99	.43 .99	.52 .99	.82 .99
45	.01 .67	.02 .77	.03 .87	.05 .96	.08 1.03	.10 1.06	.12 1.08	.19 1.10	.24 1.10	.30 1.10	.38 1.10	.47 1.10	.74 1.10
50	.01 .70	.02 .80	.03 .91	.04 1.01	.07 1.11	.09 1.14	.11 1.17	.17 1.21	.22 1.21	.28 1.21	.35 1.21	.43 1.21	.67 1.21
55	.01 .72	.02 .83	.02 .94	.04 1.07	.06 1.17	.08 1.22	.10 1.25	.16 1.30	.20 1.32	.25 1.32	.32 1.32	.40 1.32	.62 1.32
60	.01 .73	.01 .85	.02 .98	.04 1.12	.06 1.23	.07 1.29	.09 1.33	.15 1.40	.18 1.42	.23 1.43	.30 1.43	.37 1.43	.57 1.43
65	.01 .75	.01 .87	.02 1.01	.04 1.15	.05 1.29	.07 1.35	.09 1.40	.14 1.49	.17 1.52	.22 1.54	.28 1.54	.34 1.54	.53 1.54

TABLE XXIV. STRETCH FLANGE LIMITS; 0° - 120° FLANGE; COLD FORMED ON RUBBER PRESS; TYPE 301 STAINLESS STEEL 1/4 HARD (Ref. 104)

CONTOUR RADIUS (Rc)	MATERIAL THICKNESS (t)												
	.016	.020	.025	.032	.040	.045	.050	.063	.071	.080	.090	.100	.125
	FLANGE HEIGHT (h) LIMITS												
5	.30 .39	.42 .48											
10	.21 .47	.30 .55	.42 .65	.61 .79	.85 .96								
15	.17 .53	.24 .62	.34 .72	.50 .86	.69 1.02	.83 1.12	.97 1.23	1.37 1.50					
20	.15 .59	.21 .68	.30 .79	.43 .94	.60 1.10	.72 1.20	.84 1.30	1.18 1.56		1.69 1.91	2.03 2.13		
25	.14 .63	.19 .73	.26 .85	.38 1.00	.54 1.17	.64 1.27	.75 1.37	1.06 1.63		1.52 1.97	1.81 2.18		
30	.12 .67	.17 .78	.24 .91	.35 1.07	.49 1.24	.58 1.34	.68 1.44	.97 1.70		1.39 2.05	1.65 2.25		2.71 2.98
35	.11 .71	.16 .82	.22 .95	.32 1.12	.45 1.30	.53 1.41	.63 1.51	.90 1.78		1.28 2.12	1.53 2.32		2.51 3.03
40	.11 .74	.15 .86	.21 1.00	.30 1.18	.42 1.36	.50 1.48	.59 1.58	.84 1.85		1.20 2.19	1.43 2.39		2.34 3.10
45	.10 .77	.14 .89	.20 1.04	.29 1.22	.40 1.42	.48 1.53	.56 1.65	.79 1.92		1.13 2.27	1.35 2.46		2.21 3.17
50	.10 .80	.13 .93	.19 1.08	.27 1.27	.38 1.47	.45 1.59	.53 1.71	.75 1.99		1.07 2.34	1.28 2.54		2.10 3.25
55	.09 .83	.13 .96	.18 1.11	.26 1.31	.36 1.52	.43 1.64	.50 1.76	.71 2.05		1.02 2.41	1.22 2.61		2.00 3.31
60	.09 .85	.12 .99	.17 1.14	.25 1.35	.34 1.56	.41 1.69	.48 1.81	.68 2.11		.98 2.48	1.17 2.68		1.91 3.38
65	.08 .87	.12 1.01	.16 1.17	.24 1.38	.33 1.60	.40 1.74	.46 1.86	.66 2.17		.94 2.54	1.12 2.75		1.84 3.46
70	.08 .89	.11 1.04	.16 1.20	.23 1.42	.32 1.65	.38 1.78	.45 1.91	.63 2.23		.90 2.61	1.08 2.82		1.77 3.54

TABLE XXV. SHRINK FLANGE LIMITS; 0° - 120° FLANGE.; COLD FORMED ON RUBBER PRESS; TYPE 301 STAINLESS STEEL 1/4 HARD (Ref. 104)

CONTOUR RADIUS (Rc)	MATERIAL THICKNESS (t)												
	.016	.020	.025	.032	.040	.045	.050	.063	.071	.080	.090	.100	.125
	FLANGE HEIGHT (h) LIMITS												
5													
10													
15													
20													
25	.13 .25	.20 .25											
30	.11 .30	.17 .30	.25 .30										
35	.10 .34	.15 .35	.22 .35										
40	.09 .38	.13 .40	.20 .40	.31 .40									
45	.08 .41	.12 .44	.18 .45	.28 .45									
50	.07 .44	.11 .47	.16 .51	.26 .51	.39 .51								
55	.07 .46	.10 .51	.15 .54	.24 .56	.36 .56	.45 .56							
60	.06 .49	.09 .53	.14 .58	.22 .61	.34 .61	.42 .61	.51 .61						
65	.06 .51	.09 .56	.13 .61	.21 .65	.31 .66	.39 .66	.47 .66						
70	.05 .53	.08 .59	.12 .64	.19 .68	.29 .71	.37 .71	.44 .71						

TABLE XXVI. STRETCH FLANGE LIMITS; 0° - 120° FLANGE; COLD FORMED ON RUBBER PRESS; TYPE 301 STAINLESS STEEL 1/2 HARD (Ref. 104)

CONTOUR RADIUS (Rc)	MATERIAL THICKNESS (t)												
	.016	.020	.025	.032	.040	.045	.050	.063	.071	.080	.090	.100	.125
	FLANGE HEIGHT (h) LIMITS												
5													
10	.26 .42	.36 .50	.51 .59										
15	.21 .48	.29 .56	.41 .65	.60 .79	.85 .94								
20	.18 .53	.25 .61	.35 .72	.51 .85	.72 1.00	.87 1.09	1.02 1.19						
25	.16 .57	.22 .66	.31 .77	.45 .91	.64 1.06	.77 1.15	.90 1.25	1.29 1.49					
30	.14 .61	.20 .70	.28 .81	.41 .96	.58 1.12	.70 1.22	.82 1.31	1.17 1.55		1.69 1.87			
35	.13 .64	.18 .74	.26 .86	.38 1.01	.53 1.18	.64 1.28	.75 1.37	1.07 1.61		1.56 1.93	1.87 2.12		
40	.12 .67	.17 .77	.24 .90	.35 1.06	.50 1.23	.59 1.33	.70 1.43	1.00 1.68		1.45 2.00	1.73 2.18		
45	.11 .69	.16 .80	.22 .93	.33 1.10	.46 1.28	.56 1.38	.66 1.49	.94 1.74		1.36 2.06	1.63 2.25		2.70 2.90
50	.11 .72	.15 .83	.21 .97	.31 1.14	.44 1.32	.53 1.43	.62 1.54	.88 1.80		1.28 2.12	1.54 2.31		2.55 2.96
55	.10 .74	.14 .86	.20 1.00	.29 1.18	.42 1.36	.50 1.48	.59 1.58	.84 1.85		1.23 2.18	1.46 2.36		2.42 3.03
60	.10 .76	.14 .89	.19 1.03	.28 1.21	.40 1.40	.48 1.52	.56 1.63	.80 1.91		1.16 2.24	1.39 2.43		2.31 3.09
65	.09 .78	.13 .91	.18 1.06	.27 1.24	.38 1.44	.46 1.56	.54 1.67	.77 1.96		1.11 2.30	1.33 2.49		2.21 3.15
70	.09 .80	.12 .93	.18 1.08	.26 1.28	.36 1.48	.44 1.60	.51 1.72	.74 2.00		1.06 2.36	1.28 2.55		2.12 3.21

TABLE XXVII. SHRINK FLANGE LIMITS; 0° - 120° FLANGE; COLD FORMED ON RUBBER PRESS; TYPE 301 STAINLESS STEEL 1/2 HARD (Ref. 104)

CONTOUR RADIUS (Rc)	MATERIAL THICKNESS (t)												
	.016	.020	.025	.032	.040	.045	.050	.063	.071	.080	.090	.100	.125
	FLANGE HEIGHT (h) LIMITS												
5													
10													
15													
20	.13 .19												
25	.10 .24	.16 .24											
30	.09 .28	.13 .29	.21 .29										
35	.07 .31	.12 .33	.18 .34	.29 .34									
40	.07 .35	.10 .36	.16 .38	.25 .38									
45	.06 .38	.09 .40	.14 .42	.23 .43	.35 .43								
50	.05 .41	.08 .43	.13 .46	.21 .48	.22 .48	.40 .48							
55	.05 .44	.07 .47	.12 .49	.19 .52	.29 .53	.36 .53	.45 .53						
60	.04 .46	.07 .50	.11 .53	.17 .56	.27 .58	.34 .58	.41 .58						
65	.04 .49	.06 .52	.10 .56	.16 .59	.25 .62	.31 .62	.38 .62						
70	.04 .51	.06 .55	.09 .59	.15 .63	.23 .66	.29 .67	.36 .67	.56 .67					

FIGURE 69. TRAPPED RUBBER FORMED STAINLESS STEEL TEST PARTS BEFORE AND AFTER BENCHING

Courtesy of North American Aviation, Inc , Columbus Division

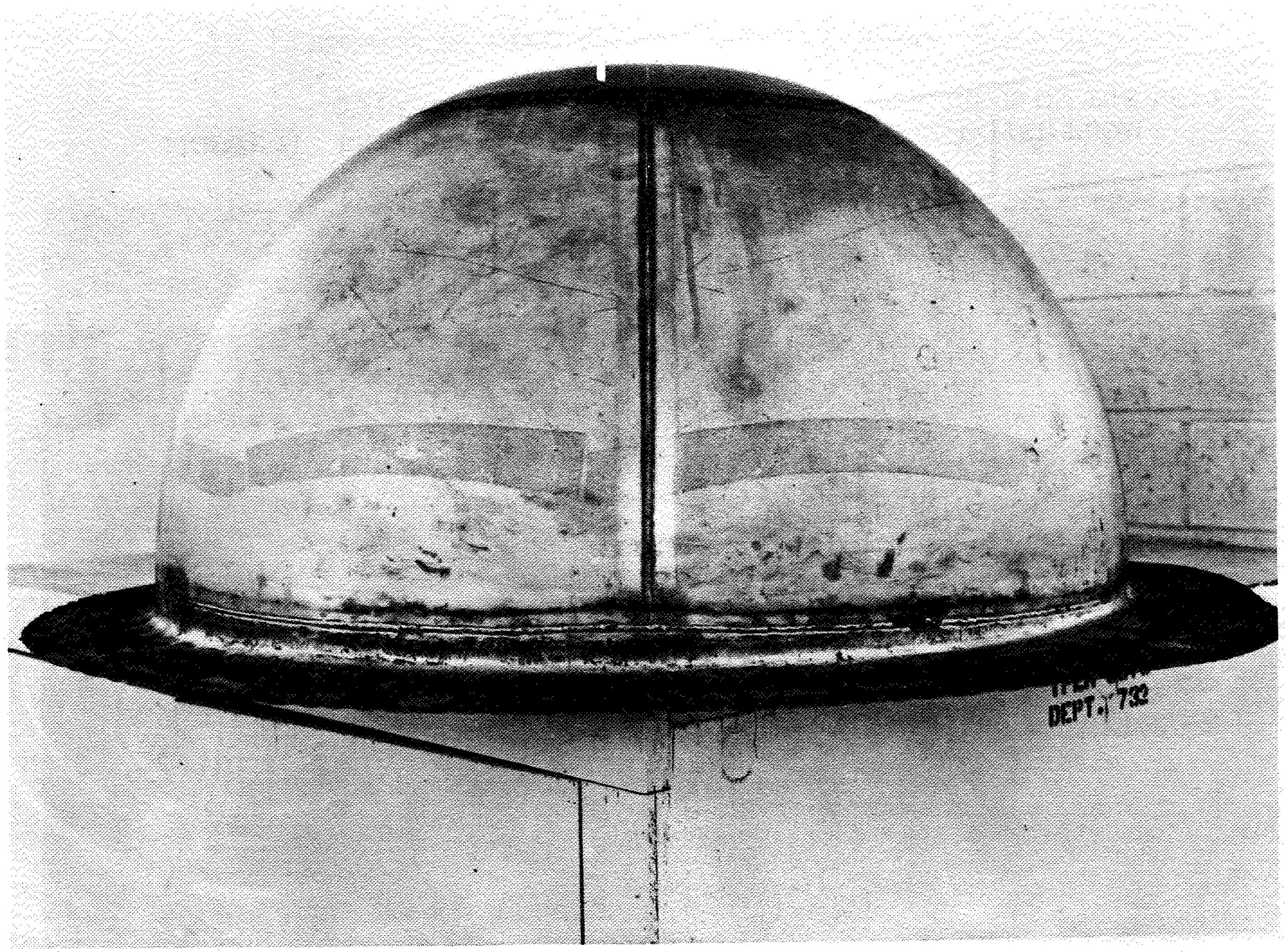


FIGURE 70. TYPE 321 STAINLESS STEEL HEMISPHERICAL DOME BULGE FORMED FROM A WELDED PREFORM

Courtesy of General Dynamics Convair Division, San Diego, California

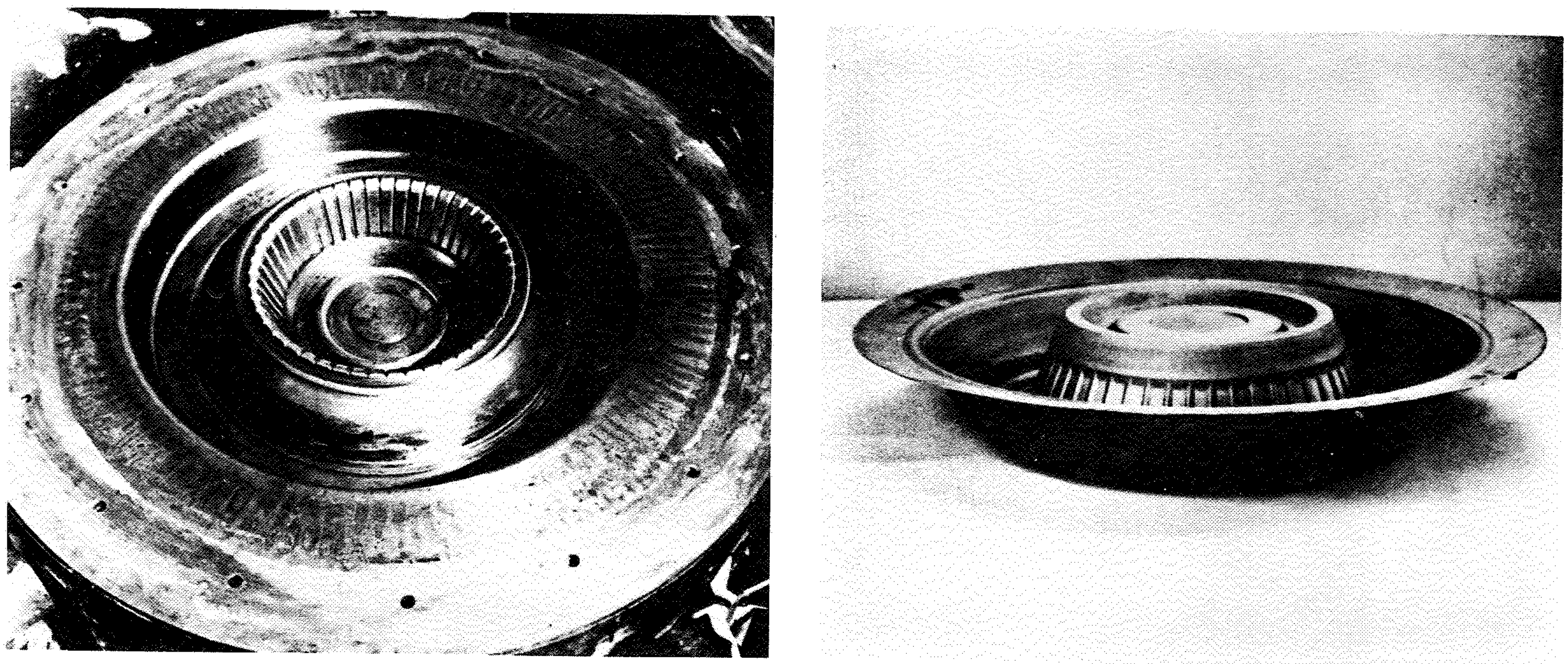


FIGURE 71. EXPLOSIVELY FORMED PROTOTYPE WHEEL COVER FROM TYPE 301 STAINLESS STEEL AND DIE. THE DIE IS ON THE LEFT

Courtesy of Martin Company, Denver, Colorado

DROP-HAMMER FORMING

Introduction. Drop-hammer forming is a progressive deformation process for producing shapes from sheet metal in matched dies with repetitive blows. The process offers advantages for parts that are difficult or uneconomical to produce by rubber and contour-forming techniques. The process is often limited to lots of less than 100 parts because soft dies are generally used. Typical applications include beaded panels and curved sections with irregular contours. Drop hammers are often used for details such as half sections of tees or elbows that can be joined together later. The process is best suited to shallow recessed parts because it is difficult to control wrinkling without a blankholder. Nevertheless, many deeply recessed parts especially those with sloping walls are made on drop hammers.

In drop-hammer forming the energy delivered per stroke depends on the mass of the ram and tooling attached to it, and the velocity at which it strikes the workpiece. Striking velocity must be controlled precisely by the operator because the energy delivered is related to the square of the velocity. Relatively large changes in the mass of the moving tool or punch can also have a considerable effect on the hammer operation. The operator must be skilled in judging the effects of changes in punch mass and velocity to insure successful and reproducible results.

Drop-Hammer Presses. The gravity drop hammer is equipped with a weight or ram that is lifted by means of some device such as a rope or a board and then permitted to drop freely. A typical rope drop hammer is shown in Figure 72. To operate this type of hammer, the operator tightens the rope around the rotating drum which then lifts the weight. When he releases the tension on the rope, it slips around the drum and the weight drops. The pneumatic hammer and the steam hammer are equipped with a pressure cylinder that lifts the ram and also adds energy to that of the falling ram (Ref. 78). The drop hammer is fundamentally a single-action press. It can be used, however, to perform the work of a press equipped with double-action dies through the use of rubber blankets, beads in the die surfaces, draw rings, and other auxiliary measures.

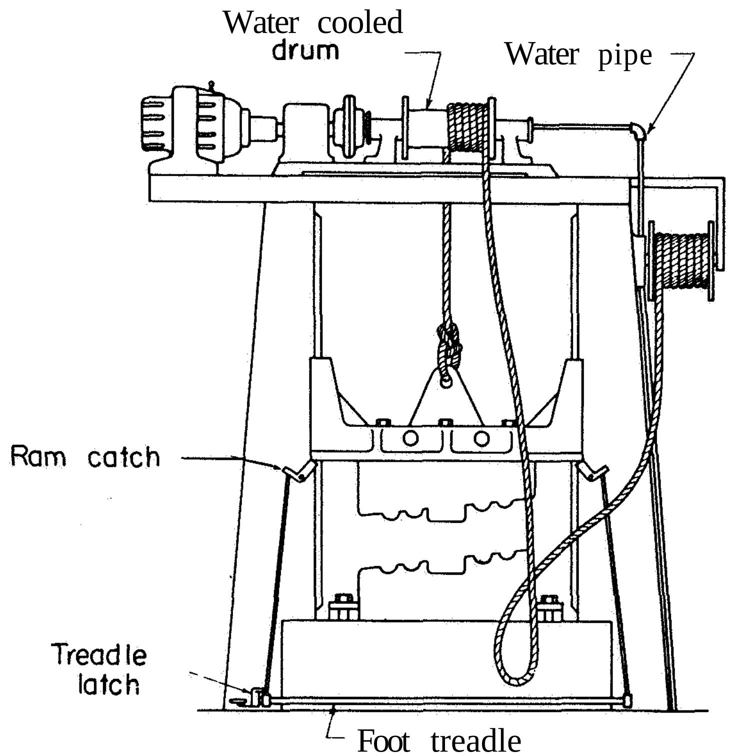


FIGURE 72. ROPE HAMMER (Ref. 78)

Platen sizes of commercially available drop hammers vary from 21 by 18 inches to 120 by 96 inches. The machines range in energy level, for free fall, from 2900 ft-lb to 90,000 ft-lb (Ref. 105).

Tooling. Common tool materials for drop-hammer forming are Kirksite and lead. Lead is preferred for the punches, since it will deform during service and conform to the female die. The wide use of Kirksite as a die material stems from the ease of casting it close to the final desired configuration. Most companies doing a large amount of drop-hammer work prepare the tooling in their own foundry. Steel inserts may be used in sharp corners of dies. Beryllium copper dies have been used for drop-hammer forming but generally the additional cost is not warranted. Ductile iron and steel dies may be used when longer tool life is desired and for some elevated-temperature forming operations.

Several typical drop-hammer dies are shown in Figure 88 with the finished parts made on them. Sometimes two punches are used, a working or roughing punch and a coining or finishing punch. When the working punch becomes excessively worn it is replaced by the coining punch and a new coining punch is prepared. Another method of achieving the same results with one punch is to use rubber pads. Rubber suitable for this purpose should have a Shore Durometer hardness of 80 to 90. Figure 74 indicates the positioning of pads for a particular part. The maximum thickness of rubber is placed where the greatest amount of pressure is to be applied in the initial forming. As the forming progresses, the thickness of rubber is reduced by removing some of the pads after each impact.

Mating surfaces of the die set must make contact uniform to avoid canning and warping which are difficult to remove in subsequent forming. Hence, male and female dies should be carefully "blued-in" with thickness allowances for the sheet to be formed. Wrinkles or cans in the parts may be removed between stages of forming with rubber mallets or lead hammers before interstage annealing.

Buckling is difficult to control in drop-hammer forming because hold-down rings are not normally used. To minimize buckling most of the deformation should result from stretching rather than shrinking. When shrinking is necessary, as in producing deeply recessed parts, a draw bead (Figure 73) will help to prevent buckling. The draw bead becomes effective only near the end

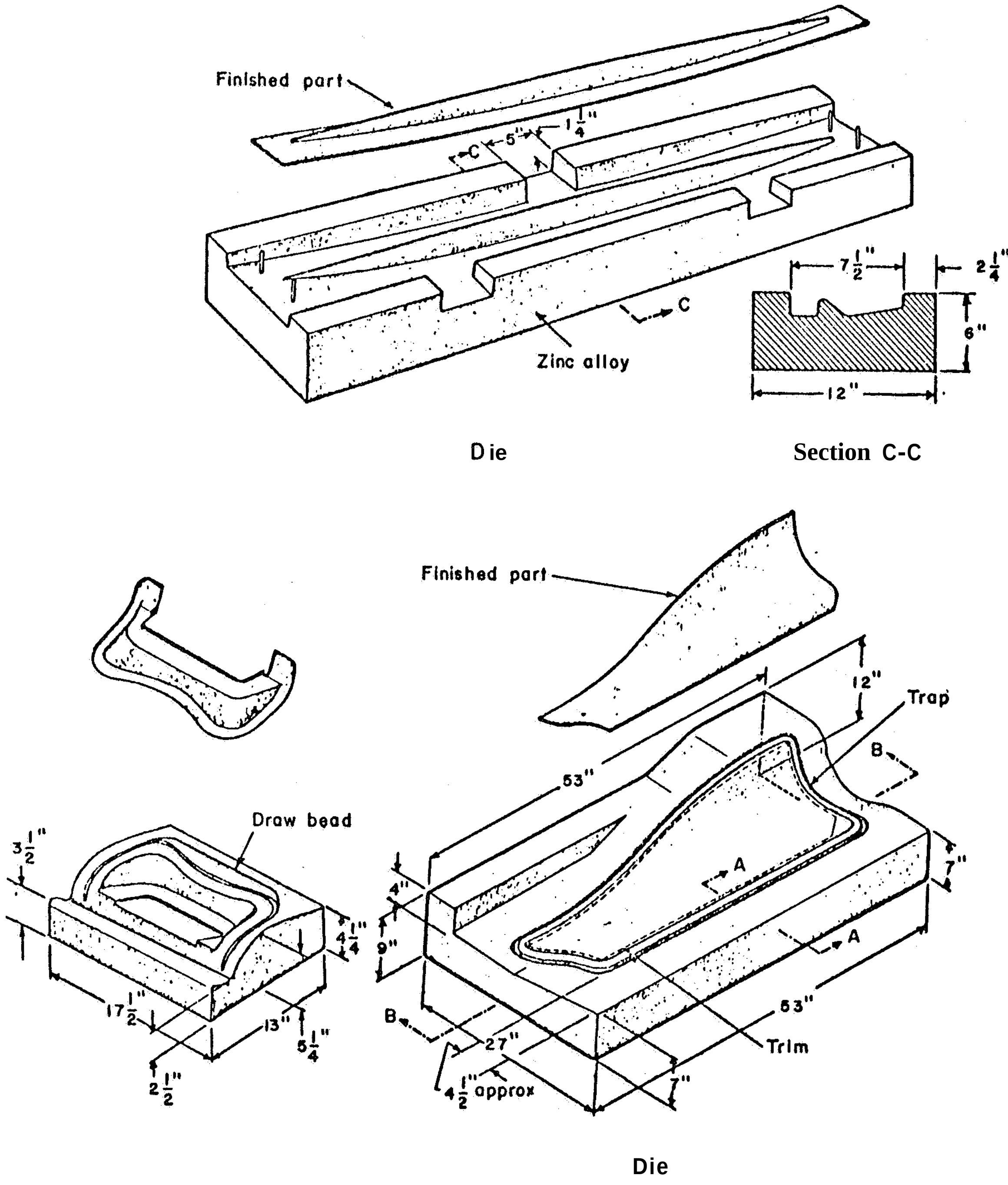
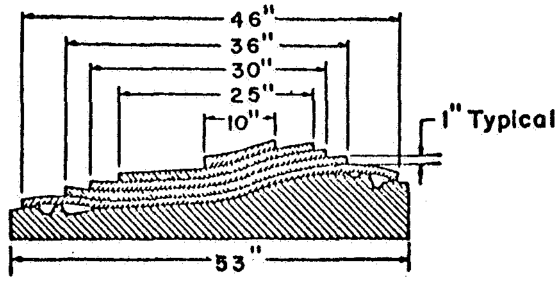


FIGURE 73. TYPICAL DROP–HAMMER DIES AND FORMED PARTS (Ref. 78)



Section B-B

FIGURE 74. POSITIONING OF RUBBER BLANKETS (Rei. 78)

The blank is placed between the die and the first pad.

of the stroke. Parts made in dies with draw beads require more material because the beaded sections have to be removed in the trim area of the part.

When parts cannot be readily formed with one blow in one die set, better results can sometimes be obtained by introducing two or more stage tools, each of which permits one-blow forming rather than using multiple blows and one set of tools. In such cases, good results can be obtained by making the part slightly oversize in the first-stage tools and by coining the final shape in the second set of tools.

Techniques of Drop-Hammer Forming. The procedures for forming stainless steels at room temperature with drop hammers resemble those used for aluminum alloys, except that greater forces are required. The process offers the advantage of flexibility, low die costs, and short delay times between design and production. A number of individual forming operations can be combined on the drop hammer, such as drawing, beading, joggling, and bending. The use of drop hammers for forming a deeply recessed part in Type 347 stainless steel is shown in Figure 75. In the forming of this part,

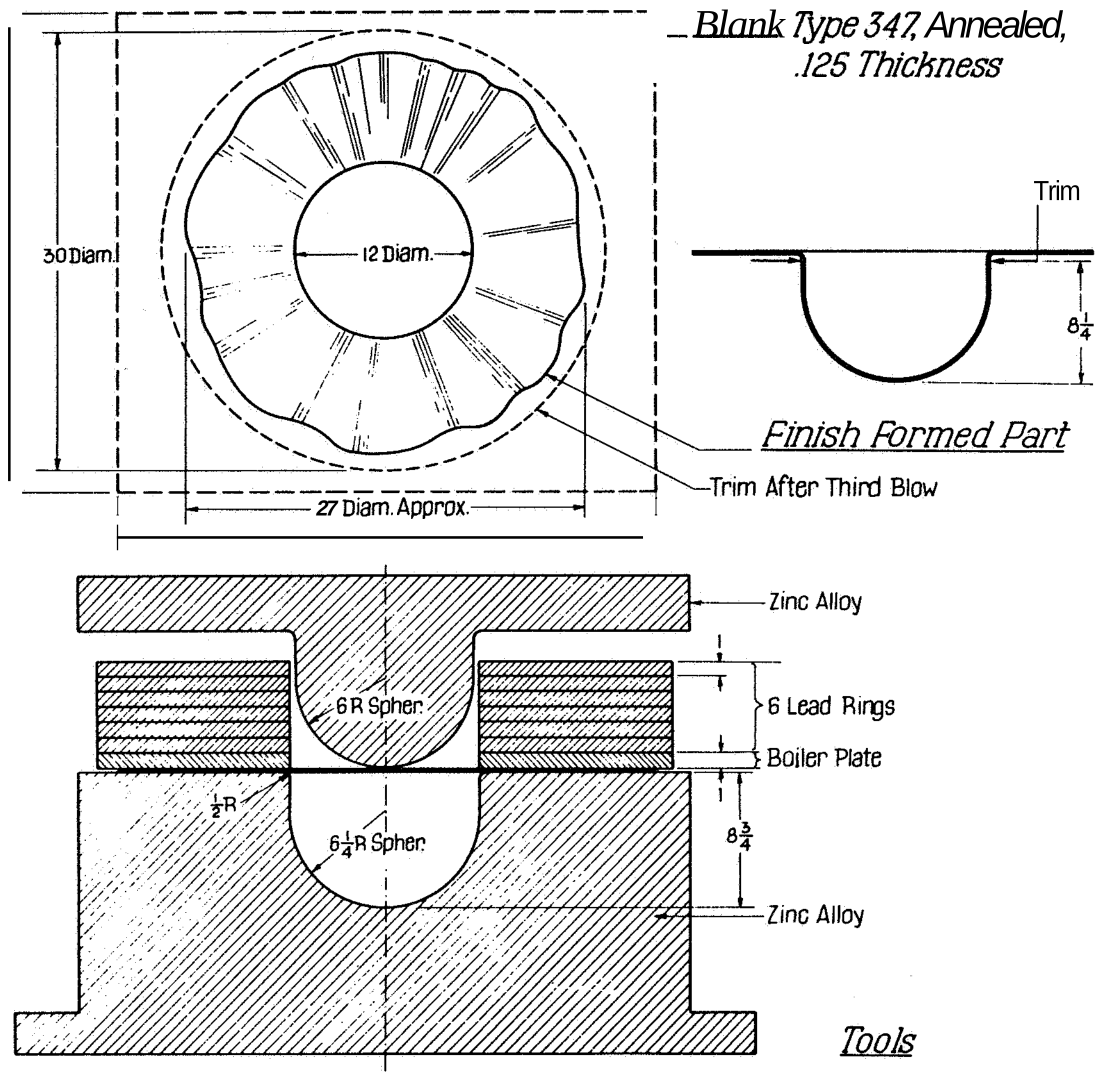


FIGURE 75. DROP-HAMMER FORMING A DOME-SHAPED PART (Ref. 78)

a lead ring was removed after every three blows of the hammer at full energy level. No intermediate anneals were used in forming this part.

There are some limits to the process that should be observed for satisfactory production. The minimum draft angle, at least 3 degrees, should be used only for the outer wall where sufficient material is available for the draw. The bend radii should be as large as possible, undercuts should be avoided, and transitions should be made as gradual as possible. Internal contours or recesses may be formed by stretching alone. Hemispherical indentations can be designed into the tooling in trim areas adjacent to the stretched recesses to absorb excess material and to prevent wrinkling. Considerable handwork and expense may be saved by allowing some wrinkling in noncritical areas. Regions where wrinkles are not objectionable should be marked on the drawing.

Whenever possible, the part should be formed with a single blow of the hammer. Repeated blows of the hammer on parts which have areas in contact with the die simply work hardens the material and may cause cracking. This point is illustrated by the data, in Figure 76, obtained by Peterson (Ref. 106). Each blow had an energy value of 50 ft-lb; the specimens were 1/4-inch right cylinders.

Drop hammers are often used for forming semitubular parts of complex design. Two halves formed in this manner are then welded to form a complete tubing assembly. In forming a semitubular part with a number of branches the major limiting design factor is the radius within the hold-down surface at the apex of a fork between two branches meeting at an acute angle. A complex semitubular part and die for drop hammer forming is shown in Figure 77. The starting blank size and the trim areas of the part after forming are indicated. This particular part required several forming stages and was made from Type 301 stainless steel.

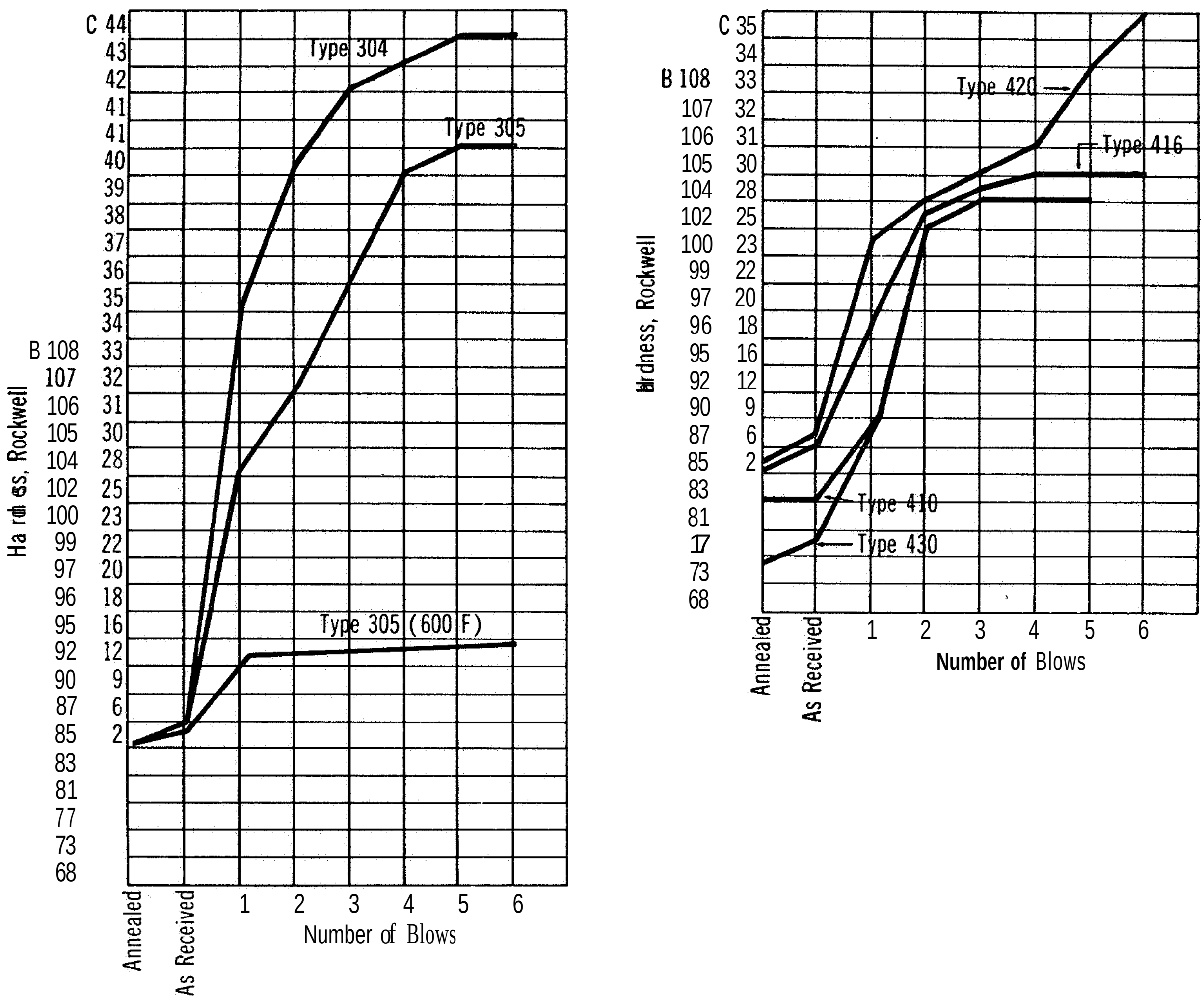


FIGURE 76. WORK HARDENING OF STAINLESS STEELS BY REPEATED BLOWS (Ref. 106)

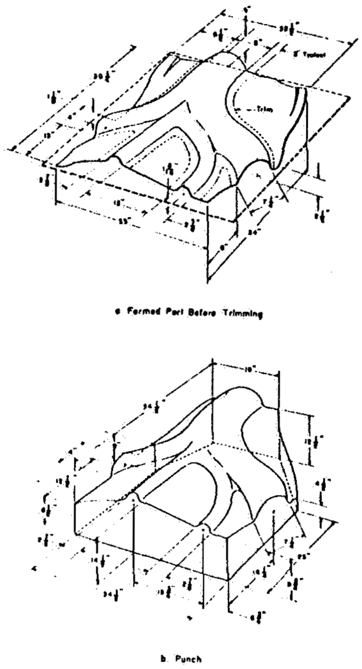


FIGURE 77. DROP-HAMMER FORMING OF SEMITUBULAR PART MADE FROM 301 STAINLESS STEEL (Ref. 78)

Lubricants. Lubricants are not normally used in drop hammer forming of stainless steels but light oil in localized areas may be helpful. Lubricants are generally swabbed onto the blank surface prior to forming and should be removed from the surface after the parts are formed. Complete removal is necessary before any subsequent thermal treatment.

Blank Preparation. The blanks for drop hammer forming are generally rectangular in shape and prepared by shearing. The blank should be large enough to yield a part with a 2- to 3-inch-wide flange in order to facilitate drawing of the material during forming. For multistage forming the part may be trimmed *so* that only a 112-inch-wide flange is left for the final forming stage.

Blanks with sheared edges are generally satisfactory for drop-hammer forming because some cracking can be tolerated in a wide flange without harming the part. The blank should, however, be deburred to reduce possible damage to the tooling.

Forming Limits. The severity of permissible deformations in drop-hammer forming is limited by both the geometrical considerations and the properties of the workpiece material. According to Wood (Ref. 69), the forming limit can be predicted by considering parts of interest as variations of beaded panels. For parts characterized in this way the critical geometrical factors are the bead radius, R, the spacing between beads, L, and the thickness of the workpiece material, T. These parameters are illustrated in Figure 78.

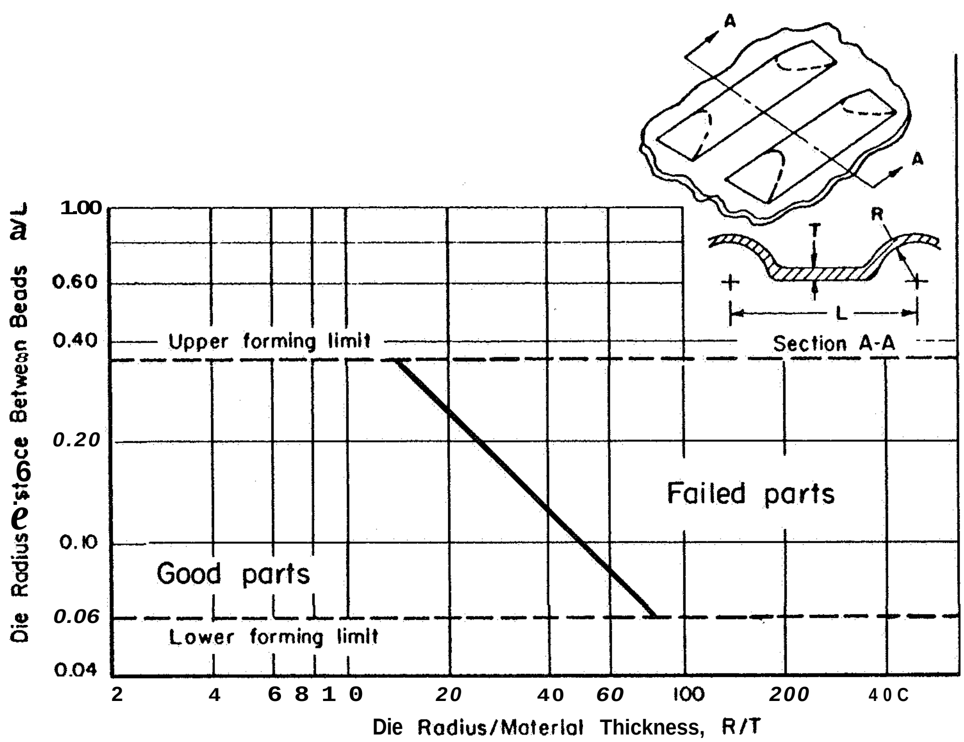


FIGURE 78. ESTIMATED DROP-HAMMER-FORMING-LIMIT CURVES FOR TYPE 300 STAINLESS STEELS

The upper and lower forming limits depend entirely on geometry and are the same for all materials. The ratio of the bead radius, R, to bead spacing, L, must lie between 0.35 and 0.06 inch. The lower formability limit is controlled by the necessity for producing uniform stretching and avoiding excessive springback. If the R/L ratio is too small there will be a greater tendency for localized stretching at the nose of the punch. Furthermore, the material may deform elastically, not plastically, and springback will occur when the load is removed.

Within the limit set for all materials by the R/L ratio, success or failure in forming beaded panels depends on the ratio of the bead radius to the sheet thickness, R/T, and on the ductility of the workpiece material. The part will split if the necessary amount of stretching exceeds the ductility available in the material. The splitting limit can be predicted from the elongation value in a 0.5-inch gage length in tensile tests. The general relationship (Ref. 69) is

$$\frac{R}{L} = \frac{50\,(e_{0.5})^2}{(R/T)} \qquad (25)$$

where

R = bead radius

L = center-to-center spacing of beads

$e_{0.5}$ = engineering strain €or 0.5-inch gage length

T = thickness of the blank.

The equation indicates that the permissible R/L ratio decreases as the R/T value increases.

Estimated formability limits at room temperature for the Type 300 stainless steels are shown in Figure 78. Although the limits apply to beaded panels they can be used with caution as guides to forming other types of parts with drop hammers.

Dimensional limits for drop-hammer forming of boxes in Type 300 stainless steels are shown in Figure 79. The minimum corner radius and maximum depth for boxes with various widths are indicated. It should be noted that regardless of the width of the part, there is an absolute limit to the ratio of part depth to corner radius which cannot be exceeded (Ref. 78). The minimum thickness for hammer-formed parts of stainless steels is approximately 0.020 inch. The low values for uniform elongation of thinner materials result in reduced formability. Heavier stock should be used for more complex shapes. Maximum gages for stainless steel are 0.062 to 0.070 inch, depending on the size and contour of the part, the capacity of the hammer equipment, and the ability of the soft tooling to take the repeated blows (Ref. 3).

It is difficult to predict the proper springback allowance for complex parts. Forming the material in the annealed condition at room temperature minimizes springback so that dies made to net dimensions will generally produce parts to tolerances of ± 1/16 inch.

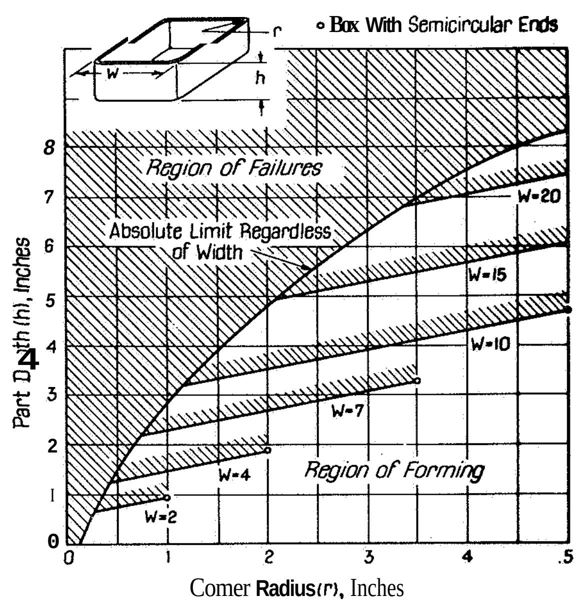


FIGURE 79. DIMENSIONAL LIMITS OF BOXES, LIMITING COMBINATIONS OF MINIMUM CORNER RADIUS (r) AND MAXIMUM DEPTH (h) FOR DROP-HAMMER-FORMED STAINLESS STEEL BOXES (Ref. 78)

A number of grades of stainless steels are suited for drop-hammer forming, but most of the forming is conducted on the Type 300 stainless steel series. Of these, the Types 301, 302, 304, 305, 347, and 321 are most commonly used. The Type 305 stainless steel is generally preferred because it has a low rate of work hardening and shows less springback. It is, however, subject to more rapid loss of ductility with cold work than Types 301 and 302. Types 302, 304, and 305 are more subject to strain cracking.

Normally, the stainless steels are formed in the annealed condition. Types 301 and 302 stainless steels have been drop-hammer formed in the 1/4-hard and 1/2-hard temper rolled condition. This is normally done to obtain higher strengths in the finished parts. Since these materials have been prehardened by rolling or stretching, the amount of ductility available in drop-hammer forming has been severely reduced. When forming the hardened materials, sheet should be kept free of dents and scratches since such defects are potential points of failure under the impact forming conditions (Ref. 3).

Examples of Drop-Hammer Formed Parts. Figure 80 shows a half duct and a channel formed on the drop hammer from 0.032-inch-thick, Type 347 stainless steel. These parts would be trimmed to final configuration before use in the next assembly. Both parts were formed in two stages without intermediate anneals.

The DC8 duct-assembly parts shown in Figure 81 were drop-hammer formed in two stages from Type 321 stainless steel. The part on the left was made from 0.025-inch stock and is shown before trimming; note the wrinkling that

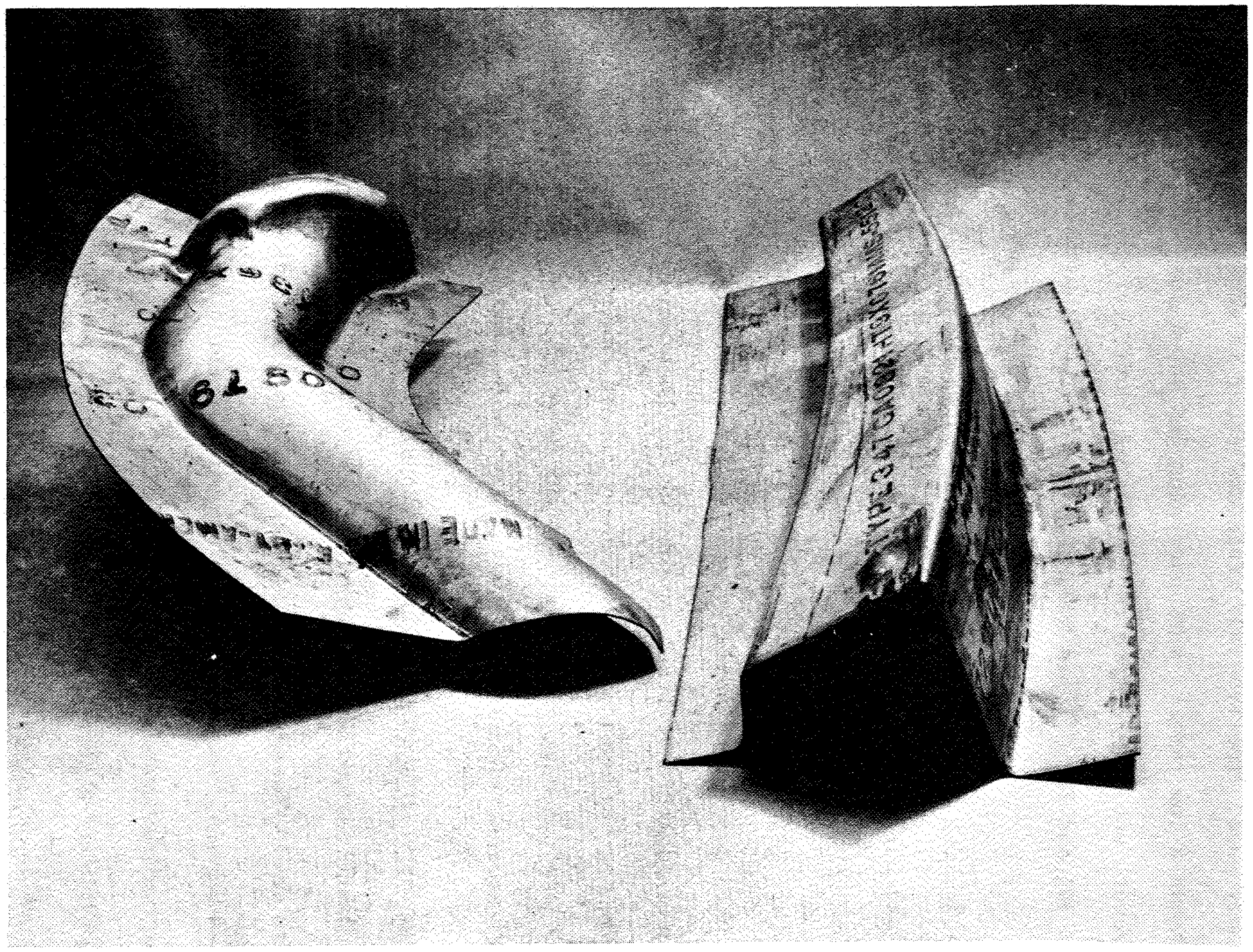


FIGURE 80. DC8 DUCT HALF AND CHANNEL, DROP-HAMMER FORMED FROM 0.032 THICK TYPE 347 STAINLESS STEEL

Courtesy of Douglas Aircraft Corporation

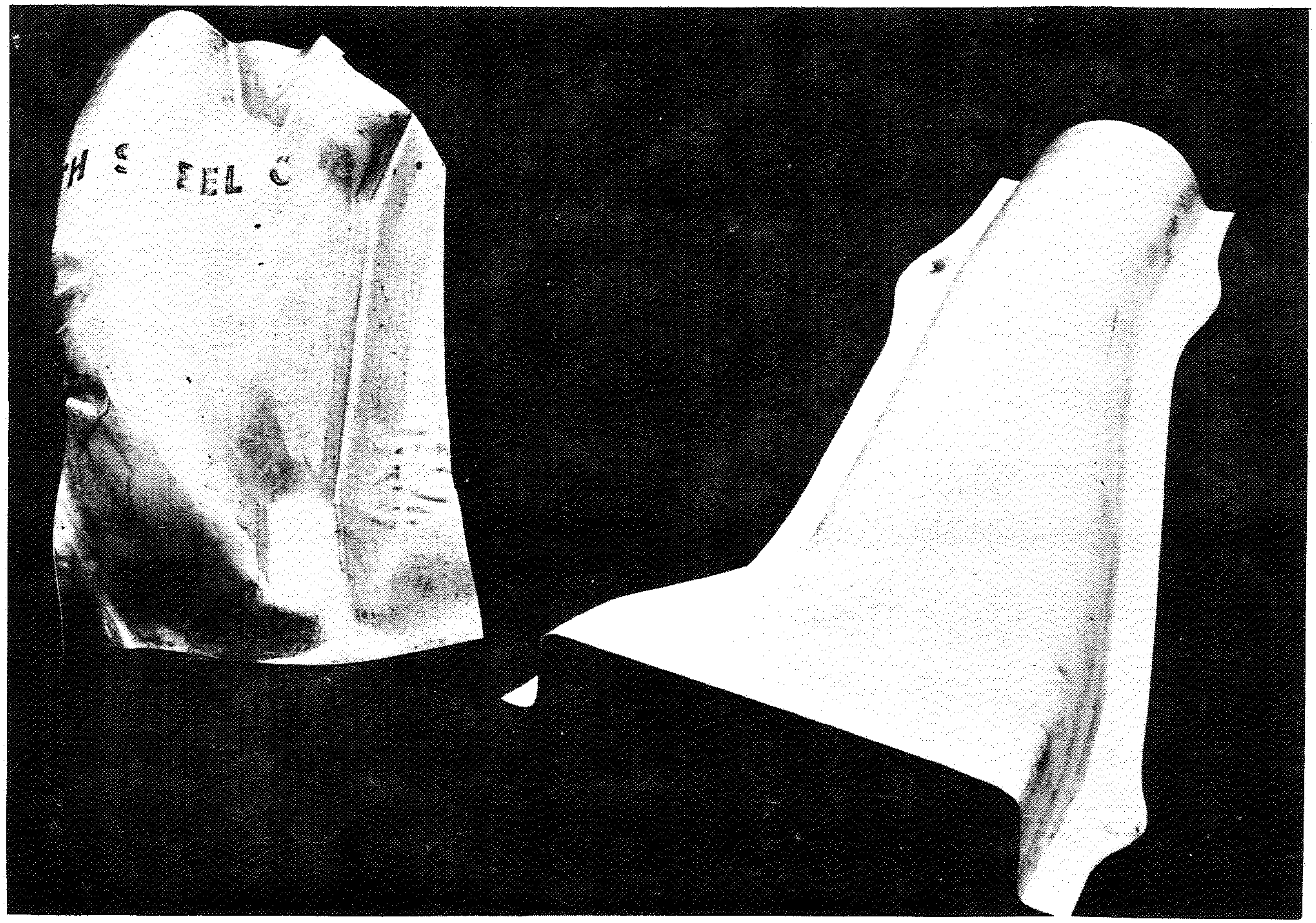


FIGURE 81. DC8 OUTLET HALF AND DUCT ASSEMBLY 0.025 AND 0.032 THICK TYPE 321 STAINLESS STEEL, DROP-HAMMER FORMED

Courtesy of Douglas Aircraft Corporation occurred in the trim area. This would have no effect on the finished part since it was removed before the next assembly. The part shown on the right hand side of Figure 80 was made from 0.032-inch-thick material. It is shown, after benching and trimming, ready for final assembly.

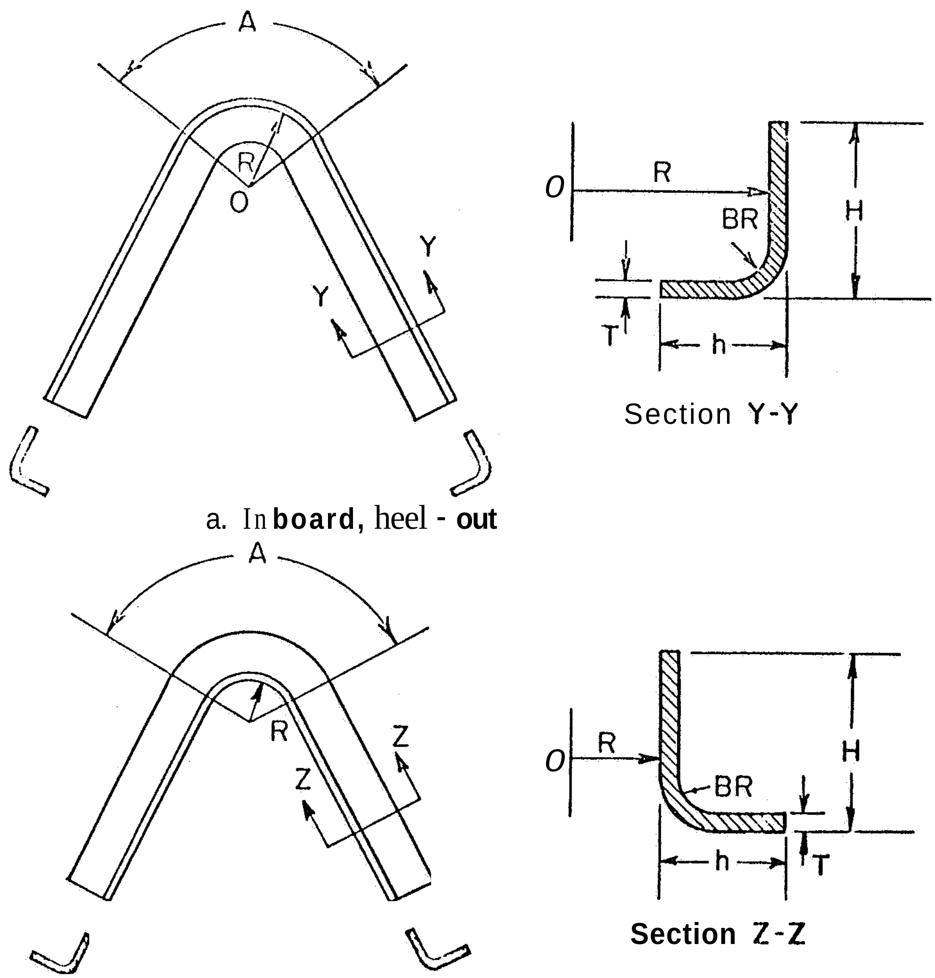
STRETCH FORMING

Introduction. In stretch forming, the workpiece, usually of uniform cross section, is subjected to a suitable tension and then wrapped around a die of the desired shape. Deformation occurs mainly by bending at the fulcrum point of the die surface. Compression buckling is avoided by applying enough tensile load to produce approximately one percent elongation in the material. The tensile load shifts the neutral axis of the workpiece towards the forming die.

The terms linear stretch forming and stretch-wrap forming denote operations on preforms such as extrusions or brake-formed parts. Figure 82 illustrates two types of linear stretch forming. The classification is based on the position of flange in the plane of forming which determines whether the flange is stressed in either tension or compression. Although the sketch shows an angle, the same classification is used when forming channels and hat sections.

Stretch forming is also used for producing double contours in sheet. Ordinarily the sheet is stretched and bent around the male die with convex curvature as shown in Figure 83. In a second double contouring technique, the sheet is pressed between matched dies after the tensile load has been applied. This type of stretch forming equipment is illustrated by Figure 84. A 250-ton press of this type is capable of forming parts which would require a 900-ton double-action draw press, (Ref. 107).

The capabilities of several stretch forming machines commercially available are given in Table XXVIII.



a. Inboard, heel - out

b. Outboard, heel-in

FIGURE 82. PARAMETERS OF HEEL–IN AND HEEL–OUT LINEAR STRETCH–FORMED ANGLES

Courtesy of North American Aviation, Inc., Inglewood, California.

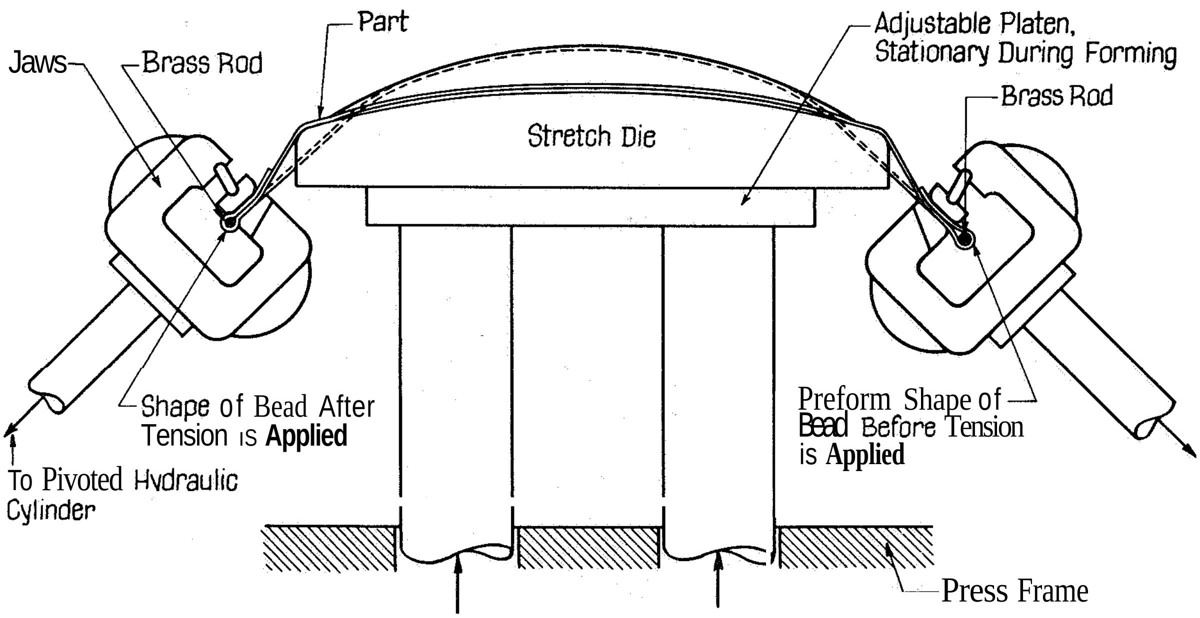


FIGURE **83.** STRETCH FORMING **A** SMOOTHLY-CONTOURED **PART** (Ref. 78)

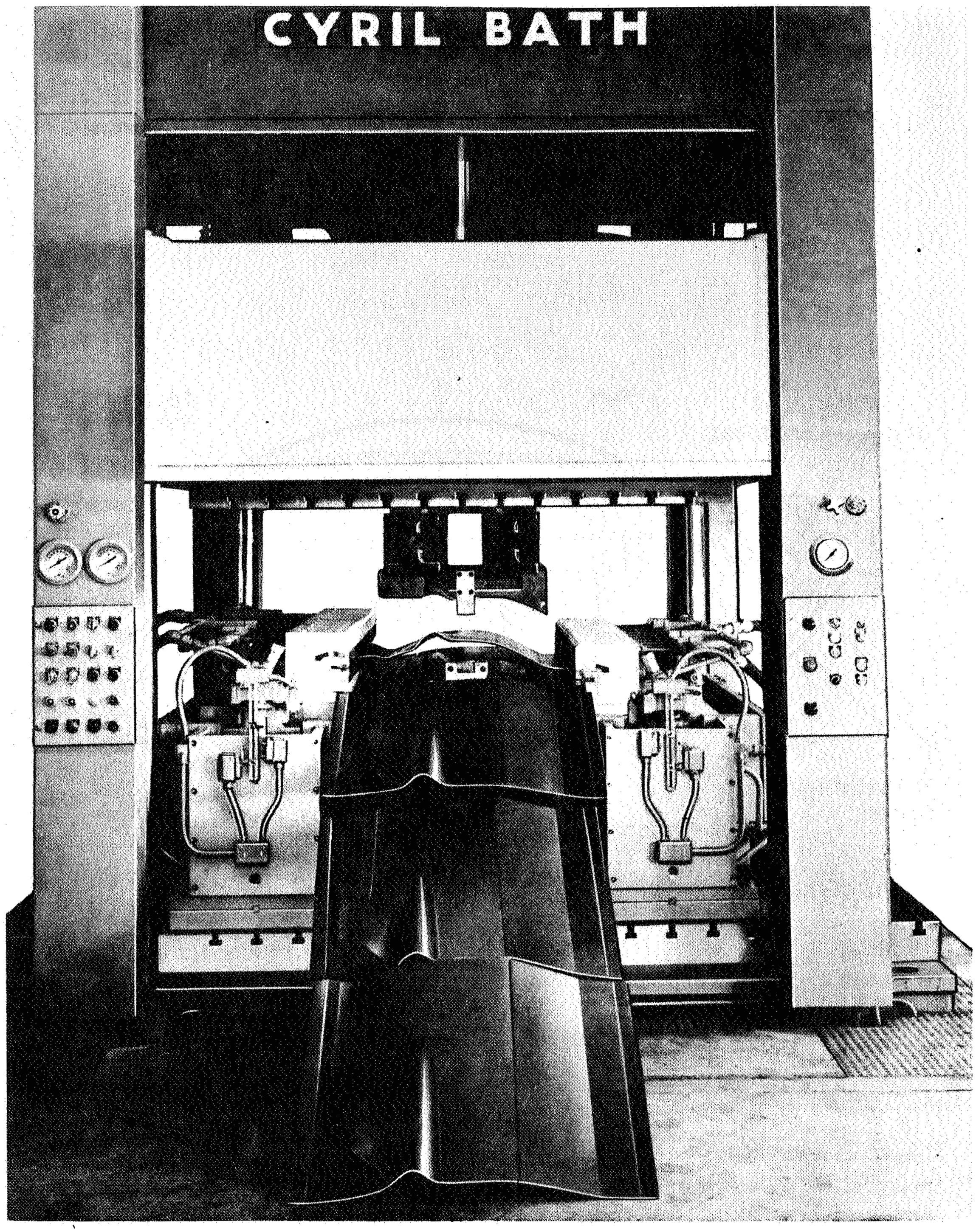


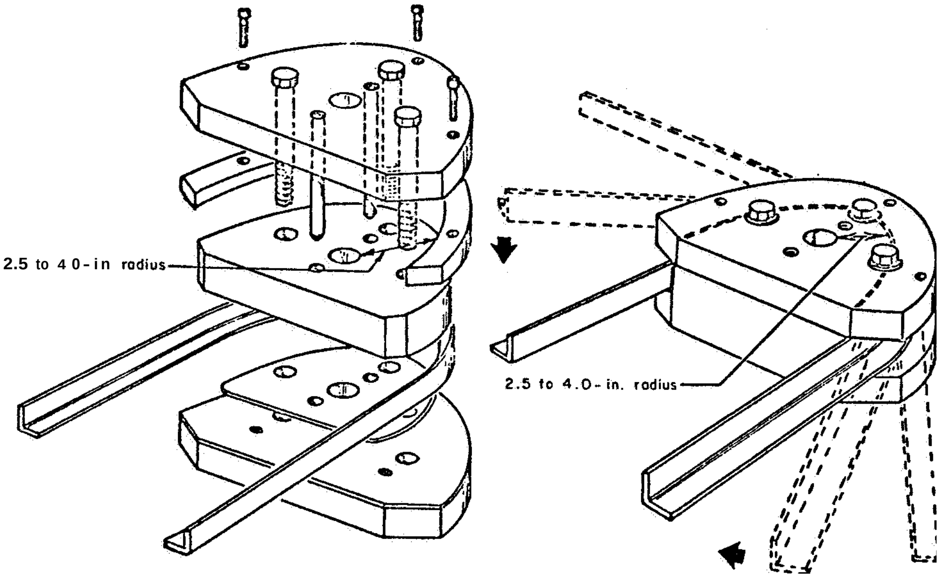
FIGURE **84.** STRETCH-DRAW-PROCESS MACHINE FOR SHEET
250-ton pressing, 85-ton stretching.
Courtesy of Cyril Bath **Company, Cleveland,** Ohio

TABLE XXVIII. CAPABILITIES OF TYPICAL STRETCH-FORMING MACHINES

Tonnage[a]	Rate of Forming, deg/min	Material Size, inches	Type
		Cyril Bath (Ref. 107)	
200-2000	--	84-144 width	Sheet stretch
150	36 max	--	Sheet or section stretch
100	36 max	--	Section stretch
75	36 max	--	Section stretch
50	36 max	--	Sheet or section stretch
25	50 max	--	Section stretch
10	90 max	--	Section stretch
50 pressing 5 stretching	--	Bed 138 X 128	Stretch-draw sheet
		Sheridan-Gray (Ref. 108)	
5	--	16-96	Section
IO	--	16-144	Sectioii
21	--	18-144	Section
54	--	28-216	Section
104	--	40-288	Section
306	--	48-288	Section
59	220 max	20-336	Sheet strztch
120-5000 stretch	--	48-240 width	Sheer stretch draw[b]
300-1000	--	96-360 length	Sheet stretch draw[b]

a) All tonnage for stretch unless otherwise noted.
(b) Presses similar to Androforming.

Tooling. The tooling for stretch forming normally consists of a male die made to the contour and dimensions desired in the final part. The choice of tool depends on the number of parts to be made. For room-temperature, linear stretch forming of sections, a composite steel die with inserts that will accommodate different thickness of the material is often used. Tooling of this kind is shown in Figure 85. Die inserts and shims are used for adjustment to various thickness and



o. Inboard Wrap   b. Outboard Wrap

FIGURE 85. STRETCH-MACHINE (ANGLE SECTIONS) TOOLS

Courtesy of North American Aviation, Inc., Inglewood, California.

angle leg lengths as shown in Figure 86. Adjustable tooling reduces the number of different-size tooling sets that have to be stocked.

For room-temperature operations on sheet, the tooling can be made from zinc-base alloys (Kirksite) or from concrete faced with. steel. The high yield strengths of stainless steel normally causes rapid wear of plastic-faced tooling. Consequently, plastic tooling is not recommended for this application. The life of zinc-base-alloy tooling can be extended by first stretch forming a thin sheet of stainless steel over the tool and using it as a protected cover. This also prevents pick up of zinc by the formed parts which might cause contamination and a reduction in properties after heat treatment.

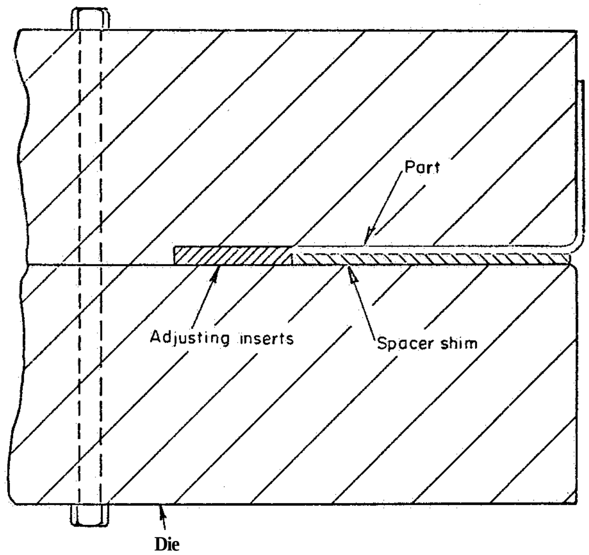


FIGURE *86.* SECTIONAL VIEW OF LINEAR STRETCH TOOLING FOR HEEL-OUT ANGLES (Ref. *66)*

Since the properties of the stainless steels change with the severity of the deformation, it is advantageous to obtain a fairly consistent amount of stretch throughout the part. This is accomplished by permitting the material to move uniformly over the tooling during stretching. Lubrication and tool smoothness have been found to have significant effects on the uniformity of stretching. Wallace reported on the use of ice as a tool covering and lubricant. (Ref. 109). He also found that greases applied to the tooling tended to squeeze out from the areas of higher normal pressure, causing a local breakdown of lubrication. Attempts were made to use rubber and other soft materials as a tool facing but this approach did not prove to be desirable. The use of porous tooling that would permit fluids to be injected between the part and the tool was also evaluated and rejected in favor of ice.

In the tests conducted by Wallace, (Ref. 109) a coating of ice was built up by spraying or brushing water on refrigerated tools. A film thickness of 0.08 inch gave the best results. For stretch forming materials at room temperature, this thickness could be maintained by holding the film temperature below 25 F. The blanks were warmed by heating with an infrared lamp, with an intensity of approximately 15 watts per square inch for 30 seconds, during forming.

The grips for stretch forming should be made of hardened tool steel with a sharp clean serations. This is particularly important when a number of grips are used as in forming sheet. If the grips are not in good mechanical working condition the workpiece may slip in some locations and tear at the grips that apply a greater holding force. Relieving the first four teeth near the jaw edges by polishing or grinding helps to prevent tearing of the sheet. Some type of grips permit the sheet to be wrapped around a rod for increased holding efficiency. This method was shown in Figure 83.

<u>Techniques of Stretch Forming</u>. In stretch forming, skilled operators and careful attention to details are essential for success. Trouble may result from exceeding the uniform elongation of the material. Since most stainless steels have good elongation and a wide spread between yield and ultimate strength, they stretch form with a minimum of difficulty.

The preformed sections or sheet material, in either the annealed, 1/4 hard, of 1/2 condition, are first loaded into the clamping jaws of the stretch press. A load is then applied to the material to produce at least one percent extension between the grips. The grips are then either rotated around the hie, as in section forming, or pulled against the die, as in sheet forming, and the load is increased slightly to assure that the part conforms with the die. The rate of movement against the die may be as high as 10 degrees per minute but slower rates of about one degree per minute are usually used. After the material is in complete contact with the die over the entire area to be formed, the stretching load is again increased to minimize springback. Since springback can be expected in room-temperature stretch forming of stainless steels, the machine is adjusted for overforming. In forming sections a springback from 5 to 10 percent of the bend angle can be expected for annealed material and as high as **30** percent for work-hardened material.

To obtain maximum formability in stretch forming, the material should be stretched in the rolling direction. For preformed angles, channels, or hat sections this requires that the prior operation be performed transverse to the rolling direction of the material. The direction of initial deformation is especially important when cold worked material is being stretched formed.

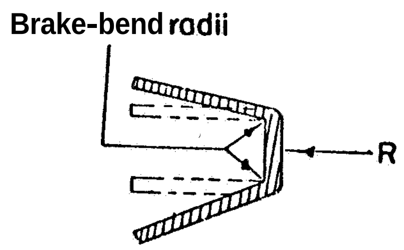
Stainless steels are normally stretch-formed at room temperature. When severe deformation is required multistage forming with intermediate anneals may be necessary.

Blank Preparation. For room temperature stretch forming the blank should have clean, smooth surfaces. Blanks with as-sheared edges are used, burrs are removed to prevent tooling damage. Sections for linear stretch forming should be cleaned after brake forming and annealed for maximum formability. Any surface contamination from the brake forming operation or thermal treatment should be removed by acid etching as described under the section on blank preparation. Where the maximum available sheet size is required to make a part, tabs may be welded onto the sheet for gripping. A reduction in strength due to the welding may limit the amount of stretching possible with this practice.

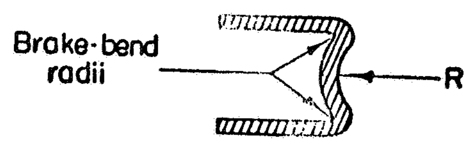
Lubricants have very little effect on stretch forming limits because of the relatively small movement of the material over the die. When used they are generally applied only to localized areas. They should be of the type that can be easily removed. Light body machine oils, soap solutions, and greases should be effective.

Stretch Forming Limits. Success or failure in stretch forming to a particular shape depends on the mechanical properties of the material and on the geometry of the part. Failures occur from buckling or from splitting as illustrated in Figure 87. The geometrical factors controlling the difficulty in forming of a section are the thickness, the height of the workpiece in the plane of bending, and the radius of the stretch forming die. The important characteristics of the workpiece material are its capacity for stretching without rupture and its ratio of elastic modulus to yield strength. These mechanical properties influence splitting and buckling, respectively. Wood (Ref. 66) demonstrated that the amount of stretching the material will withstand before splitting correlates with elongation in a two-inch-gage length in tensile tests. The maximum percent stretch in a particular operation is generally determined by the flange dimensions in the plane of forming of the section, divided by the inside radius of the bend times 100. For example, the yield elongation would amount to 10 percent for a section with a 1-inch flange formed around a 10-inch radius.

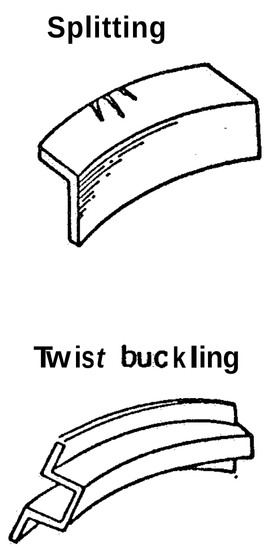
Splitting and buckling limits in Type 300 stainless steels in stretch forming have been estimated from comparisons of their tensile properties with those of Type 350 stainless steel. Figure 88 shows



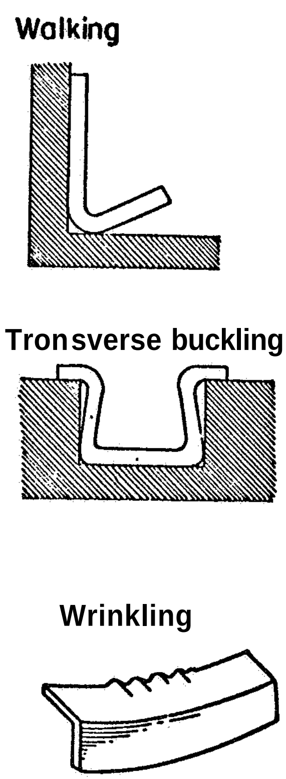
a. Springbock Due to Large-Bend Radii



b. Column Collapse Due to Large-Bend Radii



c. Major Failures



d. Minor Distortions

FIGURE 87. TYPES OF FAILURES FOR LINEAR STRETCH FORMING (Ref. 65)

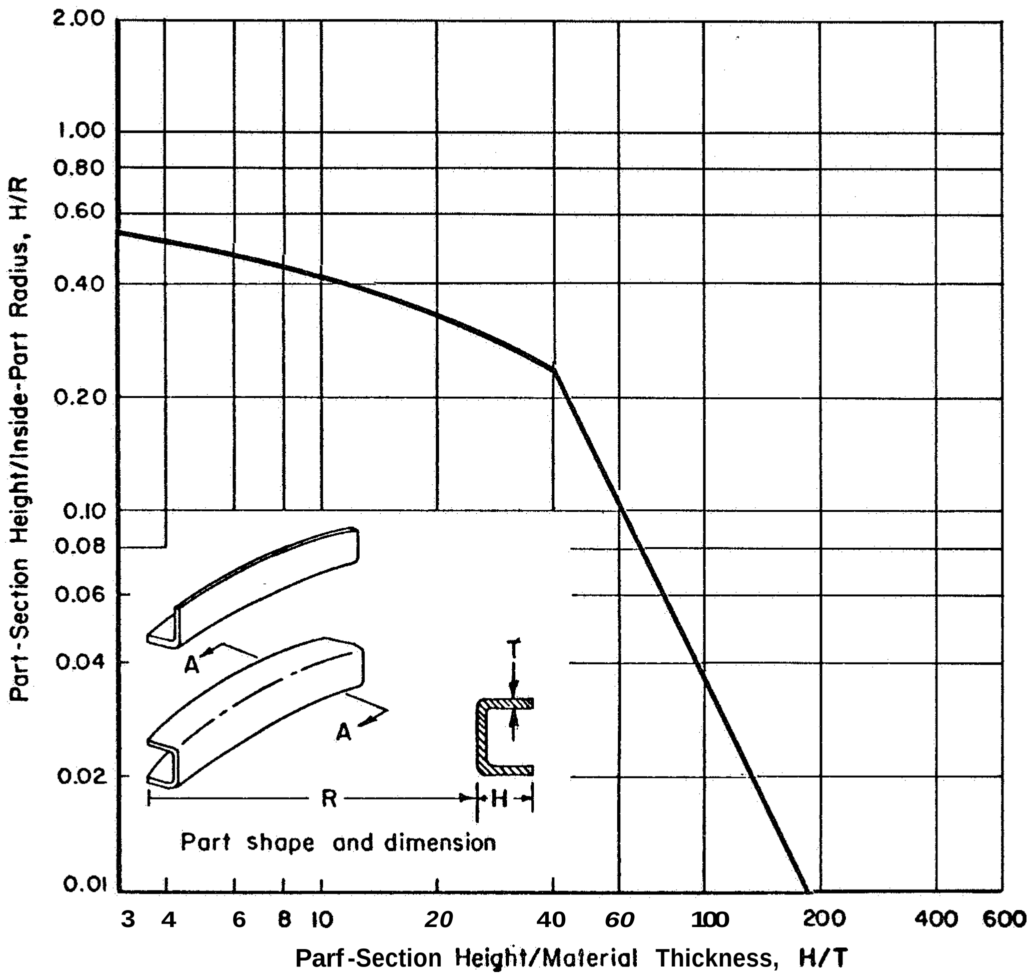


FIGURE 88. ESTIMATED LIMITS FOR STRETCH FORMING HEEL–IN ANGLE AND CHANNEL SECTIONS FROM TYPE **300** STAIN–LESS STEELS

the estimated forming limits for heel-in or outboard stretch forming of Type 300 stainless steels. Figure 89 gives the estimated formability limit curves for heel-out or inboard stretch forming of angle and channel sections. The change in part orientation causes a shift in the limiting H/R and H/T ratios because it effects the severity of deformation. The relative order of formability between the materials is not changed because it depends on the mechanical properties.

The formability limits of hat sections in the heel-in position are shown in Figure 90. The buckling limits are a little higher than for angles and channels because the flange on the hat gives some support during forming.

Elongation is the material property controlling success in stretch forming sheet; thickness has little or no effect. In double contour forming of sheet, the radii of curvature and their chord lengths are the geometrical factors controlling the limits of deformation. The products of the two limiting ratios of the radii to their chords is a constant for a particular material and forming temperature. That is, using the terminology illustrated in Figure 91

$$R_T/L) \times (R_m/T) = \text{constant}) \ . \qquad (26)$$

The tensile load should he applied in the direction necessary to stretch the sheet over the smaller radius because this requires more elongation. The blank should be oriented *so* the pull is applied in the direction in which the sheet is more ductile. Usually this is parallel to the major direction of extension in rolling.

Figure 91 shows the estimated stretch-forming limits for Type 300 stainless steels. The limits, expressed in ratios of die radii to chord

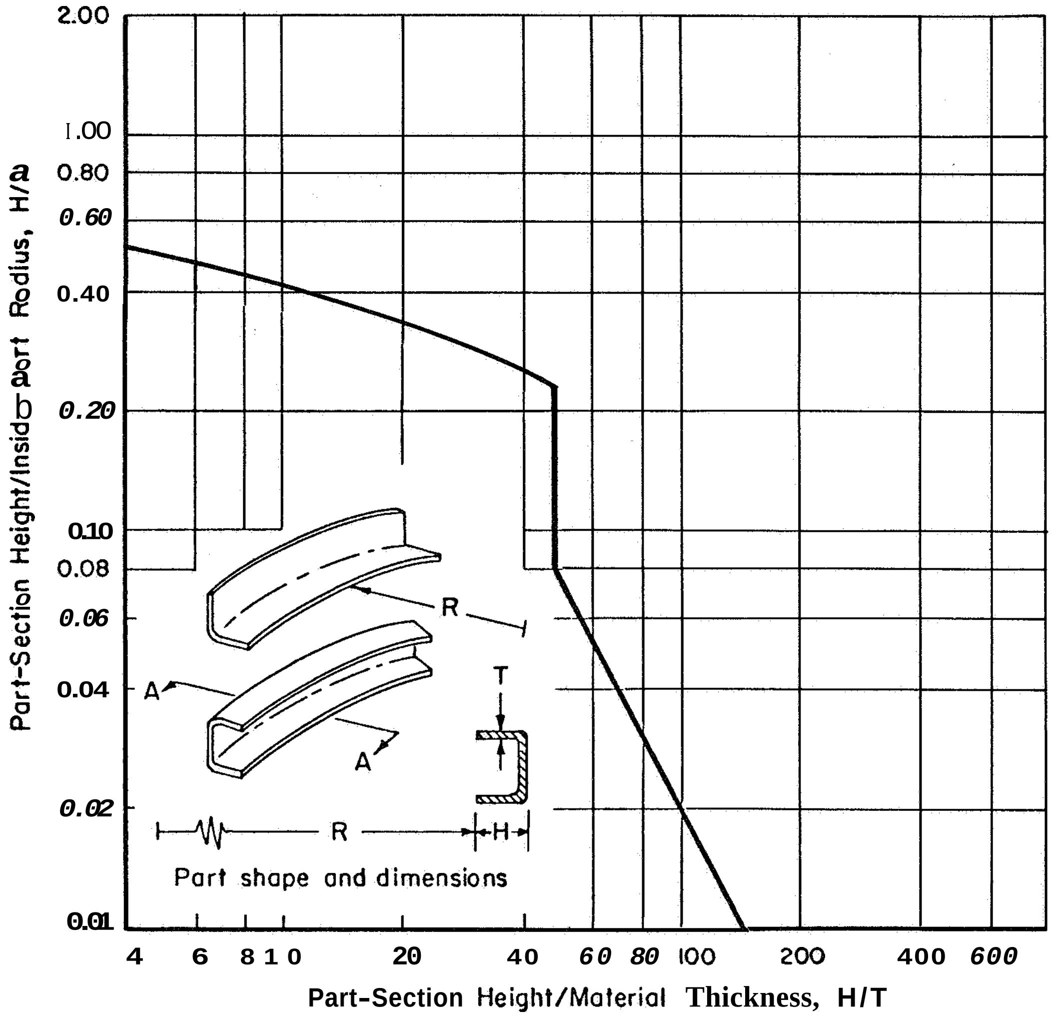


FIGURE 89. ESTIMATED LIMITS FOR STRETCH FORMING HEEL-OUT ANGLES AND CHANNELS FROM TYPE 300 STAINLESS STEELS

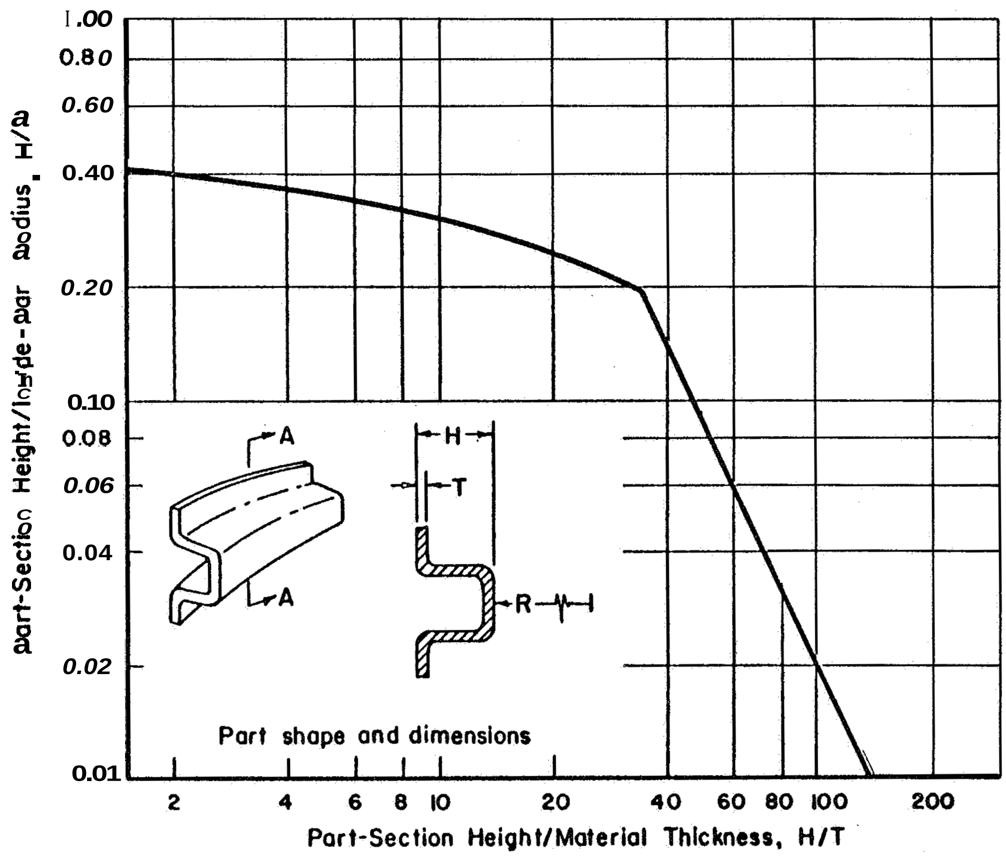


FIGURE 90. ESTIMATED LIMITS FOR STRETCH FORMING HEEL–IN HAT SECTIONS FROM TYPE **300** STAINLESS STEELS

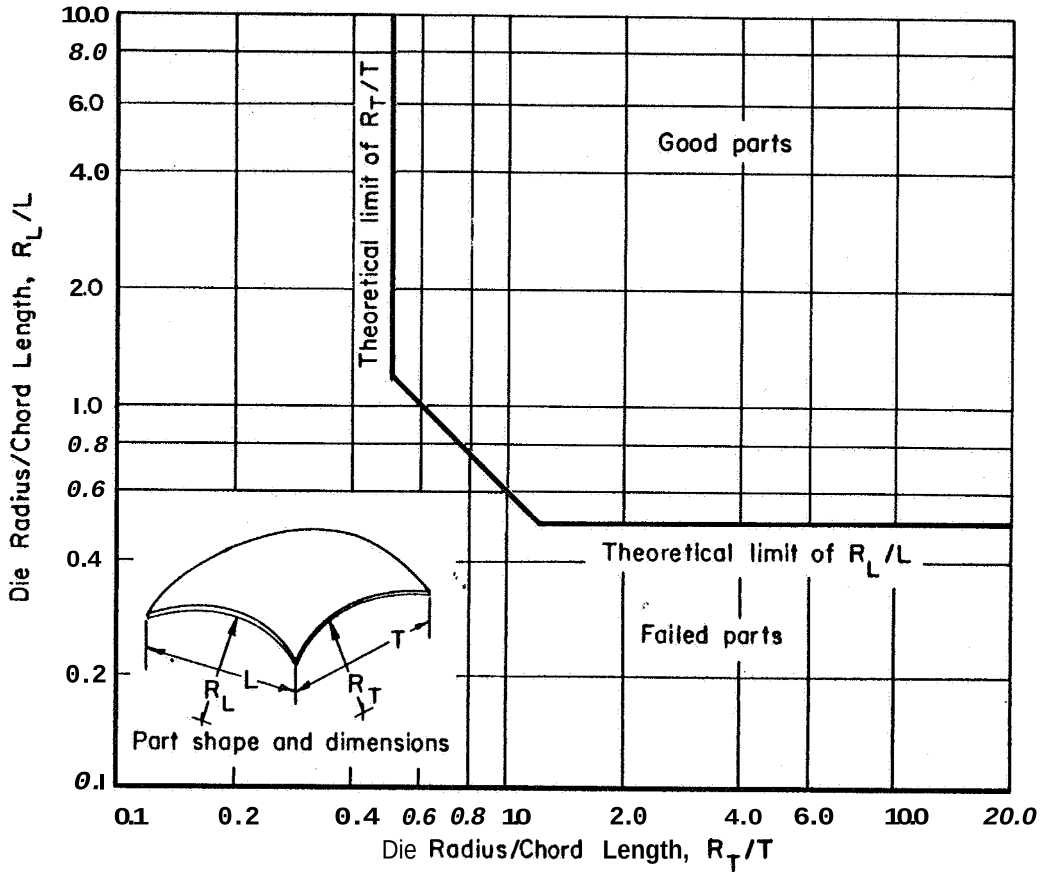


FIGURE 91. ESTIMATED LIMITS FOR STRETCH FORMING TYPE 300 STAINLESS STEEL SHEET

lengths, are based on typical elongation values in room temperature tensile tests. Sawey has suggested an equation for determining the capabilities of stretch forming based on limiting elongation values shown in Table XXIX. (Ref. 110). He indicated that it is possible to

TABLE XXIX. MAXIMUM STRETCH FOR STAINLESS STEEL SECTIONS (Ref. 110)

Material AISI Number	Condition	Elongation in/in
301	Annealed	0.19
302	Annealed	0.24
304	Annealed	0.24
321	1/4 hard	0.17
321	1/2 hard	0.20

determine whether a part can be stretched formed by first finding the maximum elongation required of the part. This is determined from the formula:

$$E_m = E_o + \frac{R_2 - R_1}{R_2} \qquad (27)$$

where

R_1 = smallest radius of part to inner fibers

R_2 = smallest radius of outer fibers

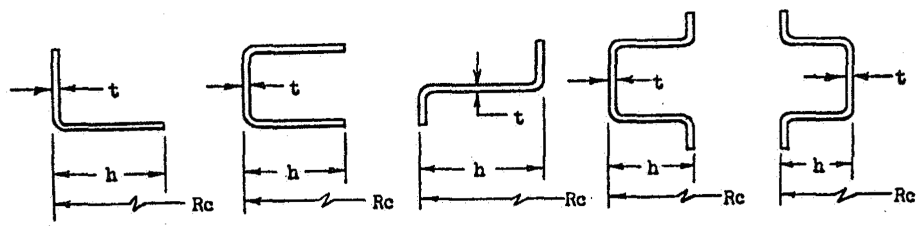
E_o = elongation specified in the design of the part.

Once the maximum elongation required to make the part has been determined this can be compared with the figures given in Table XXIX for the particular material. If the value obtained exceeds that given in Table XXIX it is highly unlikely that the part can be stretched formed successfully.

The design limitations for a given contour radius and material thickness for flanges of Types 301 and 321 annealed stainless steels are given in Tables XXX and XXXI. Similar data for Type 301 stainless steel in the quarter hard, and half hard conditions are given in Tables XXXII-XXXV. The maximum flange heights given in these particular tables were based on the ability to run production parts with low scrap loss. If some scrap can be accepted, greater flange heights can be obtained than those listed in the tables.

TABLE XXX. STRETCH FLANGE LIMITS; 0° - 120° FLANGE; COLD FORMED ON STRETCH PRESS; TYPES 301 AND 321 ANNEALED (Ref. 112)

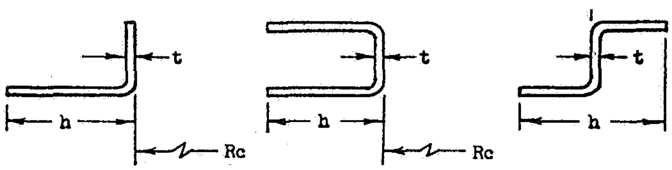
Applies to the following forms:



CONTOUR RADIUS (Rc)	MATERIAL THICKNESS (t)												
	.016	.020	.025	.032	.040	.045	.050	.063	.071	.080	.090	.100	.125
	MAXIMUM FLANGE HEIGHT (h)												
5	1.14	1.42	1.77	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12	2.12
10	1.15	1.42	1.77	2.27	2.84	3.19	3.55	4.24	4.24	4.24	4.24	4.24	4.24
15	1.21	1.46	1.79	2.27	2.84	3.19	3.55	4.47	5.04	5.68	6.36	6.36	6.36
20	1.32	1.54	1.84	2.30	2.84	3.19	3.55	4.47	5.04	5.68	6.39	7.10	8.48
25	1.41	1.65	1.93	2.35	2.88	3.20	3.55	4.47	5.04	5.68	6.39	7.10	8.87
30	1.50	1.74	2.03	2.42	2.93	3.26	3.58	4.47	5.04	5.68	6.39	7.10	8.87
35	1.58	1.84	2.13	2.53	2.99	3.31	3.63	4.48	5.04	5.68	6.39	7.10	8.87
40	1.65	1.92	2.23	2.64	3.09	3.37	3.69	4.54	5.06	5.68	6.39	7.10	8.87
45	1.72	2.00	2.32	2.73	3.19	3.47	3.75	4.59	5.11	5.70	6.39	7.10	8.87
50	1.78	2.07	2.40	2.83	3.29	3.58	3.86	4.64	5.16	5.75	6.40	7.10	8.87
55	1.84	2.14	2.48	2.92	3.39	3.68	3.97	4.70	5.22	5.80	6.46	7.11	8.87
60	1.90	2.20	2.55	3.01	3.49	3.78	4.07	4.79	5.28	5.85	6.51	7.16	8.87
65	1.95	2.26	2.62	3.09	3.58	3.87	4.17	4.90	5.34	5.91	6.56	7.22	8.87
70	2.00	2.32	2.69	3.16	3.67	3.97	4.26	5.01	5.45	5.97	6.62	7.27	8.90

TABLE XXXI. STRETCH FLANGE LIMITS; 0° - 120° FLANGE; COLD FORMED ON STRETCH PRESS; TYPES 301 AND 321 ANNEALED (Ref. 112)

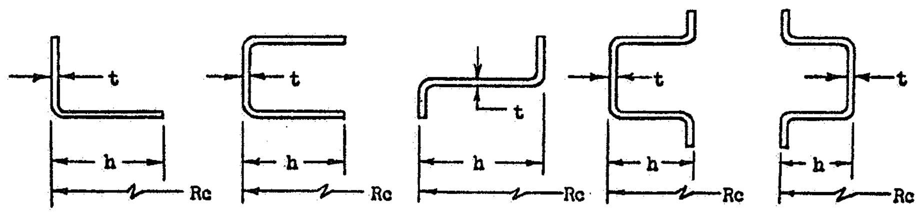
Applies *to the* following forms:



CONTOUR RADIUS (Rc)	MATERIAL THICKNESS (t)												
	.016	.020	.025	.032	.040	.045	.050	.063	.071	.080	.090	.100	.125
	MAXIMUM FLANGE HEIGHT (h)												
5	.64	.80	1.00	1.28	1.60	1.71	1.71	1.71	1.71	1.71	1.71	1.71	1.71
10	.72	.85	1.02	1.28	1.60	1.80	2.00	2.52	2.84	3.20	3.42	3.42	3.42
15	.82	.95	1.12	1.34	1.62	1.80	2.00	2.52	2.84	3.20	3.60	4.00	5.00
20	.91	1.05	1.22	1.45	1.70	1.87	2.04	2.52	2.84	3.20	3.60	4.00	5.00
25	.98	1.13	1.31	1.55	1.81	1.97	2.12	2.57	2.85	3.20	3.60	4.00	5.00
30	1.04	1.20	1.40	1.64	1.91	2.07	2.23	2.64	2.92	3.23	3.60	4.00	5.00
35	1.09	1.27	1.47	1.73	2.01	2.17	2.33	2.75	3.00	3.31	3.66	4.00	5.00
40	1.14	1.33	1.54	1.81	2.10	2.27	2.44	2.86	3.11	3.39	3.73	4.08	5.00
45	1.19	1.38	1.60	1.88	2.19	2.36	2.53	2.96	3.22	3.51	3.81	4.15	5.02
50	1.23	1.43	1.66	1.95	2.26	2.45	2.63	3.06	3.32	3.61	3.93	4.24	5.10
55	1.27	1.47	1.71	2.02	2.34	2.53	2.71	3.16	3.42	3.71	4.04	4.36	5.17
60	1.31	1.52	1.76	2.08	2.41	2.60	2.79	3.25	3.52	3.81	4.14	4.46	5.24
65	1.35	1.56	1.81	2.13	2.47	2.67	2.87	3.34	3.62	3.92	4.24	4.57	5.36
70	1.38	1.60	1.85	2.19	2.53	2.74	2.94	3.43	3.71	4.02	4.34	4.67	5.47

TABLE XXXII. STRETCH FLANGE LIMITS; 0° - 120° FLANGE; COLD FORMED ON STRETCH PRESS; TYPE 301 1/4 HARD (Ref. 112)

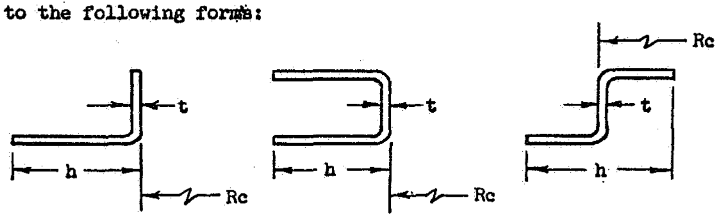
Applies to *the* following forms:



CONTOUR RADIUS (Rc)	MATERIAL THICKNESS (t)												
	.016	.020	.025	.032	.040	.045	.050	.063	.071	.080	.090	.100	.125
	MAXIMUM FLANGE HEIGHT (h)												
5	.67	.84	1.05	1.34	1.68	1.89	2.09	2.09		2.09	2.09		2.09
10	.74	.89	1.08	1.35	1.68	1.89	2.10	2.65		3.36	3.78		4.19
15	.80	.96	1.14	1.40	1.72	1.91	2.10	2.65		3.36	3.78		5.25
20	.87	1.02	1.21	1.47	1.77	1.96	2.16	2.66		3.36	3.78		5.25
25	.93	1.09	1.27	1.54	1.84	2.03	2.21	2.72		3.37	3.78		5.25
30	.99	1.15	1.34	1.60	1.91	2.10	2.29	2.77		3.43	3.81		5.25
35	1.04	1.21	1.41	1.67	1.97	2.17	2.36	2.84		3.48	3.87		5.25
40	1.09	1.26	1.47	1.74	2.04	2.22	2.42	2.91		3.54	3.93		5.28
45	1.13	1.31	1.52	1.80	2.11	2.29	2.48	2.98		3.62	3.98		5.34
50	1.17	1.36	1.58	1.86	2.18	2.36	2.54	3.04		3.68	4.06		5.40
55	1.21	1.40	1.63	1.92	2.24	2.43	2.62	3.10		3.76	4.13		5.45
60	1.24	1.44	1.67	1.97	2.30	2.50	2.69	3.16		3.82	4.20		5.50
65	1.28	1.48	1.72	2.03	2.36	2.56	2.75	3.24		3.88	4.27		5.57
70	1.31	1.52	1.76	2.08	2.41	2.62	2.82	3.31		3.94	4.33		5.64

TABLE XXXIII. STRETCH FLANGE LIMITS; 0° - 120° FLANGE; COLD FORMED ON STRETCH PRESS; TYPE 301 1/4 HARD (Ref. 112)

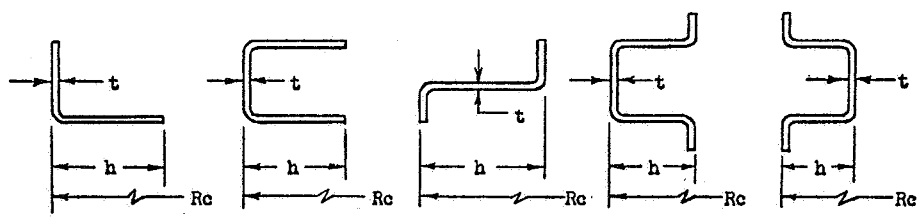
Applies to the following forms:



CONTOUR RADIUS (Rc)	MATERIAL THICKNESS (t)												
	.016	.020	.025	.032	.040	.045	.050	.063	.071	.080	.090	.100	.125
	MAXIMUM FLANGE HEIGHT (h)												
5	.39	.48	.59	.75	.94	1.06	1.18	1.43		1.43	1.43		1.43
10	.47	.55	.65	.79	.96	1.06	1.18	1.48		1.88	2.11		2.86
15	.53	.62	.72	.86	1.02	1.12	1.23	1.50		1.88	2.11		2.94
20	.59	.68	.79	.94	1.10	1.20	1.30	1.56		1.91	2.13		2.94
25	.63	.73	.85	1.00	1.17	1.27	1.37	1.63		1.97	2.18		2.94
30	.67	.78	.91	1.07	1.24	1.34	1.44	1.70		2.05	2.25		2.98
35	.71	.82	.95	1.12	1.30	1.41	1.51	1.78		2.12	2.32		3.03
40	.74	.86	1.00	1.18	1.36	1.48	1.58	1.85		2.19	2.39		3.10
45	.77	.89	1.04	1.22	1.42	1.53	1.65	1.92		2.27	2.46		3.17
50	.80	.93	1.08	1.27	1.47	1.59	1.71	1.99		2.34	2.54		3.25
55	.83	.96	1.11	1.31	1.52	1.64	1.76	2.05		2.41	2.61		3.31
60	.85	.99	1.14	1.35	1.56	1.69	1.81	2.11		2.48	2.68		3.38
65	.87	1.01	1.17	1.38	1.60	1.74	1.86	2.17		2.54	2.75		3.46
70	.89	1.04	1.20	1.42	1.65	1.78	1.91	2.23		2.61	2.82		3.54

TABLE XXXIV. STRETCH FLANGE LIMITS; 0° - 120° FLANGE; COLD FORMED ON STRETCH PRESS; TYPE 301 1/2 HARD (Ref. 112)

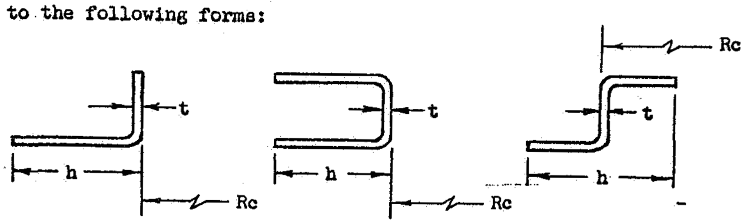
Applies *to the* following forme:



CONTOUR RADIUS (Rc)	MATERIAL THICKNESS (t)												
	.016	.020	.025	.032	.040	.045	.050	.063	.071	.080	.090	.100	.125
	MAXIMUM FLANGE HEIGHT (h)												
5	.61	.75	.94	1.20	1.50	1.69	1.88	1.95		1.95	1.95		1.95
10	.67	.80	.97	1.21	1.51	1.69	1.88	2.36		3.00	3.38		3.90
15	.73	.87	1.04	1.27	1.54	1.71	1.89	2.37		3.00	3.38		4.69
20	.79	.92	1.10	1.34	1.60	1.77	1.94	2.39		3.01	3.38		4.69
25	.84	.98	1.15	1.40	1.67	1.84	2.01	2.44		3.03	3.40		4.69
30	.89	1.04	1.21	1.45	1.73	1.90	2.07	2.50		3.08	3.42		4.70
35	.94	1.09	1.27	1.51	1.79	1.97	2.14	2.58		3.13	3.48		4.72
40	.98	1.13	1.32	1.57	1.84	2.02	2.20	2.64		3.21	3.53		4.74
45	1.02	1.18	1.37	1.63	1.90	2.07	2.25	2.70		3.28	3.61		4.71
50	1.05	1.22	1.42	1.68	1.97	2.13	2.30	2.76		3.34	3.68		4.84
55	1.09	1.26	1.46	1.73	2.02	2.20	2.36	2.82		3.41	3.75		4.90
60	1.12	1.30	1.51	1.78	2.08	2.26	2.43	2.87		3.47	3.81		4.98
65	1.15	1.33	1.55	1.83	2.13	2.31	2.49	2.92		3.52	3.87		5.05
70	1.18	1.37	1.59	1.87	2.18	2.36	2.54	2.99		3.58	3.93		5.12

TABLE XXXV. STRETCH FLANGE LIMITS; 0° - 120° FLANGE; COLD FORMED ON STRETCH PRESS; TYPE 301 1/2 HARD (Ref. 112)

Applies to the following forms:



CONTOUR RADIUS (Rc)	MATERIAL THICKNESS (t)												
	.016	.020	.025	.032	.040	.045	.050	.063	.071	.080	.090	.100	.125
	MAXIMUM FLANGE HEIGHT (h)												
5	.36	.43	.53	.67	.84	.95	1.05	1.27		1.27	1.27		1.27
10	.42	.50	.59	.72	.86	.95	1.05	1.32		1.68	1.89		2.54
15	.48	.56	.65	:79	.94	1.03	1.12	1.35		1.68	1.89		2.63
20	.53	.61	.72	.85	1.00	1.09	1.19	1.42		1.73	1.90		2.63
25	.57	.66	.77	.91	1.06	1.15	1.25	1.49		1.80	1.98		2.63
30	.61	.70	.81	.96	1.12	1.22	1.31	1.55		1.87	2.05		2.68
35	.64	.74	.86	1.01	1.18	1.28	1.37	1.61		1.93	2.12		2.75
40	.67	.77	.90	1.06	1.23	1.33	1.43	1.68		2.00	2.18		2.83
45	.69	.80	.93	1.10	1.28	1.38	1.49	1.74		2.06	2.25		2.90
50	.72	.83	.97	1.14	1.32	1.43	1.54	1.80		2.12	2.31		2.96
55	.74	.86	1.00	1.18	1.36	1.48	1.58	1.85		2.18	2.36		3:03
60	.76	.89	1.03	1.21	1.40	1.52	1.63	1.91		2.24	2.43		3.09
65	.78	.91	1.06	1.24	1.44	1.56	1.67	1.96		2.30	2.49		3.15
70	.80	.93	1.08	1.28	1.48	1.60	1.72	2.00		2.36	2.55		3.21

The double-contouring technique, called Androforming, uses shaping-system tools or elements which permit sheets to be formed to smaller radii. Under these conditions, sheet thickness as well as ductility and the part radius is important because failure can result from either buckling or splitting. A nomogram showing the limiting radii to which half-hard Type 301 stainless steel, and other materials can be formed to shallow contour is given in Figure 92. The procedure for using the nomograph is:

1. Determine the radii corresponding to the transverse and longitudinal curvatures of the part to be formed.
2. Draw a straight line from T (transverse radius) through L (longitudinal radius) to intersect the scale showing the compound-contour index. Parts can be formed successfully from any of the alloys whose forming limit is above that intersection.

Information on choosing machine settings for producing a particular part is also contained in the original report (Ref. 111).

Examples of Stretched Formed Parts. An example of stretch forming of Type 347 stainless steel is shown in Figure 93. This part was formed in the annealed condition from 0.030-inch-thick sheet on a 150-ton press. An aluminum alloy die block was used with mineral oil grease as a lubricant on the tool.

The inboard and outboard stretch formed stainless steel angles shown in Figure 94 were made from 0.080-inch-thick material. The angle legs were one inch wide and the angle bend radius was 7/64 of an inch. The material was stretched parallel to the sheet rolling direction around a three-inch-radius die using a preload of 800 pounds and a wrapping

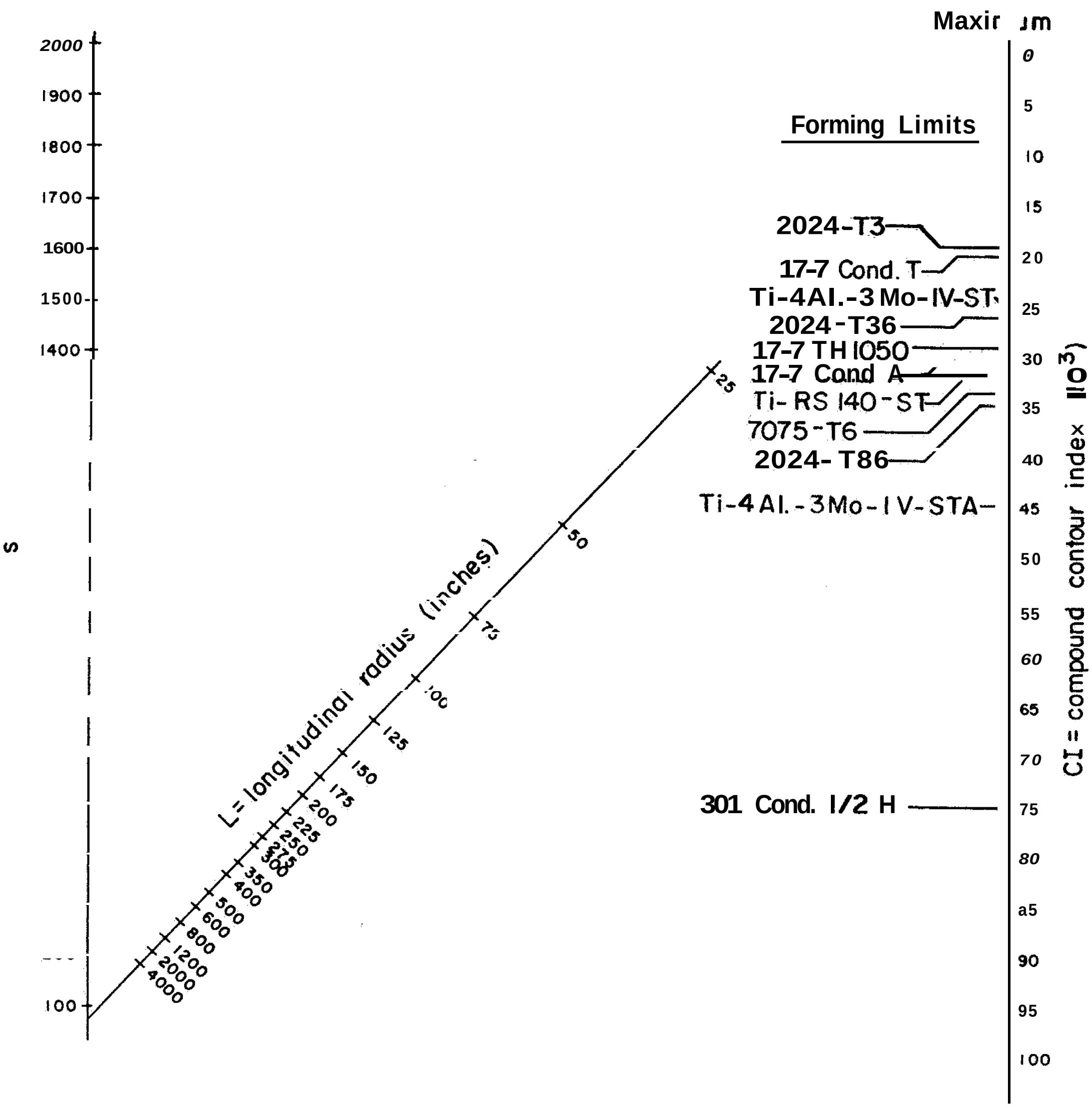


FIGURE **92.** FORMING LIMITS AND COMPOUND CONTOUR INDEX (CI) FOR .040–INCH THICK ALLOYS (Base is 36–inch wide material) **(Ref.** 111)

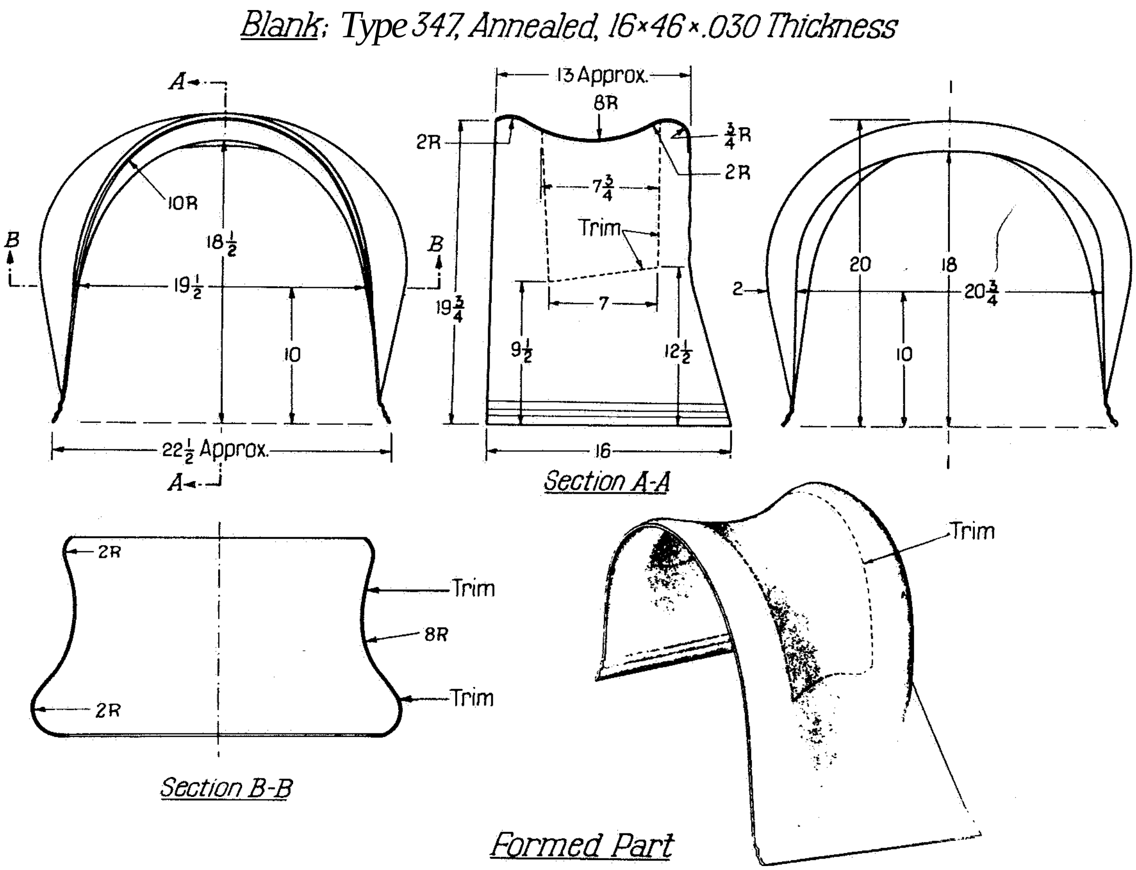


FIGURE **93.** STRETCH FORMING A SMOOTHLY–CONTOURED PART (Ref. 78)

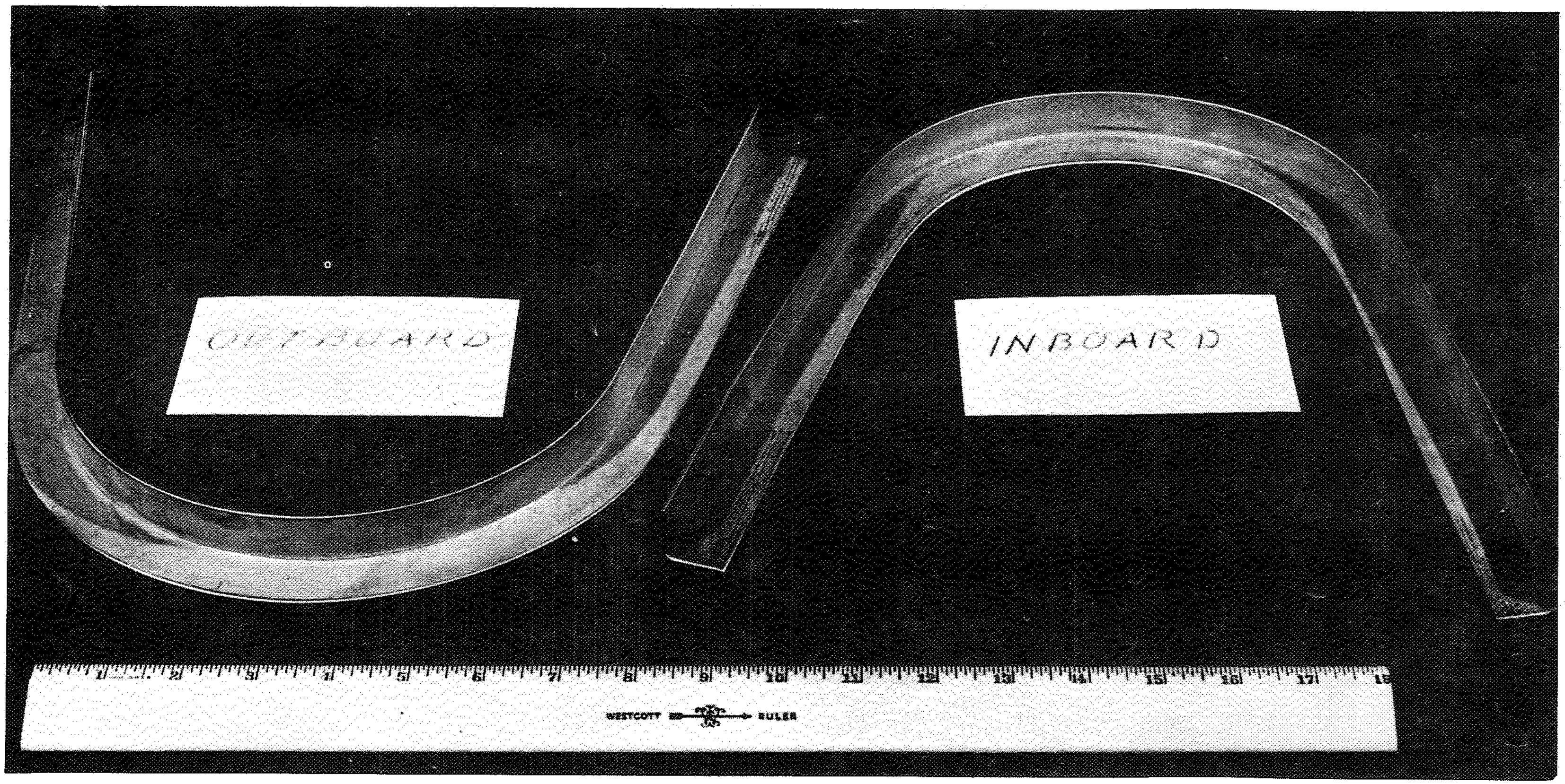


FIGURE 94. STRETCH FORMED ANGLES OF STAINLESS STEEL

Courtesy of North American Aviation, Inc.
Columbus Division

load of 775 pounds. The final "set" load of 1200 pounds resulted in a springback angles of 17 degrees for the outboard part and 11 degrees for the inboard part.

ROLL FORMING AND ROLL BENDING

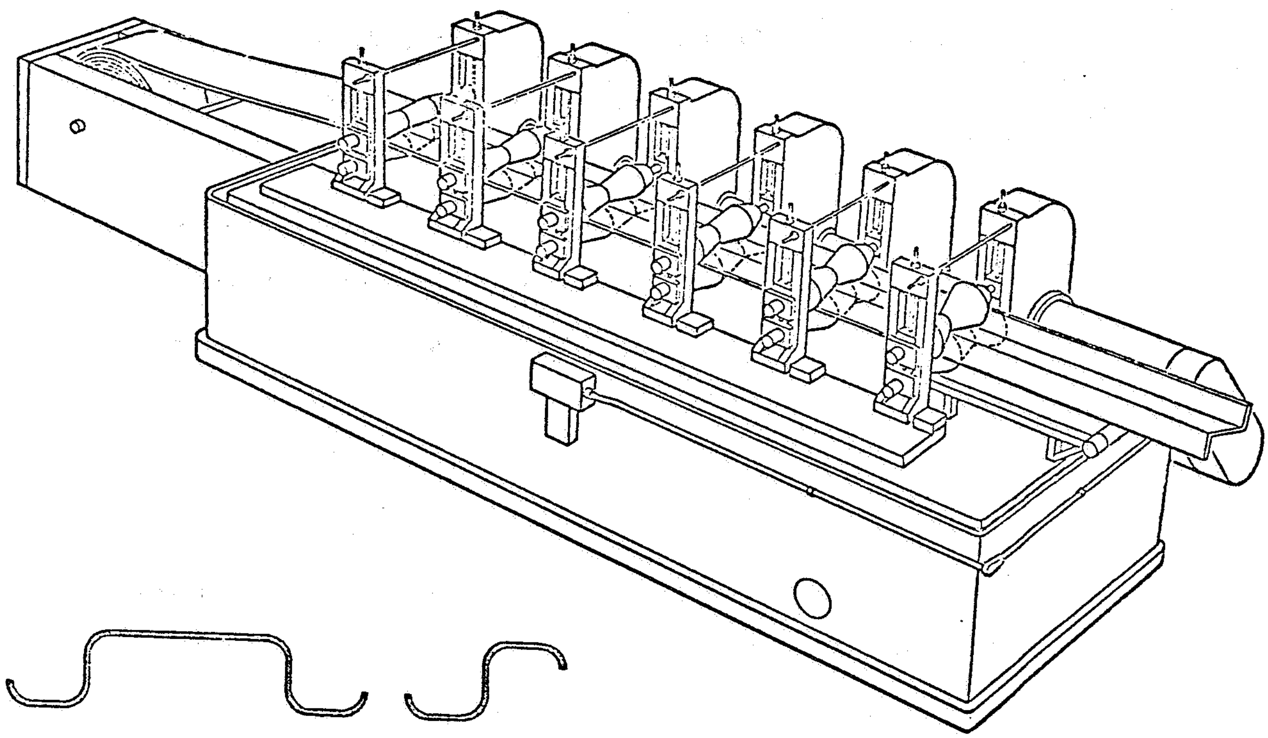
Introduction. This section discusses two types of secondary rolling operations used to change the shape of sheet or strip metal. They are:

(1) Forming by rolls whose contour determine the shape of the product. This process usually employs a sequence of power-driven rolls to produce long lengths of shaped products from sheet or strip.

(2) Bending between two or three cylindrical rolls that can be adjusted to curve sheet, bar, or shaped sections. With this technique, the length of sheet is contr'olled by the width of the rolls.

The first process, roll forming, usually refers to a continuous process performed progressively by a series of contoured rolls in a special machine. With equipment of this kind (Figure 95), which can operate at speeds to 300 rpm, tolerances as small as ± 0.005 inch can be obtained in cold forming. Roll forming is often used to bend strip into cylinders that are butt welded to produce thin-walled tubing with a relatively small diameter. The process is best suited to shapes made in large quantities.

Similar products can be made by drawbench forming and this method is recommended for the harder tempers of austenitic stainless steels such as Types 301 and 302. Drawbench forming involves pulling the strip through a series of heads or stands containing undriven, or idling, rolls similar to a Turkshead. Such methods have been used to produce limited quantities of square pipe and other shapes from the stainless steels. Both methods, roll forming and drawbench forming, are used to



Typical sections

FIGURE 95. SCHEMATIC DRAWING O F ROLL-FORMING MACHINE

Courtesy of North American Aviation, Inc.,
Los Angeles, California.

form the stainless steels into structural hat sections, angles, tee sections, and channels. Normally these operations are performed at room temperature. Parts formed on drawbenches sometimes show excessive twisting and bowing and generally require subsequent contour stretching.

The second process, roll bending, is often used to bend sheet into cylindrical, single-contour shapes that can later be welded to form tube or pipe of rather large diameters. Aircraft producers and fabricators have roll-bending facilities that are capable of contouring flat sheets into cylinders up to about 30 feet long. Facilities capable of bending structural shapes by means of rolls are available and frequently used to produce large-radius bends in channels and other sections used to support skins in aircraft.

Roll Forming. A schematic drawing of a six-stand roll-forming machine is shown in Figure 95. The strip enters from the left, passes through the series of six rolls, and emerges from the machine at the right side as a rolled shape. Sometimes auxiliary equipment for cutting the roll-formed shape to length or for welding and straightening roll-formed tubing is added to complete the production line. Figure 96

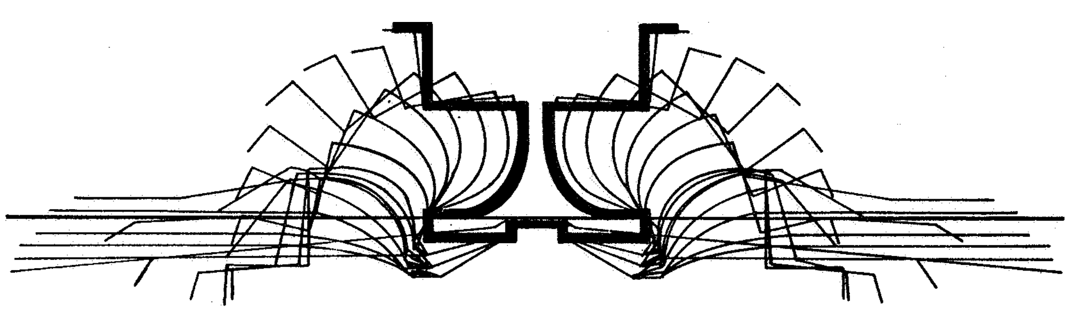


FIGURE 96. A COMPLEX SHAPE MADE FROM STAINLESS STEEL BY ROLL FORMING ON A 20-STATION MACHINE (Ref. 113)

Intermediate forming shapes are shown.

is a sketch that shows the various stages of bending that were used to produce a completed stainless steel shape by roll forming (Ref. 113). In all, 20 roll-forming stages were required.

Roll forming has many advantages over other methods. For example, parts made by roll forming have lower internal stresses than similar parts produced by impact or brake forming. Sometimes parts can be bent to a radius 1T less than the minimum bend radius in brake forming. Since roll forming is a high-speed, fast-production process, man-hour savings may be substantial compared with brake-forming and other competitive forming methods.

Equipment. Equipment for roll forming is available from a number of manufacturers in a range of sizes and capacities. The size and weight of the equipment increases as the maximum sheet thickness increases. The number of roll stands required for a particular application depends on the complexity of the bending required. A machine may consist of from 2 to 20 roll stands. By running machines in tandem, as many as 50 stations have been used (Ref. 113). Relatively simple contours can be produced by using six or less rolls. Equipment manufacturers should be consulted on equipment requirements for specific applications. Table XXXVI lists a number of manufacturers of roll-forming equipment.

Tooling. The rolls used in roll-forming equipment may be made from a variety of materials. For the roll forming of stainless

TABLE XXXVI. MANUFACTURERS OF ROLL-FORMING EQUIPMENT (Ref. 113)

Ardcor Div., Lee Wilson Engineering Co., Wickliffe, Ohio
Dahlstrom Machine Works, Inc., 4229 West Belmont Ave., Chicago 41, Ill.
Flagler Corp., 19321 Filer, Detroit, Mich. 48234
Lockformer Co., 4605 West Roosevelt Rd., Chicago 50, Ill.
McKay Machine Co., P.O. Box 180, Youngstown, Ohio 44501
Michigan Roll Form, Inc., 8952 Hubbell, Detroit 28, Michigan
Rafter Machine Co., Inc., 259 Stephens St., Belleville, N. J.
Rockford Machine Tool Co., Maplewood Div., Rockford, Ill.
Tishken Products Co., Box 3798, Oak Park, Mich. 48237
Yoder Co., 5528 Walworth Ave., Cleveland 2, Ohio

steels, rolls generally are made either of oil-hardened tool steels, high carbon, high-chromium air hardening steels (1 to 2.25 percent carbon, 12 to 13 percent chromium) or case-hardened carbon steels. Rolls are generally hardened in the range of Rockwell 60 to 66 C for use with the stainless steels and often are plated with hard chromium to minimize wear and produce good finishes on the roll-formed parts (Ref. 114). When not plated, they are polished to produce good finishes. Sometimes, for severe forming, roils are faced with bronze to reduce "pick-up". When this is done, the rolls are machined under-size to allow for the application of 1/8-inch minimum thickness of bronze (Ref. 115). In some cases, the last roll may be made of aluminum bronze to minimize marring and scratching of the roll-formed shape. (Ref. 78). Often the roll-formed stock is passed through a straightening die as it emerges from the last roll. Such dies may be made of bronze. Guides are used to direct the strip into the proper position as it encounters the first roll. The use of roller guides minimizes friction thereby reducing scoring and scratching.

Lubricants. A widely used lubricant for roll forming stainless steel is soluble oil diluted with water to concentrations varying between two percent (50:1) and 10 percent (10:1). Such lubricants are easy to remove from the product and are generally satisfactory. When more efficient lubrication is required, 10 percent soap solutions or extreme pressure oils are used to reduce roll wear and provide better surface finishes. Such materials are more difficult to remove. Addition of paraffin oil may be beneficial in some applications. The lubricant may be applied to the stainless steel strip by passing it between wipers .before it enters the first set of rolls or it can be piped to the individual rolls and allowed to flow. At times, sprayed-on plastics are used to reduce scuffing or scratching of the surfaces. Viscous sulfurized-chlorinated fatty oils also are used to reduce scuffing. Suppliers of lubricants should be consulted for their recommendations as to the selection and use of these products.

Material Preparation. The general precautions given in the section on blank preparation should be observed. The stainless steels generally are not as sensitive to the presence of grinding marks and scratches parallel to the length of the strip as are some of the other materials such as the titanium-, nickel-, and cobalt-base alloys.

Roll-Forming Procedures. Shapes such as channels, hat sections, and tubing are being produced routinely from the stainless steels. Procedures and equipment used for the roll forming of carbon steel are used, with modifications, for stainless steels. Welded stainless steel tubing is available in Types 304 and 321 up to 2-1/2 inches in diameter. In Type 347, the maximum size listed by one producer is 2-1/16-inch diameter. Most of the other grades are available in diameters up to 1-1/8 inches. Such materials are roll formed in the annealed condition and welded as an additional step in the continuous production line by equipment such as is shown in Figure 97. The 12-stand roll former at the right produces tube of the desired size from strip and is then automatically welded, trimmed, sized, straightened, and cut off. The number of rolls used for roll forming depends on the strength and work-hardening rate of the particular alloy involved. The critical step that limits the production of tubing in many cases is the welding operation since the roll-forming equipment can produce tubing

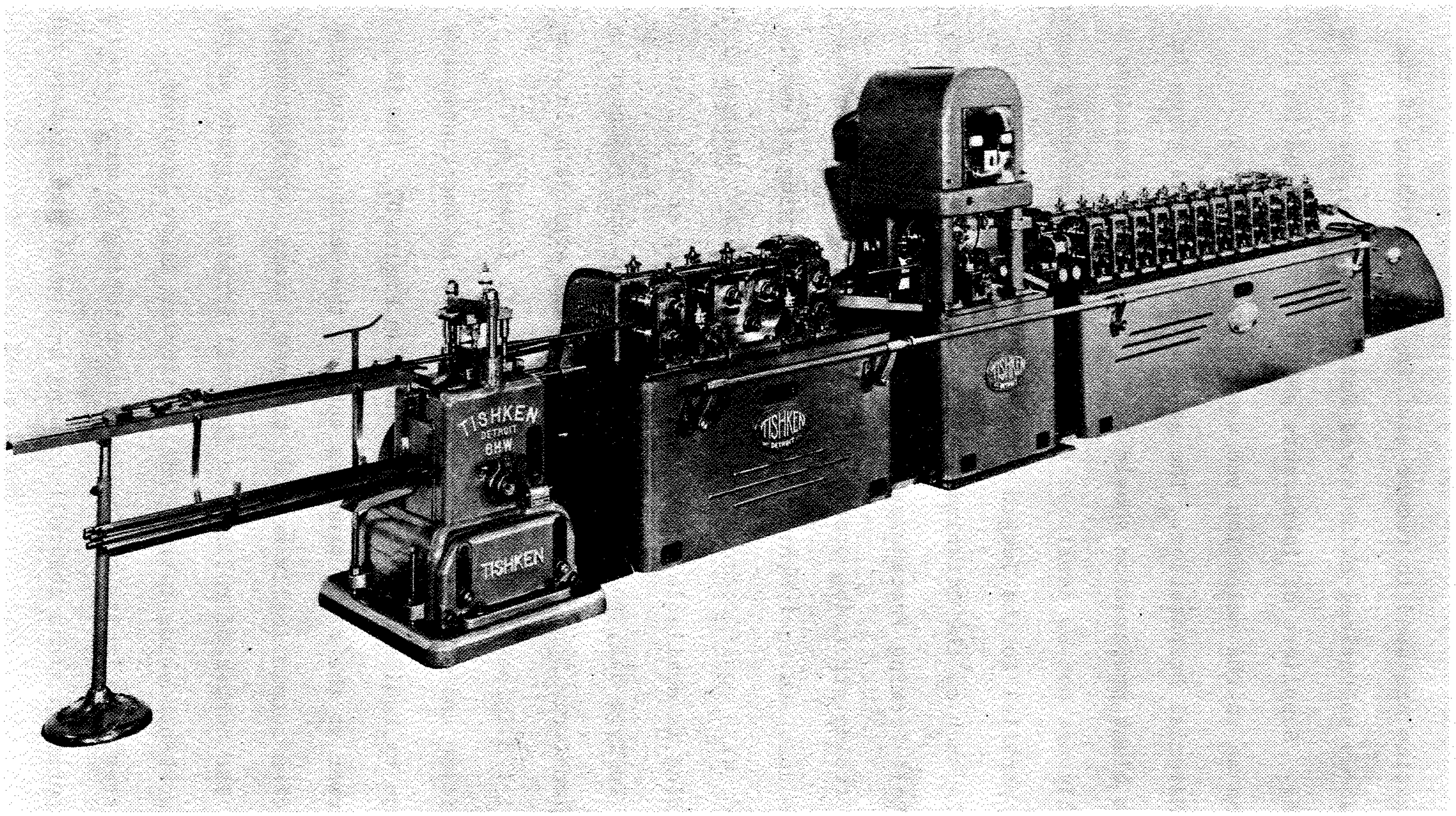


FIGURE 97. PRODUCTION LINE FOR PRODUCING WELDED TUBING

Courtesy of Tishkin Products Company,
Detroit, Michigan

for welding speeds up to about 200 feet per minute. Generally automatic welders have not yet achieved such speeds.

The limiting bend radius of the material is an important parameter in determining the number of rolls that must be used in forming a particular shape. Such data coupled with experience gained in working with similar materials enable the successful production of shapes by roll forming of strip stock.

Post-Forming Treatments. After forming, sections are straightened and sheared to desired lengths and the forming lubricant is removed. This may be done by rinsing or wiping with solvents, vapor blasting individual pieces, or by using a suitable cleaning-bath or pickling cycle. Hydrogen pickup during pickling normally is not a problem with the stainless steels. Inspection for cracks is done by the fluorescent die-penetrant method and/or visually under a low-power microscope.

Roll Bending. Roll bending is an economical process for producing single-contoured skins from sheet materials. In addition to bending flat sheet into cylindrical contours, the linear-roll-bending technique also is commonly used to curve heel-in and heel-out angle and channel sections, and tubes. The sections may initially have been produced by roll forming, on a press brake, or even by extrusion. In addition to roll bending, the final contour of a channel or other section also might be produced by stretch-forming techniques. Curved angle sections may be produced by bending channel sections to the desired contour and then splitting the channels to form the angle sections. In general, roll bending does not have the accuracy of a die-forming process.

Where the accuracies, workpiece shapes, and diameters allow the use of roll bending, it is one of the most economical processes available with more than 50 percent of the total power used going directly into the workpiece (Ref. 117).

Figure 98 is a sketch of a typical setup for the linear roll bending of channels (Ref. 69). The upper roll in the pyramid-type roll configuration can be adjusted vertically as shown in the sketch and the radius of the bend is controlled by the adjustment of this roll. The geometry for heel-in and heel-out channels also is shown in the sketch. The roll bending process is limited in diameter by the size of the rolls used as well as the shape of the section which may cause deformation on small diameter work (Ref. 116).

Roll bending is a process that depends greatly on technique. Premature failures will occur if the contour radius, R, is decreased in increments that are too severe. On the other hand, too many passes through the rolls may cause excessive work hardening in the channel. An operator usually must form several trial parts of a new material in order to establish suitable conditions.

Equipment. Linear-roll-bending equipment generally is quite simple. One common type of equipment utilizes a pyramidal design both in vertical and horizontal machines. Three rolls are used, two lower rolls of the same diameter placed on fixed centers at the same elevation, and a third or upper roll placed above and between the lower rolls. The upper roll may be adjusted vertically to produce different curvatures, and all three rolls are driven. Such equipment also can be used for making helical

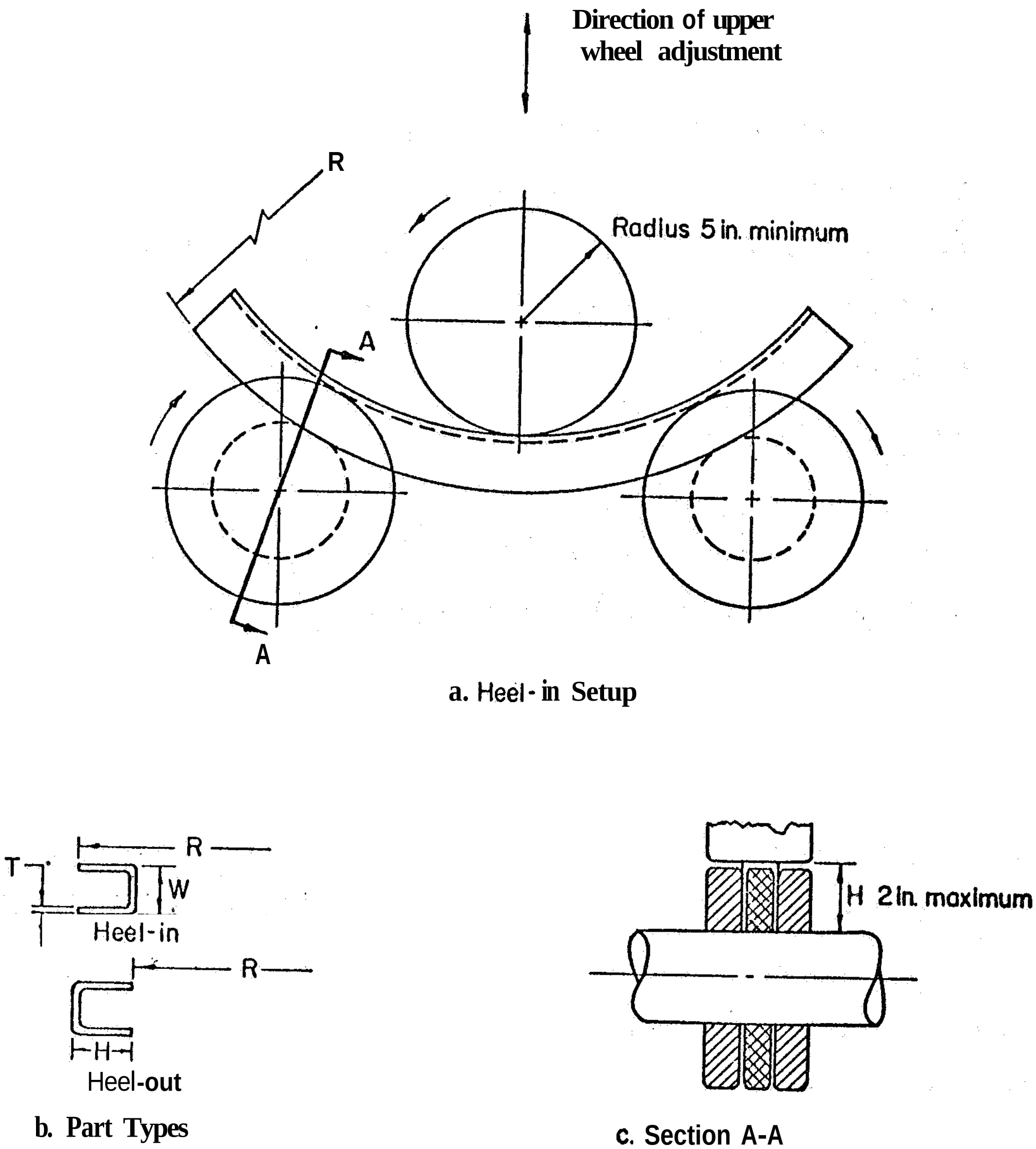


FIGURE 98. PART TYPES AND SETUP FOR ROLL BENDING (Ref. 69)

coils from angles and channels, flat sections edgewise, and pipes by changing the rolls to the appropriate design.

Another type of equipment for bending shapes is the pinch-type roll bender, so called because its two main rolls actually pinch the stock between them with sufficient pressure to pull the material through against the resistance of the bending stress. This equipment contains four rolls, as shown in Figure 99. The upper and lower main rolls are driven by a train of gears, and the lower roll, directly beneath the upper one, is adjustable vertically. The large rolls support the flanges of the shape during bending and tend to minimize buckling by supporting the sides of the flanges. The small idler rolls can be adjusted up and down, as shown in Figure 99 for changing the bend radius.

Table XXXVII gives information on a number of roll-bending machines produced by one manufacturer. The pinch-type machines have smaller capacities than the pyramid-type rolls and are largely used for relatively light aircraft parts.

In addition to rolls for contouring channels, angles, tubes, and other shapes, equipment also is available for bending sheet sections into shapes. Such equipment is available in most shops and is relatively inexpensive and simple to operate. Figure 100 is a view of the roll-bending equipment at the Columbus Division of North American Aviation. Three bending rolls of varying size are shown, the largest of which is about 15 feet long and the smallest about 4 feet long. The equipment is used to bend such aircraft parts as wing-leading edges, doors, aircraft skins, etc. One characteristic

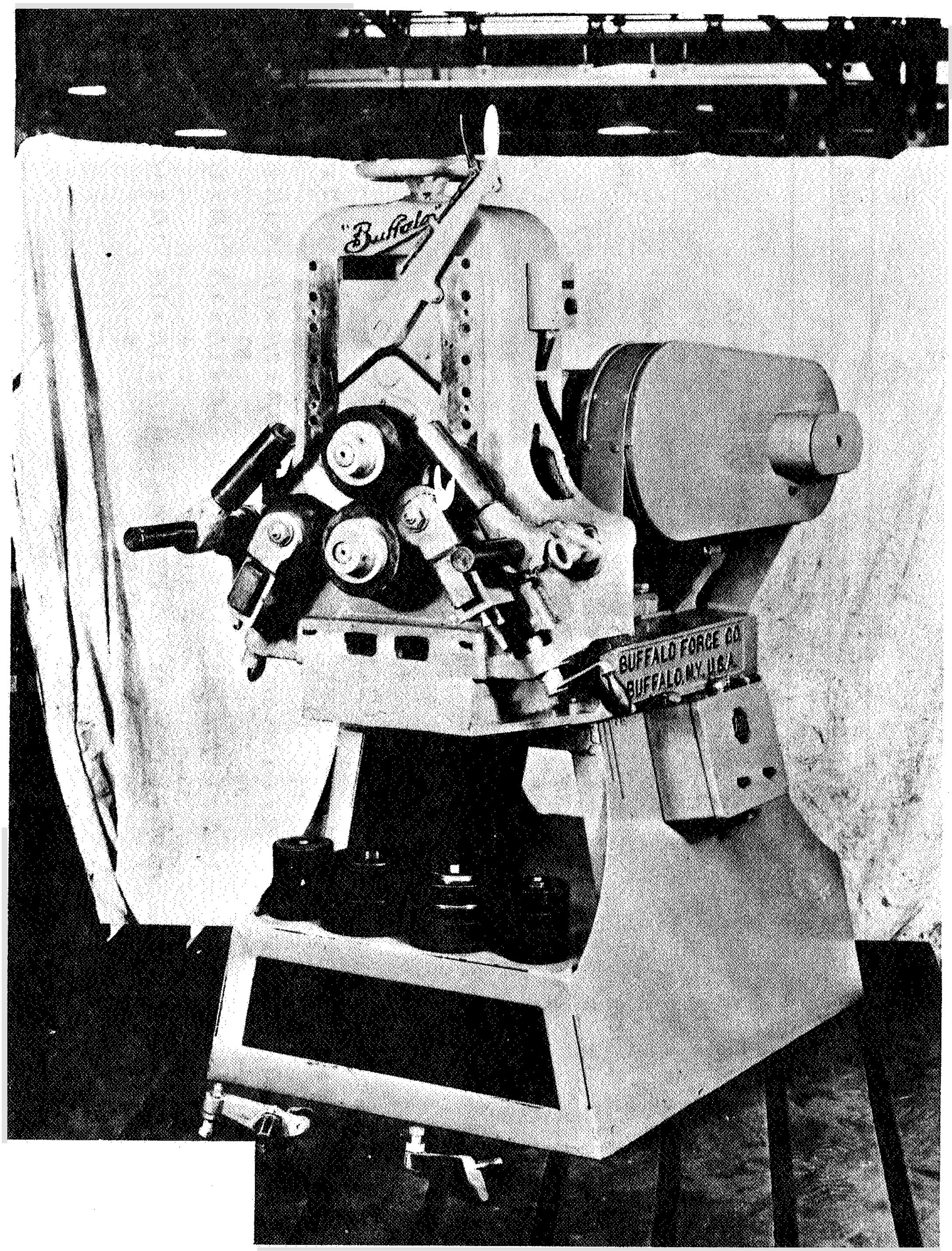


FIGURE 99. CONFIGURATION OF ROLLS IN AIRCRAFT PINCH-TYPE ROLL-BENDING MACHINE

Courtesy of Buffalo Forge Company, Buffalo, New York

TABLE XXXVII. PERTINENT DATA ON ROLL-BENDING MACHINES PRODUCED BY ONE MANUFACTURER[(a)]

	Vertical Bending			Vertical Pinch	
Type Model No.	1/2	1	2	00	0
Centers Lower Rolls	8	12	18	--	--
Diameter-Angle Rolls, in.	7	11-3/8	16-1/2	3-1/4	5-1/4
Rolls, rpm	18	11.2	7	72.5	40
Feet per Minute	33	34	31	65	60
Size Motor, hp	5	10	20	1-1/2	2
Motor Speed, rpm	1800	1800	1800	1800	1800
Diameter, Upper Shaft, in.	3	4-3/4	6	1-5/8[(b)]	2-1/2[(b)]
Diameter, Lower Shaft, in.	2-1/2	4	5	1-5/8	2-1/2
Gear Ratio	97	156	250	24	45
Length, in.	47	61	82	34	42
Width, in.	60	62	78	30	36
Height, in.	41	58	65	34	50
Weight With Motor, lb	2300	6300	13,200	875	1175
		Capacities (Typical)			
Angles, Leg Out, in.	2 x 2 x 1/4	3 x 3 x 3/8	4 x 4 x 5/8	7/8 x 7/8 x 1/8	1-1/2 x 1-1/2 x 3/16
Minimum Diameter, in.	20	24	40	20	24
Angles, Leg-In, in.	1-1/2 x 1-1/2 x 1/4	2-1/2 x 2-1/2 x 3/8	3-1/2 x 3-1/2 x 5/8	3/4 x 3/4 x 1/8	1-1/4 x 1-1/4 x 3/16
Minimum Diameter, in.	18	30	48	30	48
Smallest Angle, Leg-Out, in.	3/4 x 3/4 x 1/8	1-1/2 x 1-1/2 x 3/16	1-1/2 x 1-1/2 x 1/4	1/2 x 1/2 x 1/8	1/2 x 1/2 x 1/8
Minimum Diameter, in.	8	13	18	4	6
Smallest Angle, Leg-In, in.	3/4 x 3/4 x 1/8	1-1/2 x 1-1/2 x 3/16	2 x 2 x 1/4	1/2 x 1/2 x 1/8	1/2 x 1/2 x 1/8
Minimum Diameter, in.	9	14	24	6	7
Channels, Heel-In, in.	3 - 4#	5 - 11-1/2#	9 - 20#	--	--
Channels, Heel-Out, in.	--	5 - 9#	7 - 14-3/4#	--	--
Minimum Diameter, in.	16	18	48	--	--

(a) Data taken from Bulletins 326/F and 352/G of the Buffalo Forge Company, Buffalo, New York.
(b) At roll.

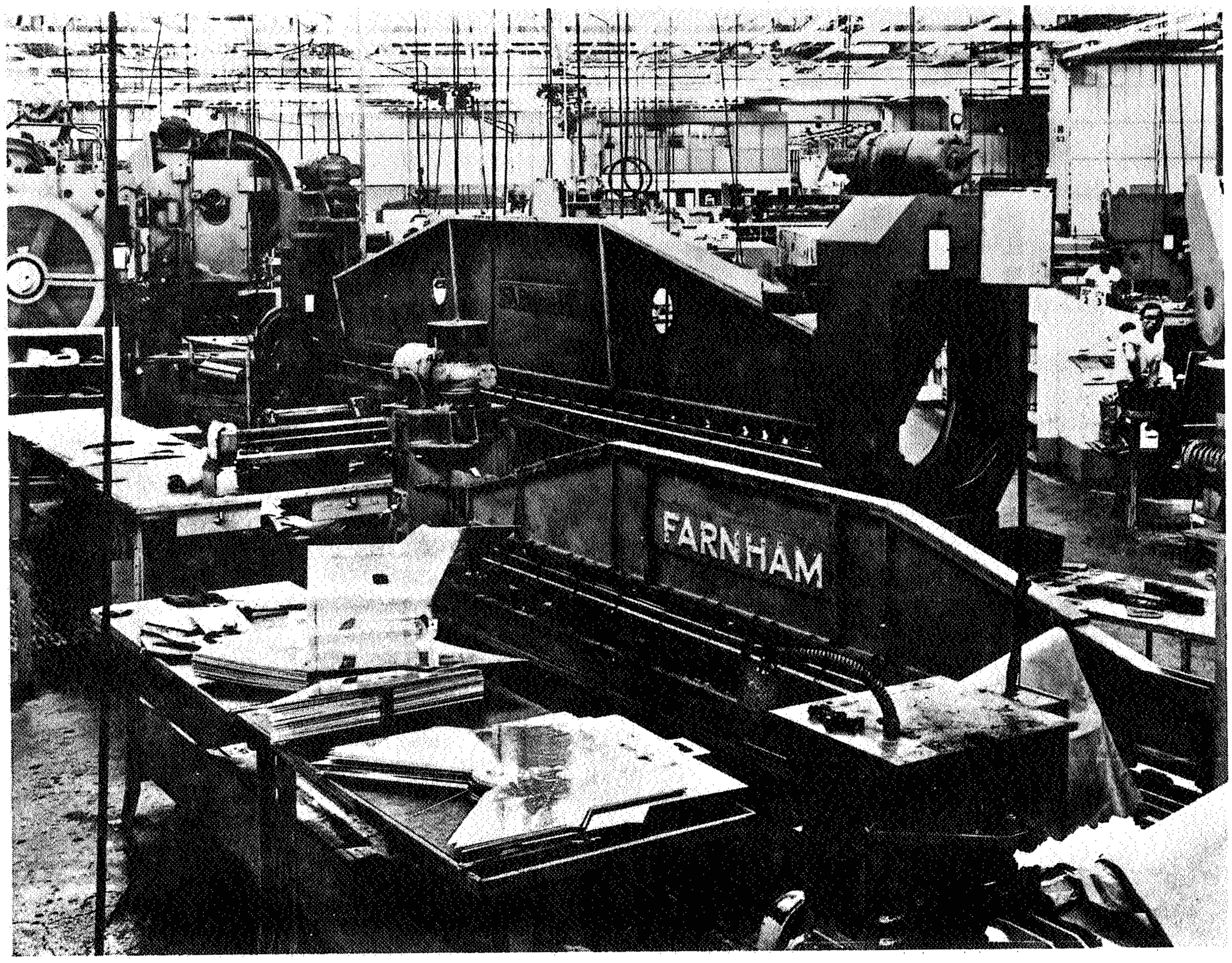


FIGURE 100. PHOTOGRAPH SHOWING THREE SIZES OF SHEET ROLL-BENDING EQUIPMENT RANGING IN LENGTH FROM 4 TO 15 FEET

Courtesy of North American Aviation, Inc., Columbus, Ohio.

of this type of equipment is that the diameter of the rolls is rather small, frequently 1-1/2 to 2 inches. The rolls are backed up by a series of smaller rollers to prevent bending deflections during rolling.

Another type of roll-bending equipment is made specifically for producing cylindrical and other closed sections from sheet. Such equipment is called a slip-roll former or bender, and these machines feature pinch-type rolls. They are very versatile and adaptable to many operations. The equipment uses larger diameter rolls than the sheet-forming rolls just described, and is characterized by the ability of the upper roll to swing open at one end (outboard bearing) to permit easy removal of the completed cylinder or other closed shape without distortion. In general, power ratings of bend rolls used for stainless steels should be about 50 percent greater than those required for carbon steel.

Tooling. Rolls for linear contour bending of shapes have been made from a variety of materials. Sometimes the rolls are made from hard rubber, urethane plastic, or beryllium copper for use at room temperature with relatively soft materials or for short runs with harder materials. Such soft rolls minimize scratching and marring of sheet during bending. Rolls on roll-bending machines are commonly made from tool steels. These may range from Grade 0-2 for room-temperature application to Grades H-11 and H-13 for elevated-temperature use. Rolls for sheet-roll-bending machines, such as are shown in Figure 100, may also be made of low-alloy steels such as Grade 4130 with flame or case-hardened surfaces. The surfaces usually have a hardness of about 50 R_C

Lubricants. Lubricants are almost never used for the roll bending of stainless steel sheet into tubular or other similarly shaped products using equipment of the type shown in Figure 100. However, for the cold or warm roll bending of shapes such as tubes, angles, and channels using equipment of the type shown in Figure 99, lubricants are almost always required. Fluids such as mineral oil, castor oil, lard oil, and mixtures of mineral oil and water function both as lubricants and coolants. When the forming forces are high, lubricants with higher viscosities give best results. In general, the exact composition of the lubricants are considered to be propietary. Solid lubricants often are used for roll forming at elevated temperatures. These would include graphite, molybdenum disulfide, metal powders, and oxides. Lubricants for cold and elevated-temperature roll forming are applied by spraying, dipping, brushing, or wiping.

Limits for Channels. Transverse buckling and wrinkling, respectively, are the common modes of failure in bending heel-out and heel-in channels. Basic equations for predicting the bending behavior of channels of various alloys in linear roll bending were developed by Wood and his associates (Ref. 69). The principal parameters, shown in Figure 101 are the bend radius, R, the channel height, H, the web width, W, and the material thickness, T. The following three equations were developed for heel-in channel to construct a formability curve of the type shown in Figure 101.

The equation for the inflection line is

$$\frac{H}{R} = 0.0146 \left(\frac{H}{T}\right)^{1/2} \qquad (28)$$

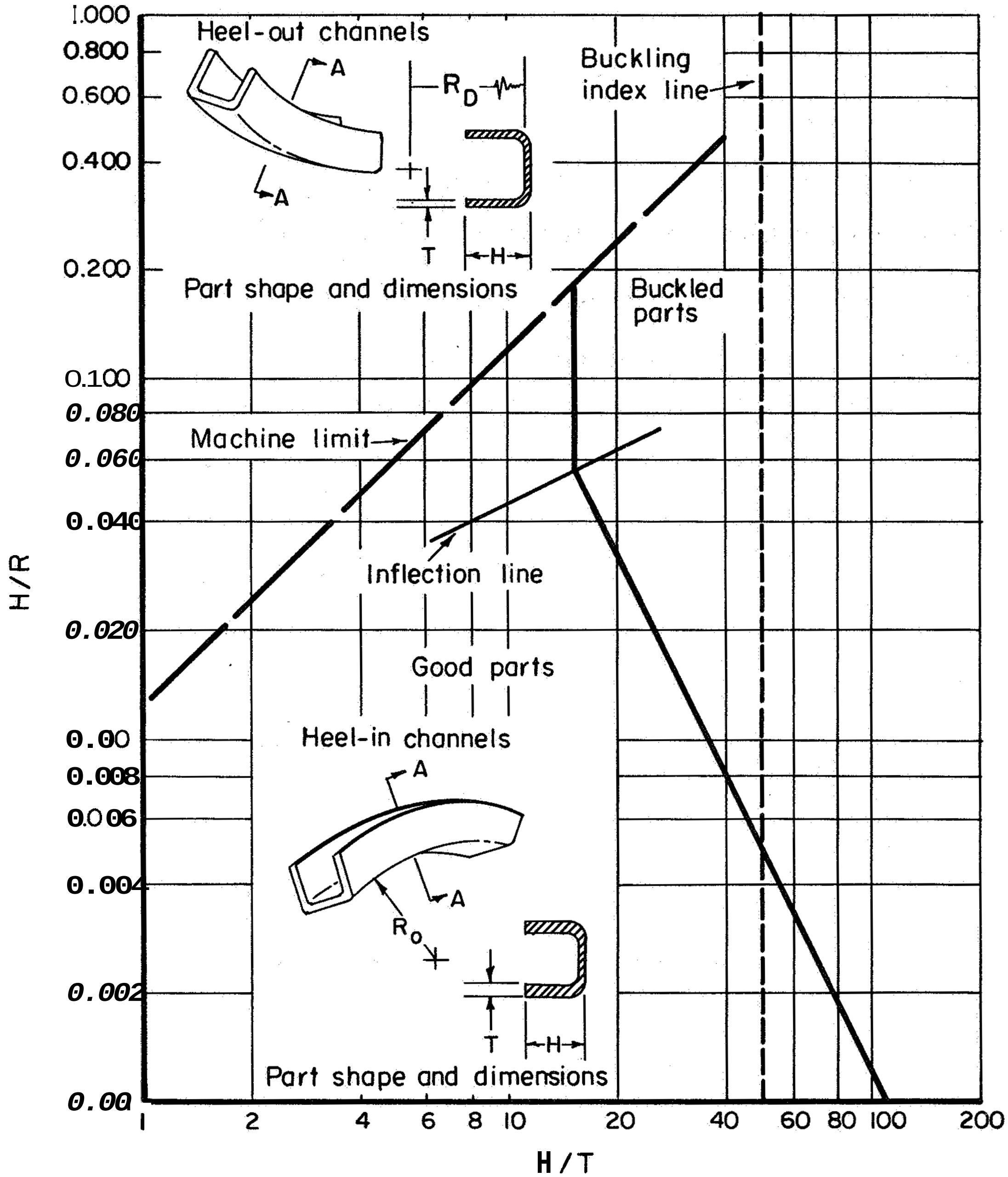


FIGURE 101. TYPE OF CURVES DEVELOPED BY WOOD AND HIS ASSOCIATES GIVING LINEAR ROLL-BENDING LIMITS FOR HEEL-IN AND HEEL-OUT CHANNELS (Ref. 169)

The equation for the elastic buckling line below the inflection 1ine

$$\frac{H}{R} = \frac{E_t}{S_{ty}}\left[\frac{0.025}{\left(\frac{H}{T}\right)^2}\right] \quad (29)$$

The equation for the buckling line above the inflection line is:

$$\frac{H}{T} = \left[1.713\,\frac{E_t}{S_{ty}}\right]^{2/5} \quad (30)$$

Similar equations were developed for the linear roll bending of heel-out channels.

The equation for the inflection line is

$$\frac{H}{R} = 0.0209\left(\frac{H}{T}\right)^{112} \quad (31)$$

The equation for elastic buckling below the inflection line is

$$\frac{H}{R} = \frac{E_c}{S_{cy}}\left[\frac{0.02116}{\left(\frac{H}{T}\right)^2}\right] \quad (32)$$

The equation for buckling above the inflection line is

$$\frac{H}{T} = \left[1.01\,\frac{E_c}{S_{cy}}\right]^{2/5} \quad (33)$$

In addition to the values defined above, the following values also are required to solve these equations:

E_t and E_c = moduli of elasticity in tension and compression, respectively. These values are very nearly equal for practical purposes

S_{ty} = tensile yield strength

S_{cy} = compressive yield strength.

The tensile yield strength is a characteristic of sheet that is commonly measured to define the strength of the sheet. Typical room-temperature values of tensile yield strength and elastic modulus are found in the literature. These values may be used to calculate the E/S_{ty} ratios required to solve Equations **(29)**, **(30)**, **(32)**, and **(33)**. It is here assumed that the compressive yield strengths, S_{cy}, required for Equations **(32)** and **(33)**, will not differ significantly from the tensile yield strengths given so that the values may be used for both cases.

The compressive yield strength is a property that commonly is not determined for sheet materials. However, ASTM standards have been agreed upon for performing this test both at room and elevated temperatures. Although the elastic modulus in compression is generally slightly higher than that in tension, they are usually considered to be equal €or all practical purposes.

In addition to the limitation on the production. of suitable roll-bent parts by both buckling and splitting of the channel, another limiting parameter is the mechanical limit of the bending machine. This limit depends on the thickness of the material, the maximum section height that the tooling will accommodate, and the minimum part radius that the machine and tooling will produce. If any of these variables are changed, the position of the machine limit line also will be changed. Needless to say, the use of other types of roll-bending equipment will change the position of the machine limit line and also that of the buckling limit line of the alloy. Therefore, it should be emphasized that the roll-bending limits derived using Wood's equations (Equations 28 through 33) are valid only when used with a pyromid-type, three-roll bending machine. The added support provided by pinch-type rolls would probably move the buckling limit line to the right (Figure 101).

Graphs of the type shown in Figure 101 can be constructed from experimental values of E/S_{ty} and E/S_{cy} for any of the stainless steel grades. Although typical values of elastic modulus and tensile yield strength can be found in the literature it is desirable to obtain these data from experiments with the particular material that is to be bent.

Roll Bending of Sheet. Stainless steel sheet has been contoured by rolling but no systematic study such as that conducted by Wood, et. al., for the roll bending of channels has been reported.

The roll-bending equipment for contouring sheet is rated on the bending of mild steel or an aluminum alloy. The yield strength of mild steel is about 50,000 psi and that of stainless steel alloys about 73,000 psi. The yield strength of the annealed stainless steels lie between about 32,000 and 90,000 psi. Thus, they would be expected to roll bend about like the mild steels.

When it is necessary roll bend a material that has a yield strength widely different from that for which the machine is rated, the capacity can be determined on the basis of the square of the thickness.

Thus, if a given piece of equipment is capable of bending 0.250-inch-thick aluminum plate (73,000 psi yield strength), it probably would have the capacity to bend about 0.338-inch-thick austenitic stainless steel plate (40,000 psi yield strength). Conversely, proportionately longer lengths of 0.250-inch-thick austenitic stainless steel plate could be bent than would be possible with the aluminum alloy plate.

TUBE FORMING

Stainless steel tubing has been used extensively in modern aircraft to transmit gases and liquids under different conditions of temperature and pressure. These aircraft tubing applications include hydraulic lines and ducts for air and hot exhaust gases. In hydraulic lines, the tubes are small in diameter and have heavy walls; for ducting and engine exhaust, the tubes are relatively large in diameter and have thin walls.

Since the ducting and hydraulic lines are installed in the aircraft only after the structural members are in place, it is necessary to produce single and complex bends with both the thin-wall ducting and also the heavier wall hydraulic lines. Some of the techniques used to bend the stainless steels are discussed in this section.

In addition, methods of forming stainless steel tubing by means of an internal pressure to force the tube outward against a restraining die also will be described. Such methods have been used not only to produce single-piece tubular structures which replace welded parts made from a number of pieces but also to reproduce intimate surface details on the formed part.

Tube Bending. The four major methods in general use for bending tubes are: (1) ram or press bending, (2) roll bending, (3) compression bending, and (4) draw bending. These are depicted schematically in Figure 102. Ram or press bending is accomplished by placing the tube between two supports and pressing the ram and tube between the supports, thus forcing the tube to bend around the ram. Roll bending is accomplished by passing the tube through a suitable series of grooved, power-driven rolls. In compression bending, both the tube and the die are stationary and a wiper die is utilized to wrap the tube around the stationary bend

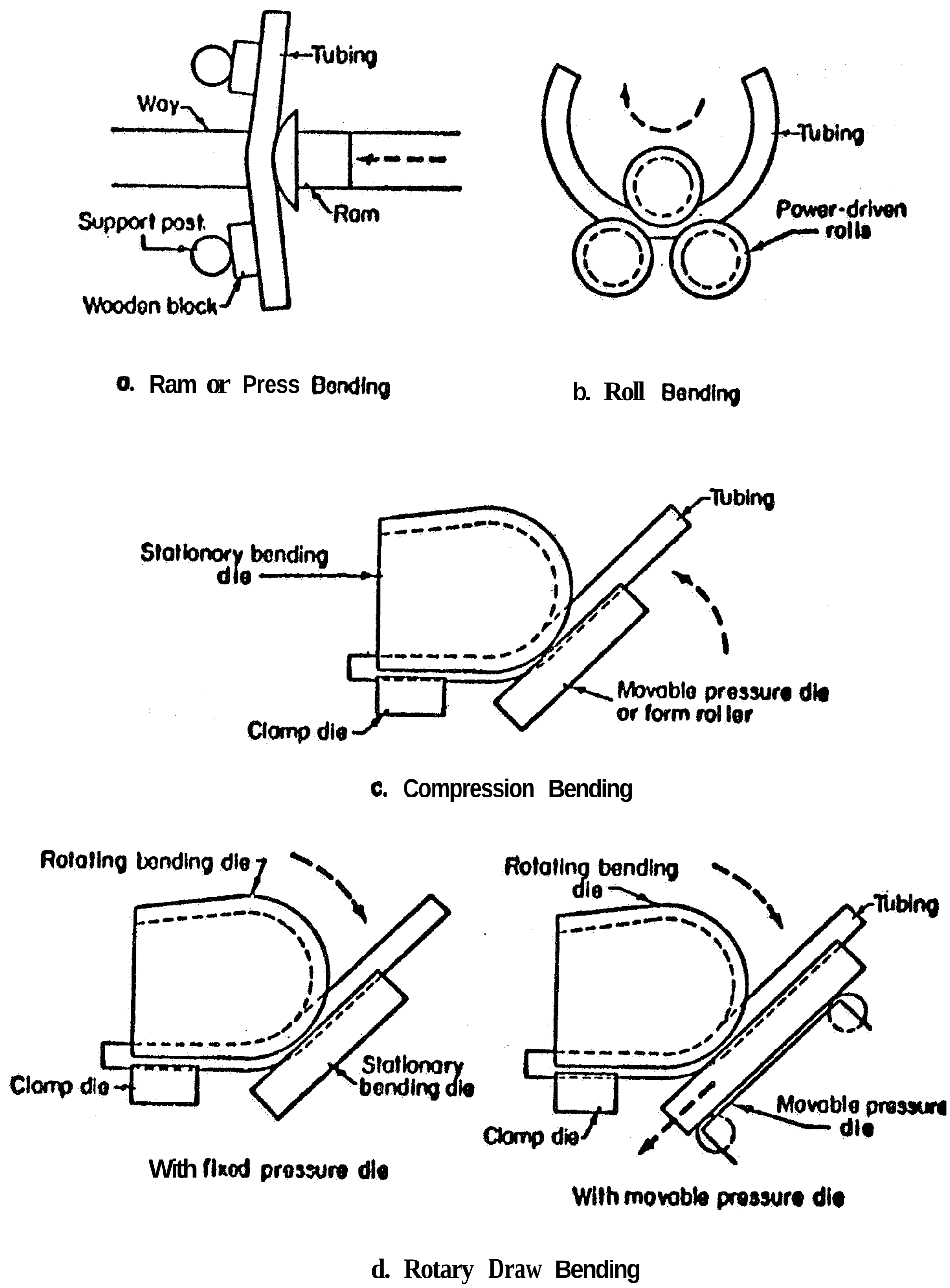


FIGURE 102. METHODS OF TUBE BENDING (Ref. 117)

die. The first three methods are used for heavy-wall tubing or tubes filled with a matrix material but are likely to cause thin-wall tubing to wrinkle, fracture, or even collapse. They are generally limited to forming generous bend radii usually more than five times the tubing diameter. The fourth method, draw bending, is used to bend thin-walled tubing and to obtain bend radii as small as 1.5 D. The tube is confined during bending, and is supported internally by a flexible mandrel.

Each method has special limitations that often control the success or failure of the operation. Generally speaking the processes can be used for the operations shown in Table XXXVIII. Figure 103 shows the various stainless steel tube sizes that can be bent by the different tube-bending processes.

TABLE XXXVIII. LIMITS OF VARIOUS TUBE-BENDING PROCESSES (Ref. 117)

Bending Process	Types of Bends Usually Accomplished	Maximum Angle of Bend, degrees
Ram or press	Single bends Tube straightening	<120
Roll	Circular Spirals Helical coils	360
Compression	Single bends	<180
Rotary draw	Single Multiple Compound	180

Aircraft and missile producers often provide guides in their manufacturing manuals to assist engineers and designers in selecting the

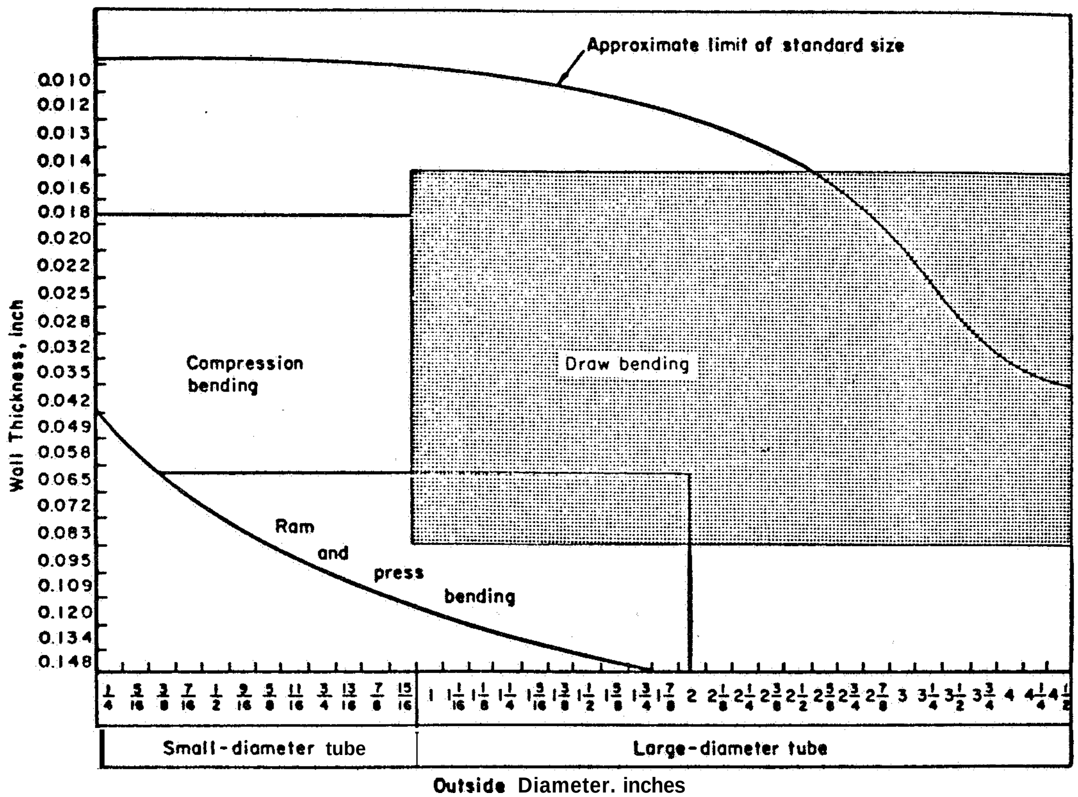


FIGURE 103. AREAS OF SUITABILITIES FOR VARIOUS BENDING PROCESSES BASED ON STANDARD TUBING SIZES OF STAINLESS STEEL (Ref. 117)

proper type of tool for a given material type and bending specification.

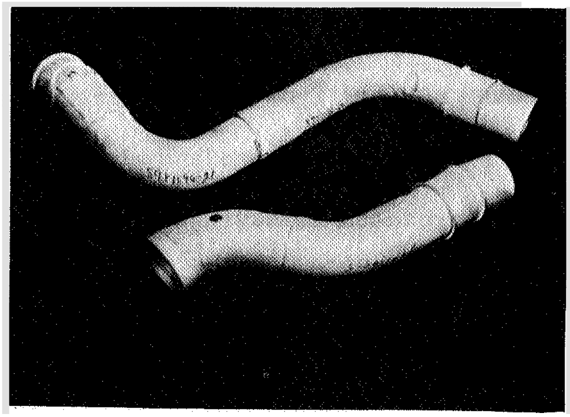
Figure 104 illustrates an engine exhaust stack of Type 321 stainless, 2-5/8-inch outside diameter x 0.065-inch wall, that is made by bending straight tube section. The one piece construction results in savings since special trimming, welding, and weld cleanup procedures are eliminated. A better quality exhaust stack was obtained by utilizing the tube bending procedure in addition to the saving of material.

An interesting and new experimental technique for bending tubing was recently developed at Battelle Memorial Institute. The process consists of filling the tube with a low-melting-point alloy and applying an axial load to the rube forcing it around a bend of the desired contour in a closed die. AM-350 tubing in the CRT condition was bent 90 degrees with a bend radius of 1 D measured to the centerline of the tube. The tube had 1/2-inch diameter with a 0.010-inch-thick wall. After forming, the wall thickness at the outer fibers was found to have decreased only 5 percent while the inner wall had increased in thickness by approximately 50 percent. Figure 105 shows one of the AM-350 tubes that was formed by this method along with half of the forming die. These techniques may also be used in bending the regular types of stainless steel.

Equipment. Stainless steel tubes are bent in commercially available equipment. The diameter of the tube dictates the equipment size, and one equipment manufacturer* supplies aircraft tube-bending equipment in the following sizes:

Bender Model No;	Maximum Tube Diameter, in.
3A	2-1/2
4	3 to 4
8A	4-1/2 to 6

* Pines Engineering Company, Inc., Aurora, Illinois



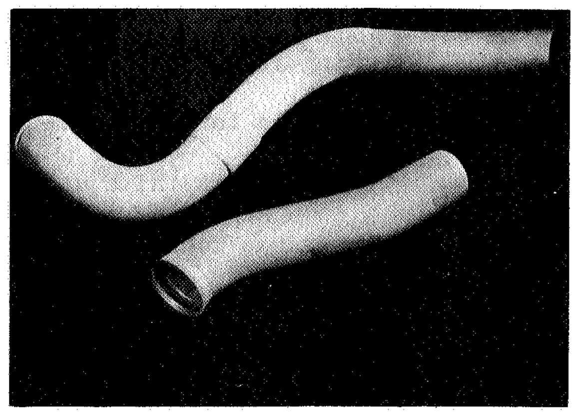


Photo G96535

(a) Welded Construction

Photo G96536

(b) One-Piece Construction by Tube Bending

FIGURE 104. ENGINE EXHAUST STACK OF TYPE 321 STAINLESS STEEL

Tube 2-5/8-inch outside diameter x 0.065-inch wall bent to form one piece unit[(b)]; formerly made by welding[(a)].

Courtesy Grumman Aircraft Engineering Corp., Bethpage, Long Island, New York.

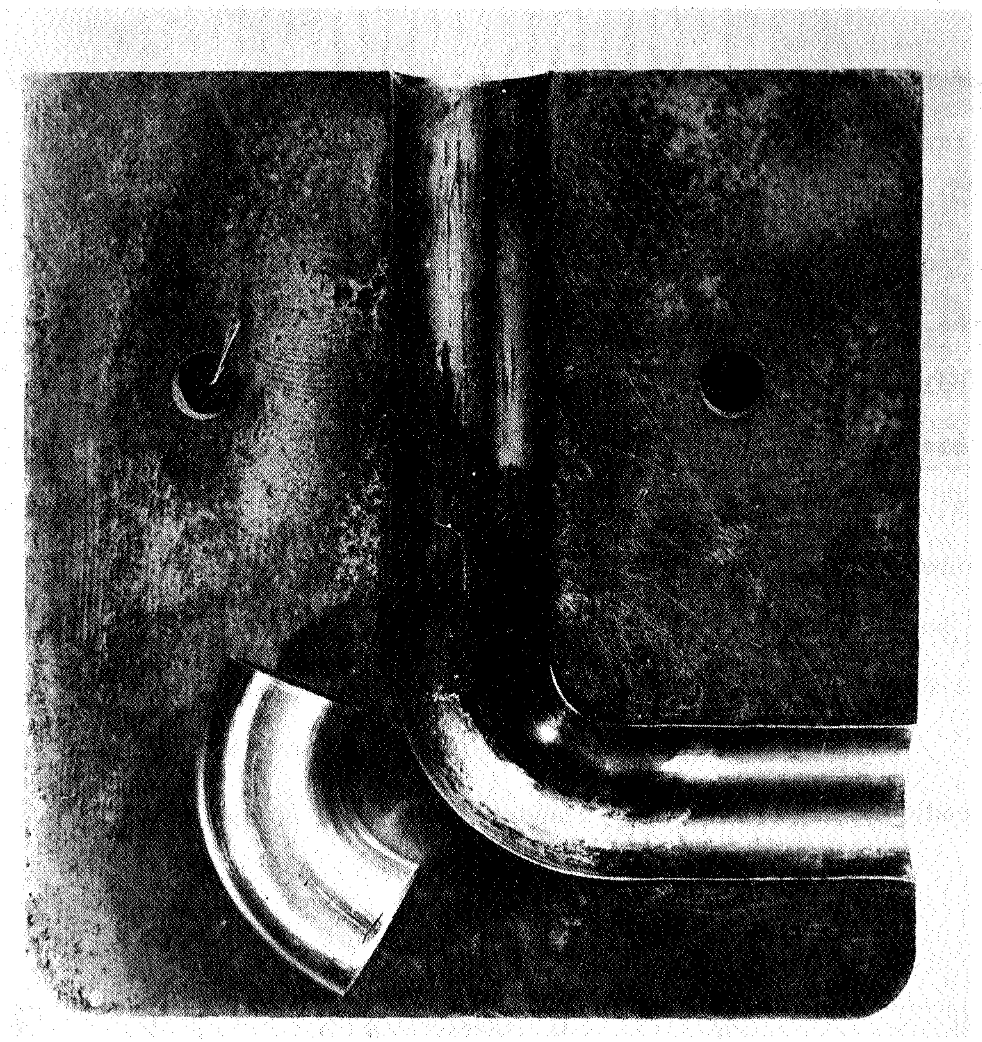


FIGURE 105. ELBOW OF AM-350 STAINLESS STEEL FORMED BY FORCING STRAIGHT 1/2-INCH-DIAMETER TUBING AROUND A BEND IN A CLOSED DIE

Courtesy of Battelle Memorial Institute, Columbus, Ohio.

Other producers of aircraft tube-bending equipment produce machines with similar capacities. Equipment for bending thin-wall tubing must be in good condition; spindles should have no more than 0.0005-inch total runout (Ref. 118). A full complement of machine controls is essential.

Numerically-controlled tube benders are being used extensively by the aircraft industry today.

Tooling. SAE 4340 steel heat treated to Rockwell C 45-48 is adequate for the pressure die because it does not slide against the tube. The wiping die and mandrel that are subjected to sliding friction should be made from aluminum bronze (Ampco 21). For bending thin-wall tubing, the bend die, wiper die, pressure die, mandrel, and clamp die must all be made to close tolerances (Ref. 118). Follower blocks with Teflon inserts have replaced highly polished chromium-plated finishes in some applications. These Teflon inserts not only are less expensive but have eliminated scoring of the tubes during bending (Ref. 119).

Figure 106 shows five basic types of mandrels that are used in bending tubing (Ref. 120). Mandrels are made of tool steel,

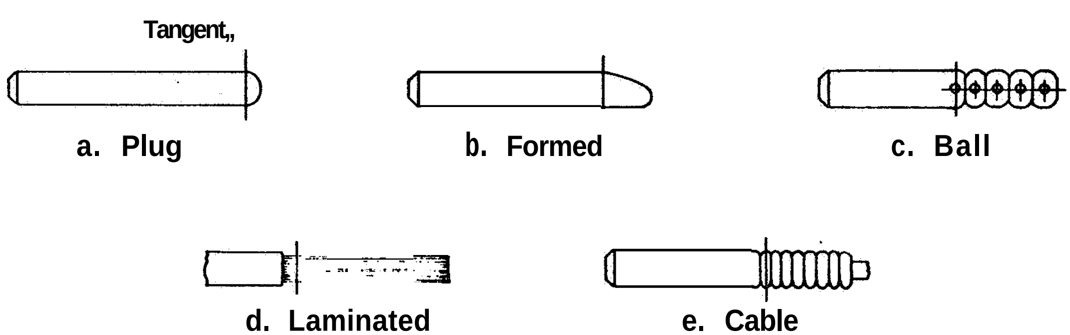


FIGURE 106. FIVE BASIC TYPES OF MANDRELS USED FOR TUBE BENDING (Ref. 120)

case-hardened steel, chromium-plated tool steels, and bronze. Ampco bronze mandrels are preferred for bending stainless steel tubes because they are resistant to galling and scoring with or without lubrication.

Tube Preparation for Bending. Tubes straight within 0.030 inch per foot give good results and are normally purchased to that specification. Straightening tubes prior to bending can reduce the elongation limits of the material by as much as 20 percent. Annealing after straightening or welding may cause problems if the tube warps during the annealing operation.

The diameters of the tubes to be bent must be held within +0.0025 to 0.007 inch and the ovality should be within 6 percent of the nominal tube diameter. These rather close tolerances are necessary to insure proper confinement of the tubes by the bending tools. Generally the tubes are cut to length with a trim allowance after forming.

Lubricants. Many conventional lubricants do not provide the continuous film needed to separate the tools from the workpieces under high bending loads. Ineffective lubrication causes galling. Drawing grease and oil has been found to be suitable for bending stainless steel tubes. Prior to bending, large amounts of lubricant are applied to the mandrel and the inside diameter of the tube. This sometimes is applied by spraying the heated lubricant (250 F), especially on the inside of the tube. Lubrication of the wiper die is essential but the coating must be thin and uniform to avoid wrinkling (Ref. 118).

Tube-Bending Precautions. If the mandrel body and balls and the wiper die are allowed to wear down more than 0.005 to 0.008 inch, the tools will not confine the tubes adequately. Under such conditions pressure-die forces and the amount of elongation required to form the parts increase. This results in high failure rates.

Bending Limits. The bending limits depend mainly on the relationship of the bend radius to the tube diameter. The angle of the bend is not important for 90-degree or larger bends. The uniform elongation of the material is affected by the wall thickness of the tubing so that a decrease in formability in bending can be expected for tubing with a wall thickness of less than 0.035 inch.

The position of the neutral axis during bending influences the tensile strain in the outer tube fibers and the compressive strain in the inner tube fibers. Figure 107 shows the calculated tensile strain

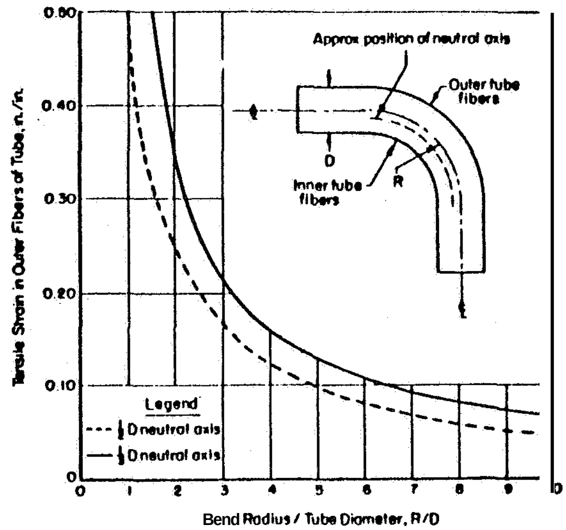


FIGURE 107. STRAIN IN THE OUTER TUBE FIBERS FOR A 90-DEGREE BEND WHEN THE NEUTRAL AXIS IS AT **1/3** D OR AT 1/2 D MEASURED FROM THE INNER TUBE WALL

in the outer tube fibers when the neutral axis is located at distances of 1/2 and 1/3 diameter from the inner fibers of the tube. **As** shown in this graph the strain in the outer fibers decreases as the neutral axis moves away from the inside tube fibers for any given ratio of bend radius to tube diameter. Consequently, equipment that shifts the neutral axis away from the inner tube fibers during bending permits smaller bend radii to diameter ratios in a given material. The position of the neutral axis during rotary draw bending is usually between 1/3 D and 1/2 D. The exact position depends on the tooling and fit of the tubing on the tooling.

Figure 107 may be used to determine the minimum ratio of bend radius to tube diameter for a given tube material and condition provided the tensile-elongation value of the material at the same thickness as the tube is known. For example, Type 410 stainless steel in the annealed condition has a tensile elongation of approximately 30 percent. Tubing of this material could therefore be bent to a minimum ratio between 1.6 and 2.25 D depending on the position of the neutral axis in the bending procedure.

As the wall thickness of the tubing is decreased, the limiting factor in tube bending changes from elongation to compression stability. Buckling of the thin wall material on the inner tube fibers becomes more of a problem as the wall thickness is decreased and this condition is accentuated by a shift of the neutral axis away from the inner tube fibers. The minimum bend radii ratio should be increased by at least one number when the material thickness is 0.035 inch or less.

Post-Forming Operations. The tubing is generally trimmed to final length after forming when precise assembly work is required. The tubes are then cleaned to remove any lubricant or foreign material. For tubing that can be heat treated, the bending operation is generally carried out with the material in the annealed condition.

Tube Bulging. Introduction. In bulging an internal pressure is applied to form a tube to the desired shape. The internal pressure can be delivered by expanding a segmented punch, or through a fluid, rubber, or other elastomer. The process, characterized by the use of simple and low-cost tooling, is adaptable to fast operations and is capable of forming an acceptable part in one step. For the stainless steels, the process is limited to forming in the annealed condition.

The two types of bulge forming can be classified as die forming and free forming. As the names imply, the die-formed component is made in a die that controls the final shape while the free-formed part takes the shape that will contain the internal pressure. Either type of operation can be carried out by a variety of processes.

Equipment Setup. Conventional processes for bulge forming apply internal pressure to the tubing at a slow rate by the motion of mechanical and hydraulic presses. A liquid or semiplastic filler material is normally used inside the tube as indicated in Figure 108, so that a hydrostatic pressure is approached.

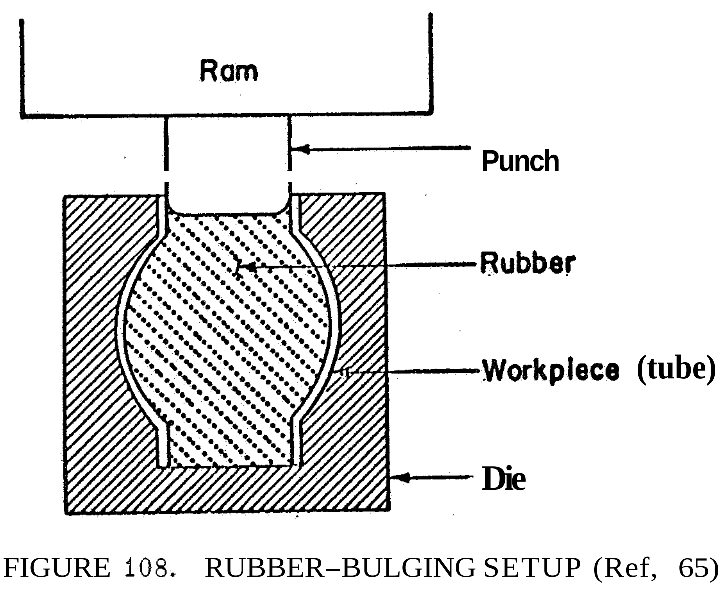


FIGURE 108. RUBBER-BULGING SETUP (Ref, 65)

The behavior of the filler material will control how closely hydrostatic conditions prevail during forming operations. When the ram shown in Figure 108 has been retracted, the rubber returns to its original diameter so that it may be withdrawn from the tube. This technique is commonly used because it does not present the sealing difficulties associated with the use of a liquid filler. The use of low-melting-point solids such as Wood's Metal as a filler material has shown promise for producing large deformations. In this process the ram can apply axial force to the tube as well as pressure on the filler. If additional tubing material is fed into the die as the forming progresses, greater amounts of deformation are possible with this technique.

The use of expanding mandrels for bulging tubes is generally restricted to high-production applications because of the cost of the mandrels. Friction between the metal mandrel and the tubing limits the force that can be applied and the maximum deformation that can be obtained with this technique.

Some of the high-velocity techniques that have been applied to tube bulging with the greatest success employ low explosives and electric discharges as energy sources. The electric-discharge techniques are based on the liberation of energy stored in capacitors as sparks, exploding bridge wires, or magnetic coils. All of these processes except magnetic forming require some medium, generally water, to transmit the pressure to the tubing.

Figure 109 shows an electrical-discharge bulge forming machine having a rated energy of 172,000 joules. The time required to charge the capacitor bank is 20 seconds and the machine can be operated on a 30-second tool cycle. The machine has a capacity for flat plate

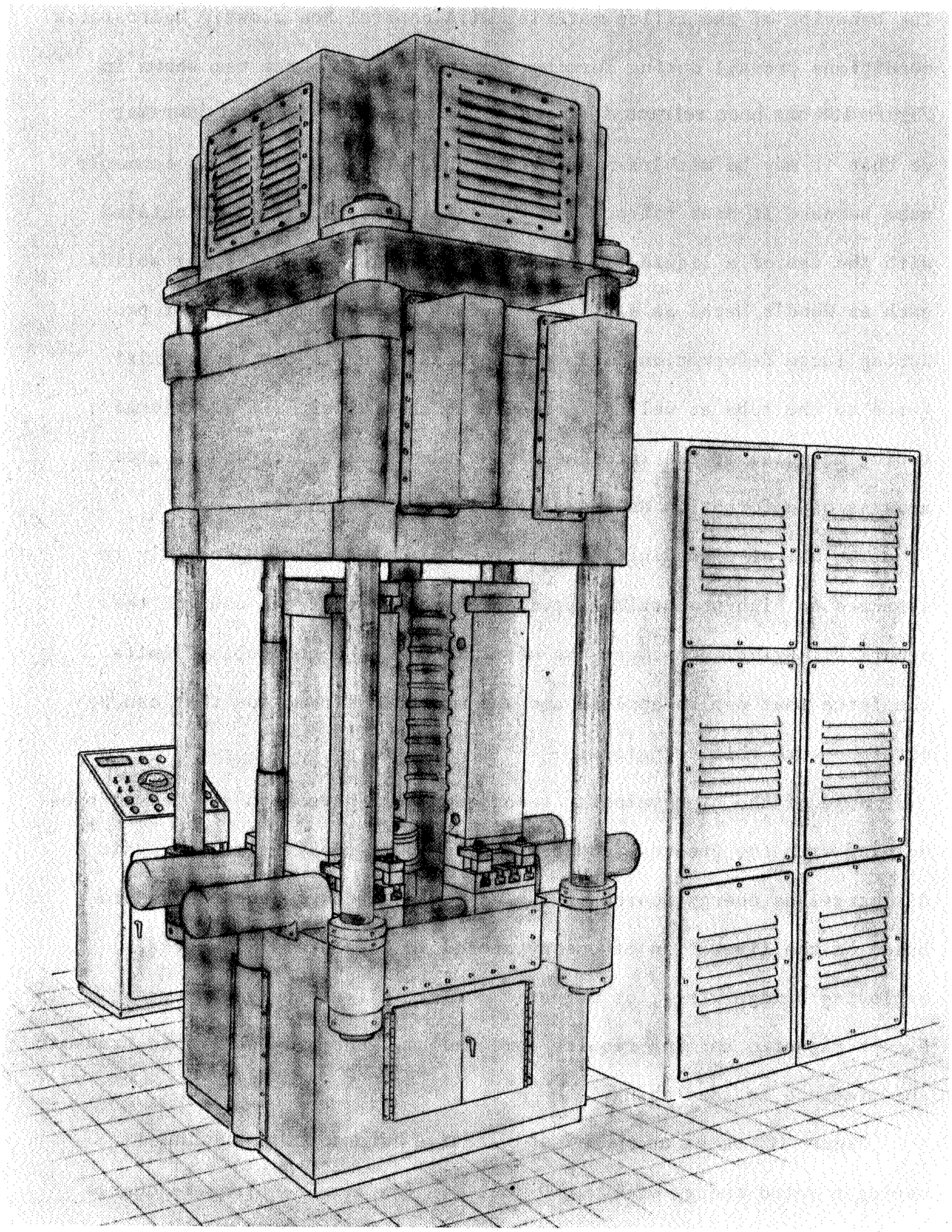


FIGURE 109. SCHEMATIC DRAWING OF ELECTRICAL DISCHARGE BULGE-FORMING MACHINE
Courtesy of Electro-Form, Inc., Fort Worth, Texas.

24 inches in diameter and can form to 8 inches of depth. For tubing, the maximum diameter that can be formed is 13 inches and the length limitation is 24 inches (Ref. 121).

Table XXXIX gives data on electrical discharge forming machines produced by another manufacturer. All of these machines are somewhat smaller and less powerful than that previously described. However 1/8-inch stainless steel also can be formed in these machines which will accept flat blanks to 22 inches in diameter and tubes up to 12 inches in diameter and 30 inches long.

TABLE XXXIX. STANDARD POWER SUPPLIES AVAILABLE IN ELECTRICAL DISCHARGE FORMING MACHINES AVAILABLE FROM ONE PRODUCER[(a)]

Model Number	Capacity, joules	Stored Energy, foot-pounds

Tubes also are bulge formed explosively in some commercial applications. Explosive forming is utilized when the parts are too large to be formed in conventional forming equipment or when conventional energy sources cannot provide enough energy to produce the precise detail that is required in a given part. In considering explosive forming, it is advisable to determine the safety requirements in a given community, since these often are rather stringent.

Explosive forming usually is done outdoors and often in a pit. The general requirements are quite simple needing only a die, usually split, against which the expanding tube or plate is forced. Another requirement is a means of detonating the explosive. As for electrical discharge forming, water is commonly used to transmit the energy produced in the explosion to the tube.

The volume between the tube and the die should be evacuated to prevent high-temperature and burning due to entrapped air. Shock-wave reflectors have been used with low-explosive and electrical-discharge systems to obtain unusual free-formed shapes. Most of the information on the subject, however, is considered proprietary and has not been released for general publication.

Magnetic forming is the only metalworking process that does not require direct contact between the forming medium and the workpiece. Consequently, the frictional limitations on forming encountered in most processes are absent.

If the pressure for deforming a tube is considered to be hydrostatic in nature, then the pressure required to initiate deformation can be determined from

$$p = 2TS/d \tag{34}$$

where

p = pressure, psi

T = tube-wall thickness, inches

S = average flow stress of the tube material, psi

d = tube diameter, inches.

This equation is simple to use for estimating pressure requirements at the start of deformation, but some modifications are required to present the total picture. As the tube is stretched, the flow stress will increase due to work hardening of the material. At the same time, the diameter increases and the thickness decreases. For estimates of the final or maximum pressure, the conditions prevailing after forming should be considered in the equation.

Tooling. Tooling for bulge forming may include zinc base (Kirksite) alloys, glass-cloth reinforced plastic, 1010 low-carbon steel, 7075-T6 aluminum alloy, low alloy steels such as the 4130 and 4340, and tool steels (Ref. 122). The choice of material depends on the number of parts to be made and the detail desired in the finished parts. The dies usually are split to facilitate loading and unloading of parts. Often massive outer rings having tapered sides are used to increase the rigidity and strength of the die assembly. An example of this procedure is shown for an explosive forming die assembly in Figure 110. The taper between the die and the outer ring is 4-1/2 degrees and the die is fastened by bolting with the clamp plate.

Material Preparation. Both seamless and welded stainless steels tubing are generally available in diameters from 0.012 to 4.5 inches and wall thicknesses from 0.004 to 0.148 inch. Larger size and thicker walled tubing has generally been made from roll- or brake-formed and welded sections. Some difficulty has been experienced in obtaining sufficient ductility in the heat-affected weld zone for bulge-forming operations. Some of the troubles may have been caused by improper manufacturing practices. It is normally desirable to planish weld beads before bulging and to stress relieve welded preforms.

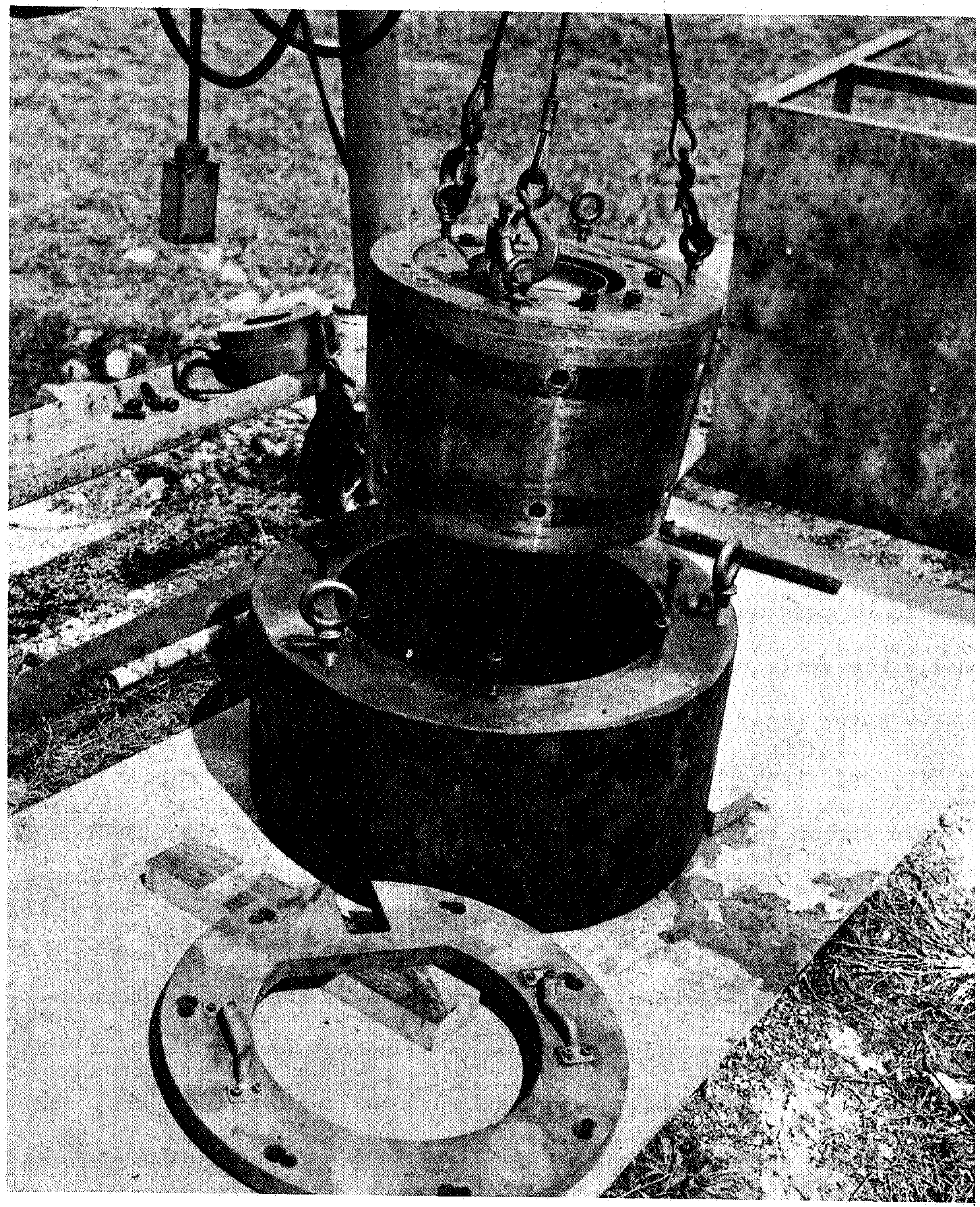


FIGURE 110. TOOLING CONSISTING OF 4140 STEEL DIE INSERT AND 4340 STEEL OUTER RING WITH TAPERED INTERFACE USED FOR EXPLOSIVE TOOL BULGING

Courtesy of the Martin Company, Baltimore, Maryland

Where considerable reduction in ductility is experienced in the weld heat-affected zone, a heavier section may be left in this area to equalize the strength of the tube. This technique, shown in Figure 111, will result in a part with uniform strength but may cause considerable difficulty in forming due to the reduced ductility in the heat-affected zone.

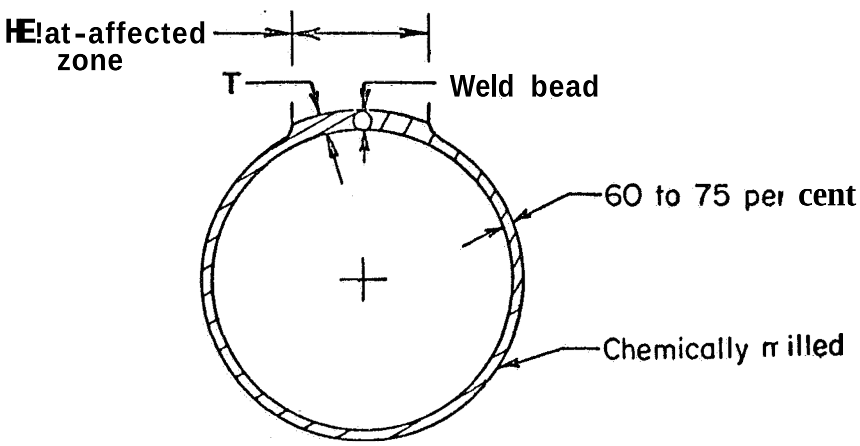


FIGURE 111. METHOD OF EQUALIZING STRENGTH BETWEEN WELD AND WALL AREAS FOR DIE-FORMED TUBES **(Ref. 66)**

Bulge-Forming Limits. Two limitations must be considered in bulge-forming operations: ductility of the workpiece material and design of the tooling. The final part shape determines the maximum percentage increase in diameter. This can be calculated:

$$\text{Percent Increase} = \frac{d_f - d_o}{d_o} \times 100, \qquad (35)$$

where

d_o = original diameter

d_f = final diameter.

If no material is drawn in along the tube axis during forming, this may also be considered as the percentage stretch. The elongation values normally obtained in tensile tests cannot be used to determine this limitation since only uniform elongation is of practical importance. If necking occurs, as in the tensile test, the bulged component would be scrapped due to excessive metal thinning.

Tooling influences the amount of expansion because of the constraints it places on metal movement. If extra material is drawn in from the ends of the tubing or if the length of the tubing is shortened during forming, additional tube expansion is possible. The percent increase in diameter can sometimes be increased by applying an axial load to the tube to assure feeding additional material to the bulged section.

Another limitation besides percent stretch is the bending strain that occurs if the tube is made to bulge over too tight a bend radius. This condition results in splitting as shown in Figure 112. The minimum bend radii in tube forming should not be less than that used in other forming operations such as brake forming.

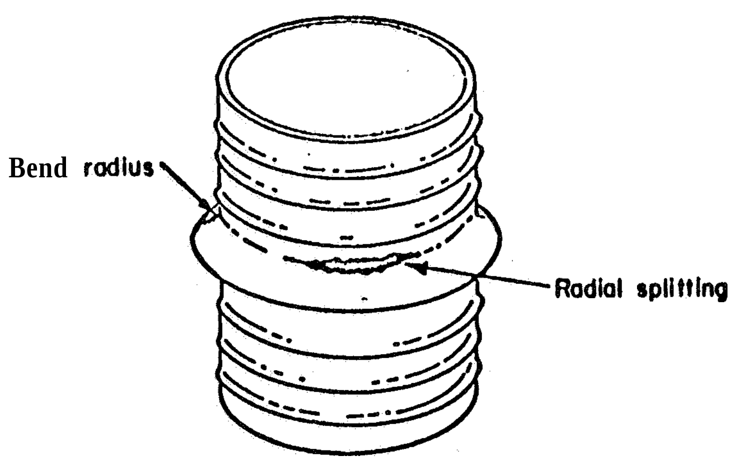


FIGURE 112. EXAMPLE OF FAILURE IN TUBE BULGING (Ref. 66)

In the bulged portion of a tube is considered as a bead, the strain for any given die design can be determined. The important strains, on the basis of where failure will occur during bulge forming, are represented in Figure **113.** The severity of deformation is determined by the amount of stretching and the amount of bending. Consequently, the radius at the entrance to the bulged areas as well as the diameter of the bulged section are both important considerations in establishing design limits in bulge forming. Figure **114** may be used to determine E_A when the R_1/W ratio is known. The combined strain $\epsilon_A + \epsilon_{Br1}$ determines failure limits so that the limiting bending conditions must be considered for the particular alloy of interest. This limit based on R_1/T or bend radius over material thickness is the same as for brake forming.

Examples of Bulae Formed Parts. Figure 115 shows a bulge Type 304 stainless steel part not yet removed from the Rohr electrical-discharge type bulge forming machine. A 6-inch-diameter welded tube was expanded to 8-inch diameter. The photograph shows that good detail can be obtained. The massive dies used for bulge forming are well illustrated in this photograph.

Figure 116 shows a five-inch-diameter by 12-inch-long welded tube of Type 316 stainless steel with a 0.070-inch-thick wall, explosively formed into a 12-sided tube in one shot. The detail on the outside diameter of the tube matched the die within 0.002 inch. The tube section before and after forming rests on the die outer ring used to contain the split die.

The 4-112-inch-diameter tube of Type 321 stainless steel shown at the right in Figure 117 was bulge formed into the experimental rocket

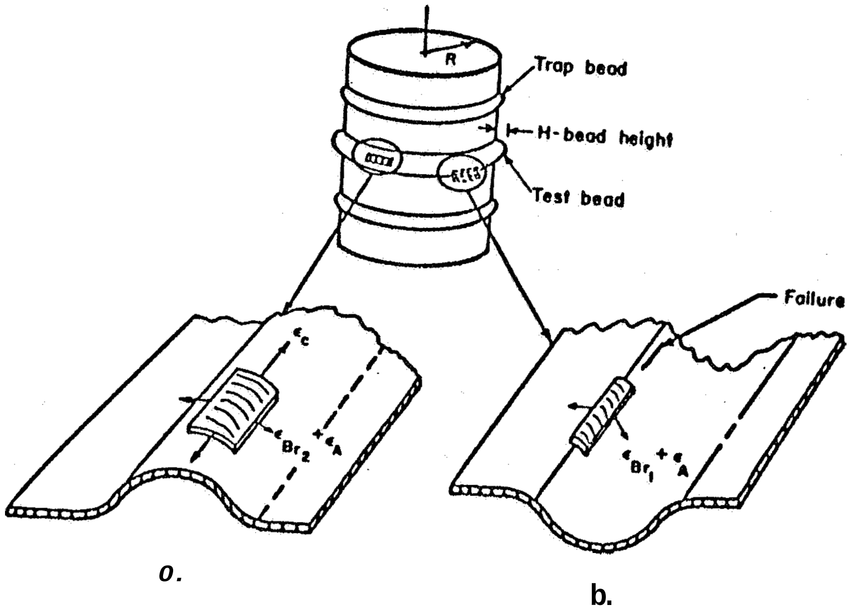


FIGURE 113. STRAIN CONDITIONS IN BULGE FORMING (Ref. 66)

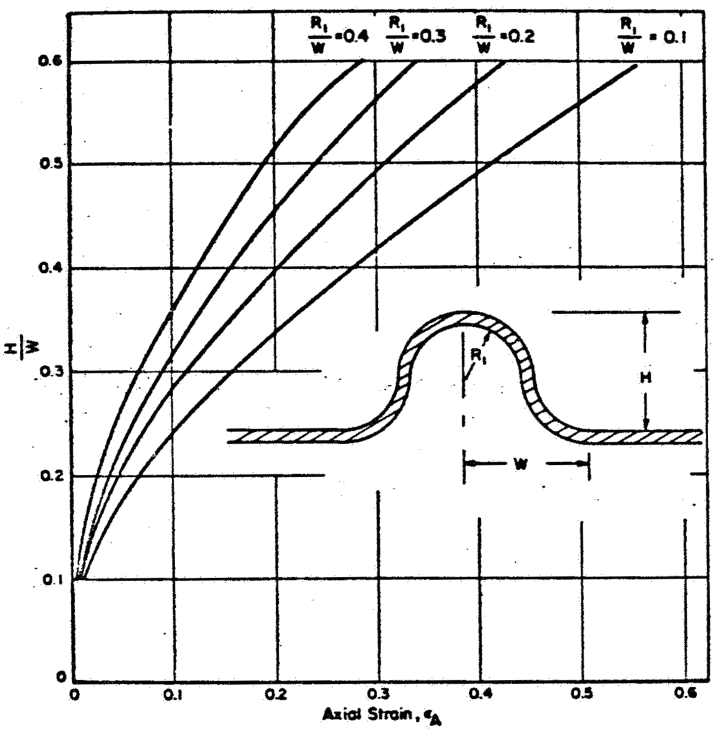


FIGURE 114. H/W VERSUS AXIAL STRAIN ϵ_A FOR VARIOUS VALUES OF R_1/W (Ref. 66)

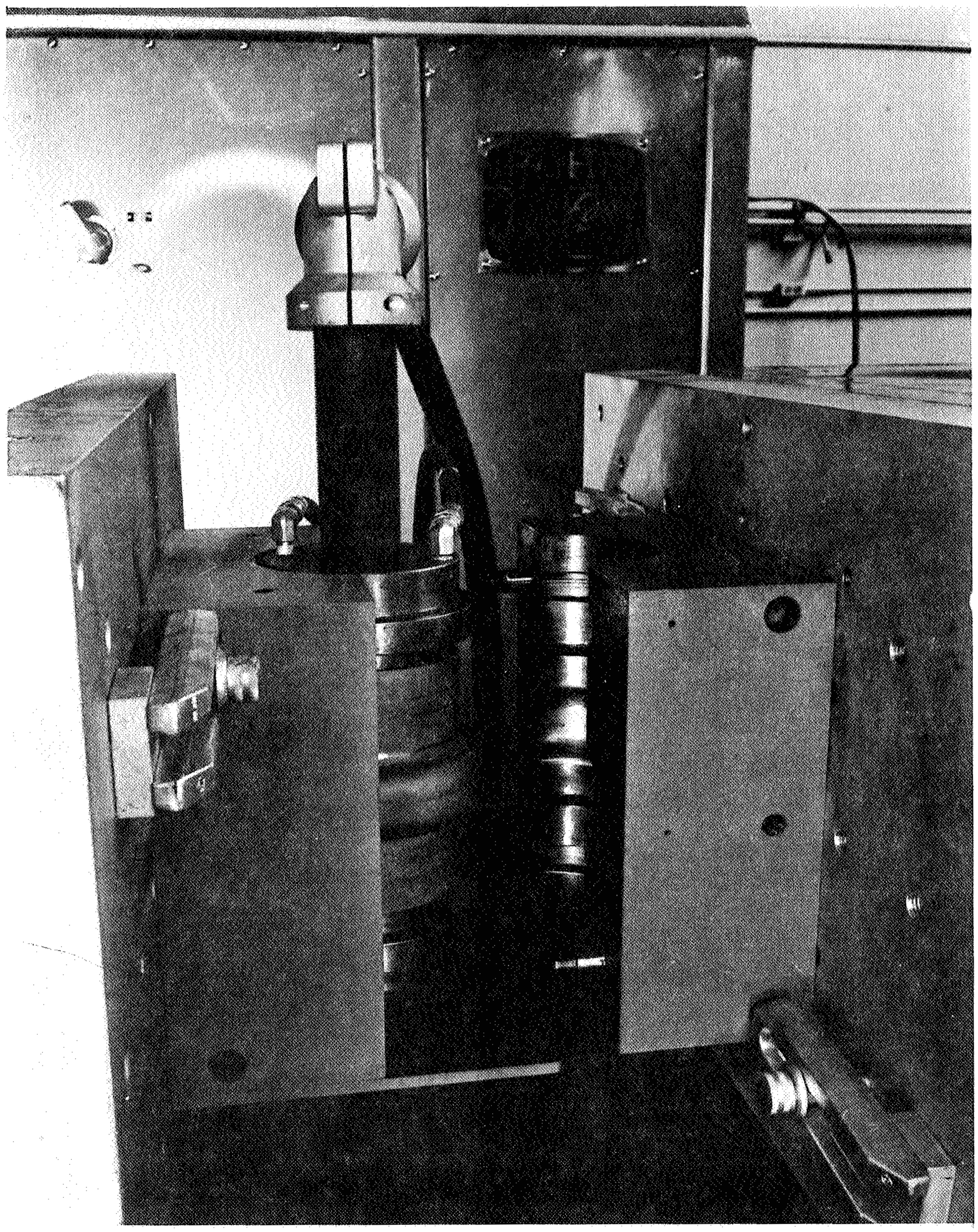


FIGURE 115. BULGE-FORMED TUBE PRODUCED BY ELECTRICAL-DISCHARGE FORMING

Courtesy of Rohr Corporation, Chula Vista, Calif.

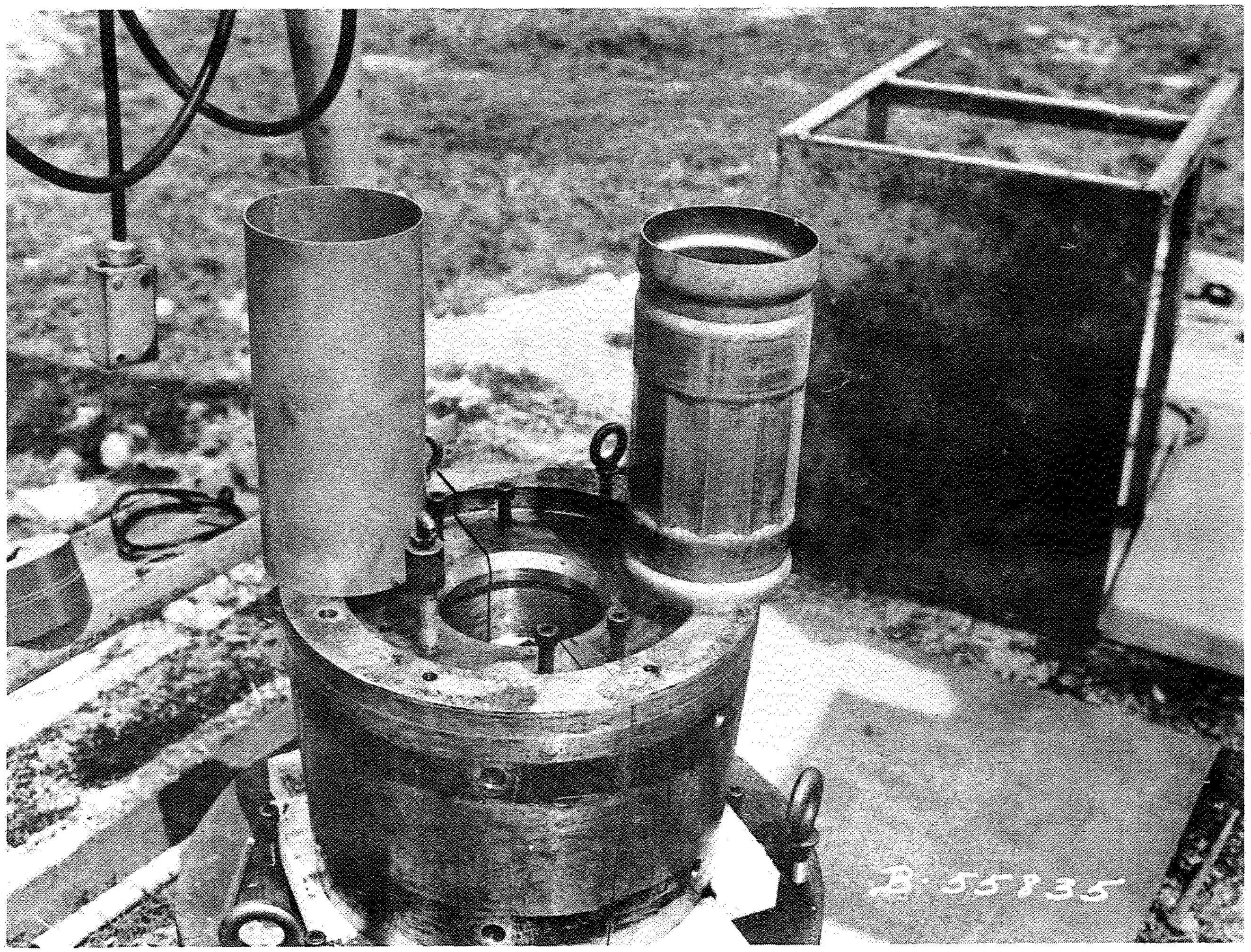


FIGURE 116. TYPE 316 STAINLESS STEEL WELDED TUBE EXPLOSIVELY FORMED INTO 12 SIDED TUBE

Courtesy of the Martin Company, Baltimore, Maryland

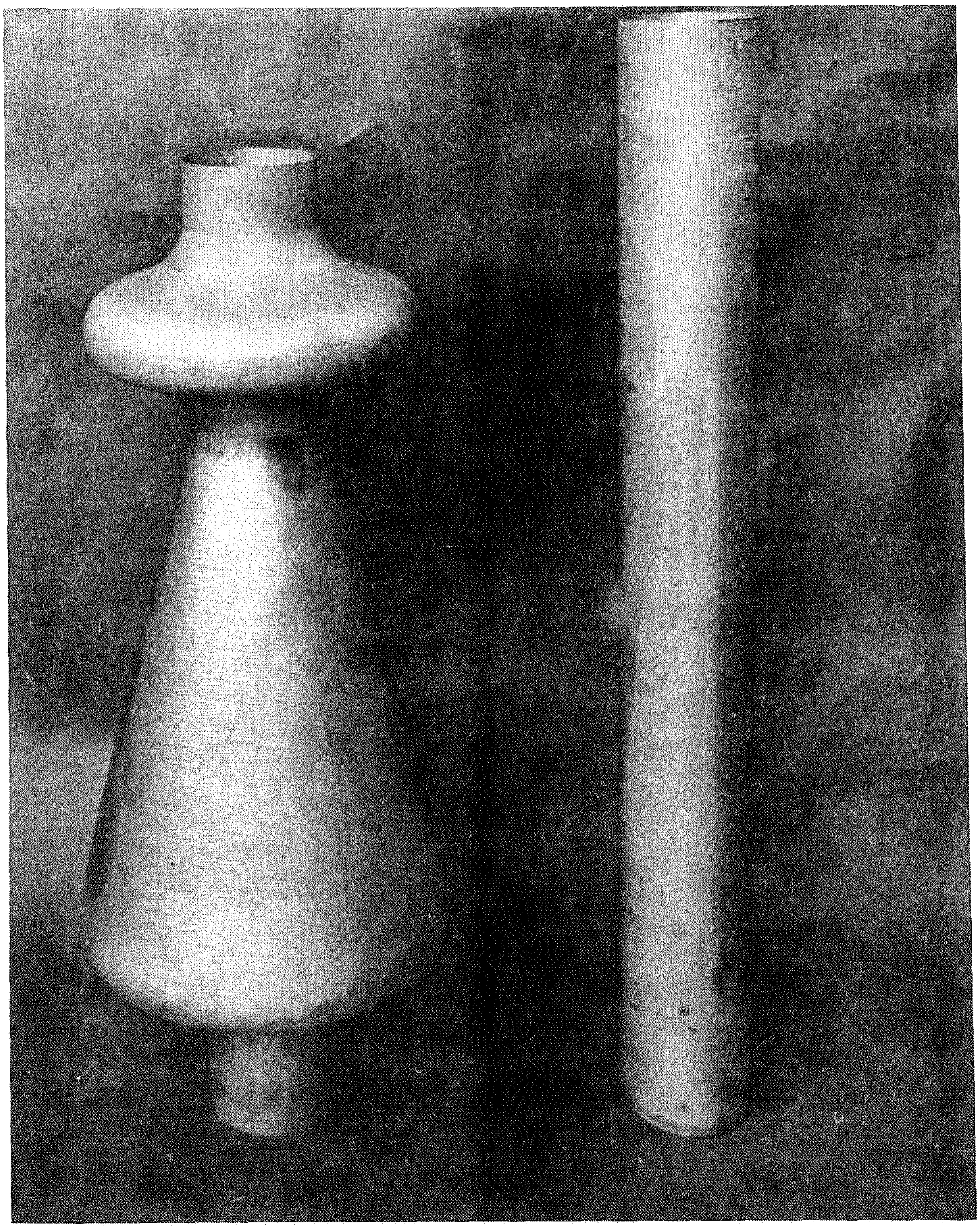


FIGURE 117. WELDED 4-1/2-INCH-DIAMETER TUBE OF TYPE 321 STAINLESS STEEL HIGH ENERGY FORMED INTO AN EXPERIMENTAL ROCKET NOZZLE WITH A 13-3/4-INCH-DIAMETER SKIRT

Courtesy of Rohr Company, Chula Vista, Calif.

nozzle shown at the left in a single shot. The skirt on the nozzle has a diameter of 13-3/4 inches. **It is** interesting to note that the tube was shortened considerably during forming. The rocket nozzle was formed in a single shot using a Rohr electrical-discharge forming machine.

JOGGLING

Introduction. A joggle is an offset in a flat plane produced by two bends at the same angle. Joggling permits flush connections to be made between sheets, plates, or structural sections. The bend angle for joggles is usually less than 45 degrees, as indicated in Figure 118. Because the bends are close together, the same flange will contain shrunk and stretched regions in close proximity to each other. The two types of deformation tend to compensate for each other.

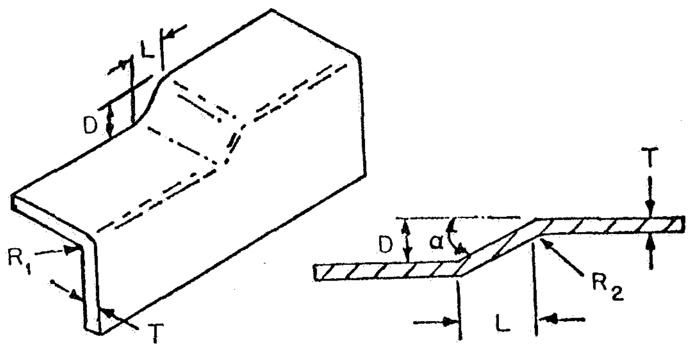
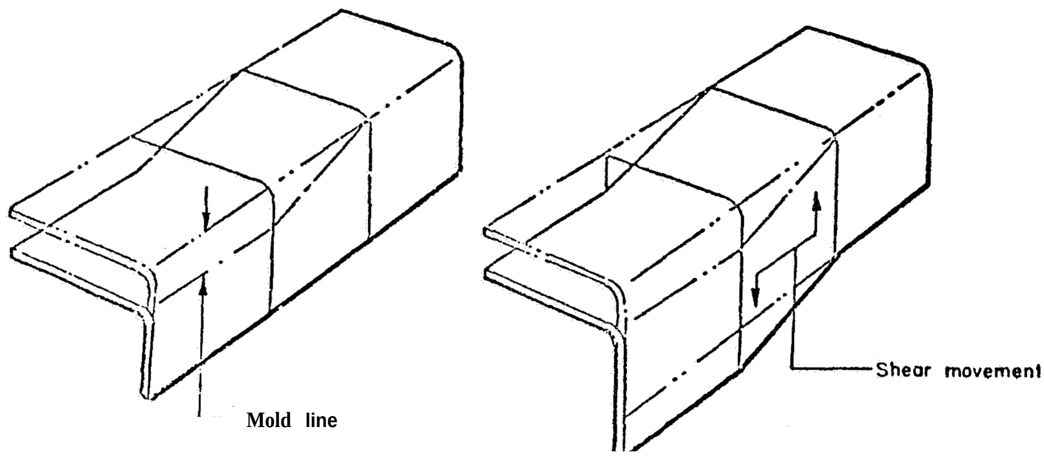


FIGURE 118. JOGGLE IN AN ANGLE (Ref. 69)

a = joggle bend angle
D = joggle depth
L = joggle length or runout
T = thickness of workpiece
R_1 = radius on joggling block
R_2 = radius of bend on leading edge of joggle block.

Equipment. Joggles may be formed either in straight or curved sheet-metal sections by a variety of techniques. Whenever possible, the joggle is formed as part of another forming operation but at times a separate operation is used to produce a joggle. Often joggles are formed as part of trapped-rubber forming of stainless steel parts.

Presses with special joggle dies are often employed for forming joggles in angles and channels. Hydraulic presses are preferred for joggling at elevated temperatures because they simplify control of pressure and dwell time. The joggles usually are formed either by a wiping action or a section movement, as shown in Figure 119.



a. Wipe Joggling b. Section Joggling

FIGURE 119. BASIC METHODS OF FORMING JOGGLES (Ref. 69)

Tooling. The stainless steels are often joggled at room temperature. Nickel-chromium-molybdenum tool steels will give satisfactory service as joggle dies when heat treated to R_C 50-55. For higher temperatures, tooling constructed from high-strength, heat-resistant alloys or ceramic materials must be used.

A schematic drawing of a universal joggle die, similar to that used by Wood, et al. (Ref. 69) in their studies is shown in Figure 120. This type of tooling requires an additional hydraulic cylinder to apply

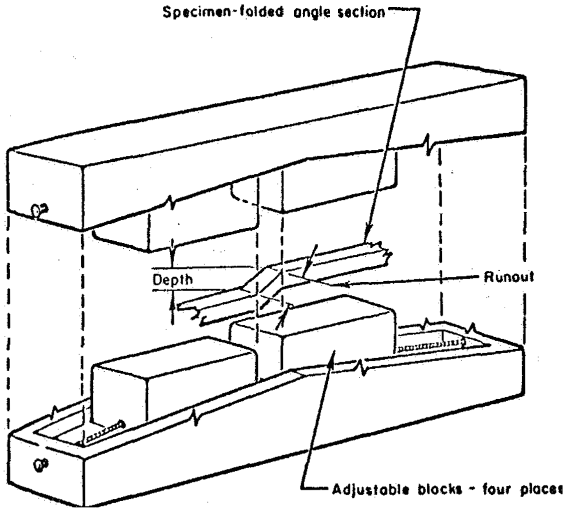


FIGURE 120. UNIVERSAL JOGGLE DIE

Courtesy of North American Aviation, Inc., Inglewood, California

horizontal forces to clamp the side of the angle specimen to the die. Suitable shims are added to the die to produce the shape desired in the part. For production runs, mated, rather than universal, adjustable joggle dies are usually used.

Material Preparation. Precautions covered in the section on blank preparation apply to the preparation of sheet for joggling.

Lubricants. Lubricants are generally used in the production joggling of stainless steel sheet metal. The high-pressure drawing lubricants containing inert filler and having high film strength would be satisfactory. To prevent carburization, all lubricants must be completely removed before any thermal treatment is used on the parts.

Joggling Limits. The common types of buckling and splitting failures encountered in joggling are illustrated in Figure 121. Wood

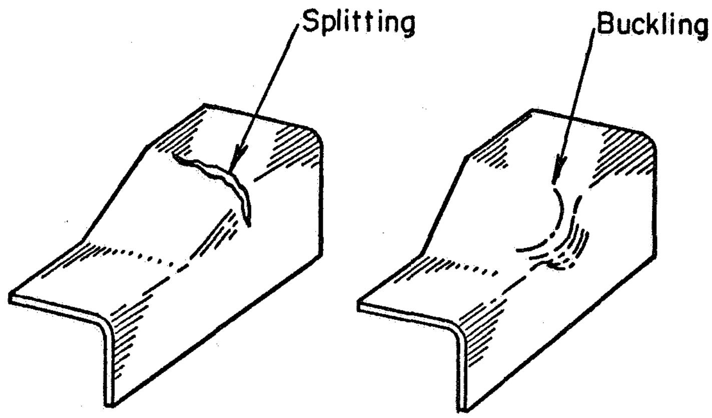


FIGURE 121. MAJOR JOGGLING FAILURES (**Ref.** 69)

and his associates (Ref. 69) studied the relationships between the properties of the workpiece and the formability limits in joggling. They then constructed charts of the type shown in Figure 140 for specific alloys. The following equations are utilized in constructing such diagrams:

(a) For splitting limit line:

$$\frac{D}{L} = \left[\epsilon_{0.02} \left(1.44\ \epsilon_{0.02} + 2.4\right) \right]^{1/2} \quad (35)$$

(b) For elastic buckling limit line:

$$\frac{D}{L} = \frac{E}{S_{cy}} \left[\frac{0.0050625}{\left(\frac{D}{T}\right)^2} \right] \quad (36)$$

(c) For elastoplastic-buckling limit line:

$$\frac{D}{T} = \left[0.0118\ \frac{E}{S_{cy}} \right]^{2/5} \quad (37)$$

(d) For inflection line:

$$\frac{D}{L} = 0.43 \sqrt{\frac{D}{T}} \quad (38)$$

This line has a slope of + 1/2 and crosses the D/L axis at *0.43.*

(e) For finding the intersection of the elasto-plastic- and elastic-buckling-limit line at a point on the inflection line:

$$\frac{D}{T} = \left[0.0118 \frac{E}{S_{cy}} \right]^{2/5} \qquad (39)$$

The buckling-formability index line runs vertically upward from the D/T intercept 2.25. The terms D, L, and T define the geometry of the joggle and are shown in Figure 118. The following mechanical properties of the workpiece are needed to solve the equations:

E = Young's modulus of elasticity

S_{cy} = Compressive yield strength based on original cross-sectional area

$\epsilon_{0.02}$ = Conventional strain to rupture measured on a 0.02-inch gage length.

Although values of $\epsilon_{0.02}$ are not commonly reported they can be determined by special tests. If the mechanical properties are known, they can be used in Equations 35 through 39 to construct joggling limits by following the procedures indicated in Figure 140. Unfortunately Wood, et. al (Ref. **69)** did not include the 200-, 300-, and 400-series of stainless steels in their program but showed the methods used to calculate them.

An empirical approach that may be used to choose joggle dimensions is described in a North American Aviation Specification (Ref. 123). The length or runout, L, of the joggle, shown in Figure 118 can be determined **from** the following formulas and the factors A, B, and C given in Table XL.

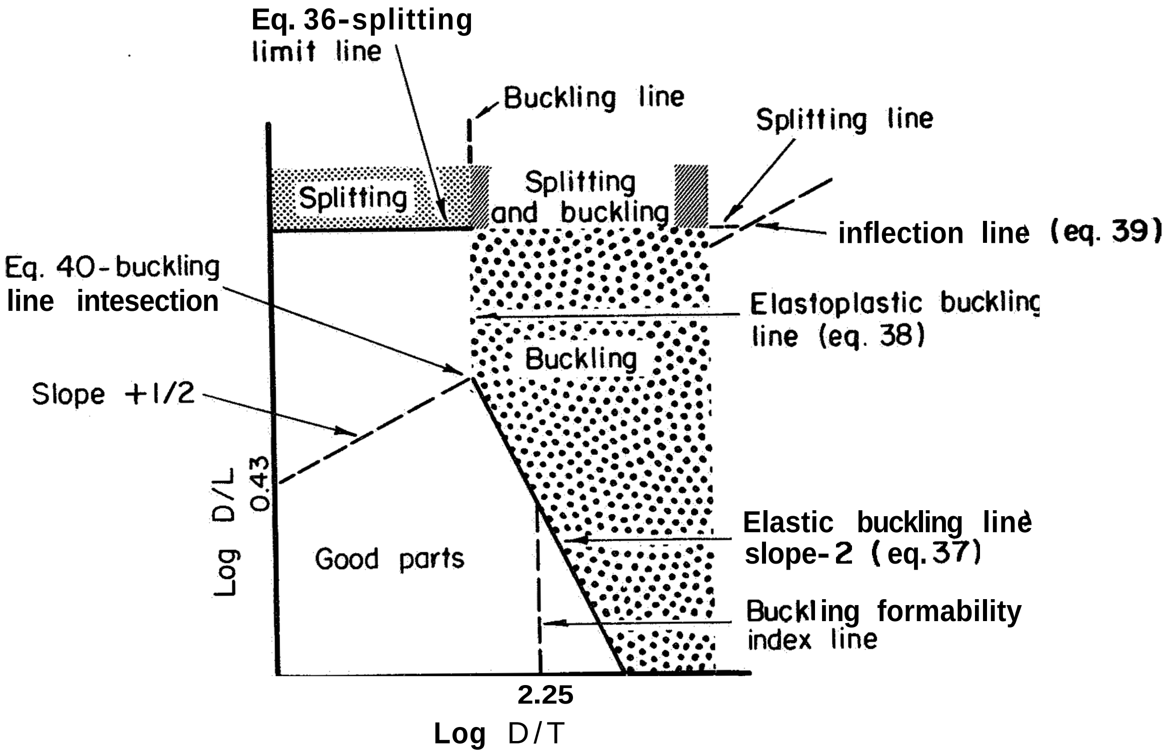


FIGURE 122. EFFECT OF GEOMETRY ON SUCCESS OR FAILURE IN JOGGLING (Ref. 69)

TABLE XL. JOGGLE–FORMING–LIMIT FACTORS FOR SELECTED STAINLESS STEELS (Ref. 123)

Alloy Type	Minimum Bend Radii Factor, R/T [(a)]	Minimum Joggle Runout Factors[(b)] A/T	B	C/T
301 (annealed)	90° : 1 180° : 2 90" : 2	0.35	4	6
301 (1/2 hard)	180° : 3 90" : 1	0.59	4	10
321 (annealed)	180' : 2 90° : 1	0.35	4	6
347 (annealed)	180° : 2	0.35	4	6

(a) To obtain bend radii, multiply R/T value by material thickness, T.
(b) To obtain A and C, multiply A/T and C/T values by material thickness, T.

(1) If the joggle depth is greater than A, the length of the joggle runout equals B times the joggle depth or $L = BD$ (when $D > A$).

(2) If the joggle depth is less than A, the length of the joggle runout is equal to the square root of the joggle depth times the quantity C minus the joggle depth or

$$L = \sqrt{D(C - D)} \quad (\text{when } D < A).$$

(3) For joggles in flat sheets, the projected distance between tangents may be determined from the equation for reverse curve as follows:

$$L = \sqrt{D(4R_2 + 2T - D)} \quad (\text{see Figure 118}).$$

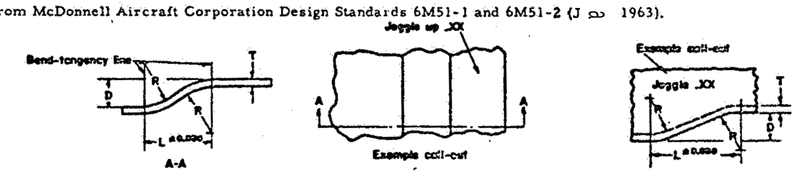
Values suggested for minimum runout and minimum bend radii are given in Table XXXIX for several stainless steels. Table XLI gives joggle-design specifications used at McDonnell Aircraft Corporation for both flat and flanged sheet joggled at room temperature in the annealed condition.

Springback occurring in joggles formed at room temperature for the stainless steels are usually compensated for by overbending. If parts are heat treated after joggling, the lubricant residue must be thoroughly and completely removed prior to heat treatment to avoid the possibility of embrittling the formed part.

TABLE XLI. JOGGLE-DESIGN SPECIFICATIONS FOR FLAT AND FLANGED SHEET OF ANNEALED STAINLESS STEELS JOGGLED AT ROOM TEMPERATURE[a]

Depth of Offset, D	Joggle Length, L(b) for Indicated Sheet Thickness, T	0.023-	0.028-	0.036-0.044	0.045-0.054	0.055-0.068	0.069-0.075	0.076-0.084	0.085-0.097	0.098-0.113	0.114-0.139	0.140-0.172	0.173-0.219	0.220-0.262
						Flat Sheet-Joggled Cold[c]								
Up to 0.022	0.14	[illegible]	[illegible]	0.18	0.19	0.21	0.22	0.23	0.24	0.26	0.27	0.30	0.34	0.37
0.023-0.027	0.15	[illegible]	[illegible]	0.19	0.21	0.23	0.24	0.25	0.26	0.28	0.29	0.34	0.37	0.41
0.028-0.035	0.16	0.18	0.20	0.20	0.22	0.25	0.26	0.27	0.29	0.30	0.32	0.37	0.41	0.44
0.036-0.044	0.17	0.20	0.22	0.22	0.24	0.27	0.28	0.30	0.31	0.33	0.36	0.40	0.45	0.49
0.045-0.054	0.20	0.21	0.24	0.24	0.26	0.29	0.31	0.33	0.34	0.37	0.39	0.44	0.49	0.54
0.055-0.068	0.21	0.24	0.25	0.25	0.28	0.32	0.34	0.35	0.37	0.40	0.43	0.47	0.54	0.58
0.069-0.075	0.22	[illegible]	0.26	0.26	0.29	0.33	0.35	0.37	0.39	0.43	0.45	0.50	0.57	0.62
0.076-0.084	0.22	[illegible]	0.27	0.27	0.30	0.35	0.37	0.38	0.41	0.44	0.47	0.53	0.60	0.66
0.085-0.097	0.23	[illegible]	0.30	0.30	0.31	0.36	0.38	0.40	0.42	0.46	0.48	0.55	0.63	0.69
0.098-0.113	0.23	[illegible]	0.31	0.31	0.32	0.37	0.39	0.42	0.44	0.48	0.51	0.58	0.66	0.72
0.114-0.139	0.24	0.29	0.33	0.33	0.37	0.40	0.43	0.45	0.48	0.51	0.55	0.63	0.71	0.79
0.140-0.172	0.24	0.30	0.35	0.35	0.39	0.46	0.47	0.51	0.53	0.57	0.62	0.69	0.79	0.87
0.173-0.219	0.24	0.31	0.36	0.36	0.41	0.48	0.52	0.53	0.56	0.61	0.66	0.74	0.85	0.94
0.220-0.262	0.24	0.31	0.37			0.53	0.57	0.60	0.64	0.70	0.76	0.84	0.96	1.07
						Flanged Sheet[d]								
Up to 0.022	0.12	0.13	0.15	0.15	0.15	0.18	0.19	0.20	0.21	0.23	0.24	0.27	0.31	0.34
0.023-0.027	0.14	0.15	0.16	0.16	0.17	0.20	0.21	0.22	0.23	0.25	0.26	0.31	0.34	0.38
0.028-0.035	0.15	0.17	0.18	0.18	0.19	0.22	0.23	0.24	0.26	0.27	0.29	0.34	0.38	0.41
0.036-0.044	0.18	0.19	0.20	0.20	0.21	0.24	0.25	0.27	0.28	0.30	0.33	0.37	0.42	0.46
0.045-0.054	0.21	0.22	0.23	0.23	[illegible]	0.27	0.28	0.30	0.31	0.34	0.36	0.41	0.46	0.51
0.055-0.068	0.24	0.25	0.27	0.27	[illegible]	0.31	0.32	0.33	0.35	0.37	0.40	0.44	0.51	0.55
0.069-0.075	0.26	0.27	0.29	0.29	0.30	0.33	0.34	0.35	0.37	0.39	0.42	0.47	0.54	0.59
0.076-0.084	0.29	0.30	0.32	0.32	0.33	0.35	0.37	0.38	0.39	0.42	0.44	0.50	0.57	0.63
0.085-0.097	0.32	0.33	0.34	0.34	[illegible]	0.38	0.39	0.41	0.42	0.44	0.47	0.52	0.60	0.66
0.098-0.113	0.35	0.36	0.37	0.37	[illegible]	0.41	0.42	0.44	0.45	0.47	0.50	0.56	0.63	0.69
0.114-0.139	0.41	0.42	0.44	0.44	[illegible]	0.47	0.49	0.50	0.51	0.54	0.56	0.62	0.69	0.76
0.140-0.172	0.51	0.52	0.53	0.53	[illegible]	0.57	0.59	0.60	0.61	0.64	0.66	0.71	0.78	0.85
0.173-0.219	0.60	0.61	[illegible]	[illegible]	0.64	0.66	0.68	0.69	0.70	0.73	0.75	0.80	0.86	0.94
0.220-0.262	0.77	0.78	[illegible]	[illegible]	0.81	0.83	0.85	0.86	0.87	0.90	0.92	0.97	1.04	1.11

(a) Data taken from McDonnell Aircraft Corporation Design Standards 6M51-1 and 6M51-2 (J [illegible] 1963).
(b) Parameters:



a. Flat Sheet

b. Flanged Sheet

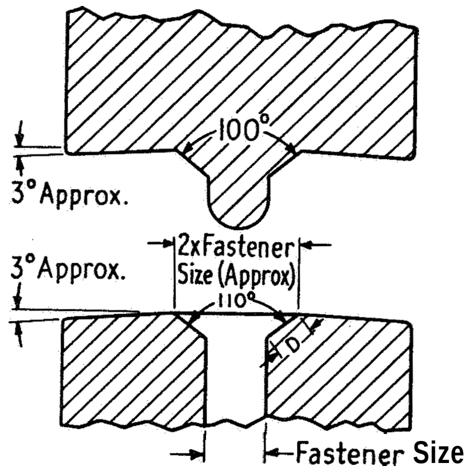
(c) Joggle dimensions are for all aluminum alloys and conditions except 7075-T6 and 7178-T6, annealed stainless steels ~~including the precipitation-hardenable grades~~, annealed or normalized alloy steels, hot-formed magnesium alloys, and annealed Inconel. Tolerances for D are ±0.03 inch for sheet thicknesses of 0.068 inch or less; ±0.02 inch for sheet thickness of 0.069 inch or greater.
(d) Joggle dimensions for all aluminum alloys the O condition, also 2024-T-3, 6061-T6, and annealed stainless steels, ~~including the precipitation-~~

DIMPLING

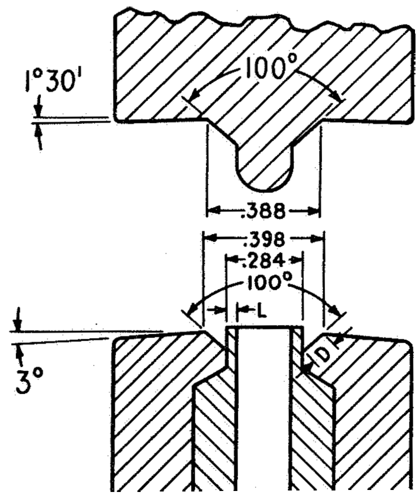
Introduction. Dimpling is a process for producing a small conical flange around a hole in sheet-metal parts that are to be assembled with flush or flat-headed rivets or screws. The process is often used for preparing fastener holes in airframe components because the flush surface reduces air friction. Dimpling is most commonly applied to sheets that are too thin for countersinking. Sheets are always dimpled in the condition in which they are to be used because subsequent heat treatment may cause distortion and misalignment of holes.

Dimples of 100 degrees for flush fasteners up to and including 1/4-inch diameter are formed successfully in sheet ranging from 0.020 through 0.062 inch annealed, 1/4 hard, and 1/2 hard stainless steel. No problems are involved in dimpling the austenitic yraaes of stainless steel such as 301 and 321 (Ref. 124). Two general types of dimpling are used for the stainless steels, coventional or radius dimpling and coin dimpling.

Radius Dimpling. Figure 123 compares schematically the tooling for radius and coin dimpling and Figure 124 is a schematic cross section of both types. In radius dimpling of the harder tempers, the radius at the intersection of the cone and the die face must be as generous as possible. The accurate mating of tne cones on the punch and the die for radius dimpling is of small importance in controlling radial cracks around the hole because of limited coining that takes place. Normally the drilled or punched hole must be large enough so that the circumferential tensile stresses on its periphery are below the critical value. Because of the relatively generous radius which must be formed around the cone in this dimpling method, an annular depression will remain around the fastener head causing a discontinuity in the surface.



*a. **Radius** Dimpling, Typical*



***b.** Ram Coin Dimpling-for #10 Screw*

FIGURE 123. SCHEMATIC COMPARISON OF TOOLING FOR RADIUS AND RAM–COIN DIMPLING (Ref. 79)

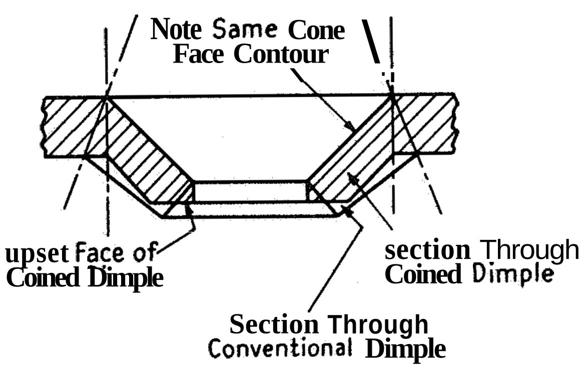


FIGURE 124. SCHEMATIC COMPARISON OF SHAPE OF CON–VENTIONAL AND COINED DIMPLES (Ref. 79)

Conical wall of coined dimple is thinned by coin–ing (forging) operation; wall thickness of conven–tional dimple is not reduced.

Coin Dimpling. Two types of coin dimpling have been developed, ram-coin dimpling and coined cone dimpling. As their names imply, both methods impart a certain amount of coining to the sheet during the dimpling operation as is shown in Figure 124. This is of advantage because the coining counteracts the tensile stresses developed on the periphery of the hole during dimpling, thus, eliminating radial cracking caused by these tensile stresses. This results in forcing metal into the intersection area forming a sharper intersection of the cone with the underside of the sheet without circumferential cracking.

Ram-coin dimpling, Figure 123b 'utilizes a spring-loaded coining ram which exerts a compressive stress on the metal around the periphery of the hole during the entire dimpling operation. Excess metal forced from the tip of the cone by the ram as well as by coining between the two accurately mating dies, is pushed into the bend area, thus securing the desired smaller radius at the intersection of the cone and the sheet. The cone surfaces of both punch and die form 100-degree angles in the example shown in Figure 123b. The punch and die diameters are adjusted to coin the entire dimple wall during forming. It is desirable to obtain a maximum area "D" while still maintaining sufficient working area in the ram, "L", to withstand ramming forces. The hole in the ram is governed by the size of the punch pilot which fits tightly inside the drilled hole.

Coined cone dimpling, although not as widely used as ram-coin dimpling, accomplished the same general results by using a die with a shoulder at the lower end of the cone as shown in Figure 125. The angle of the punch and die, shown in Figure 125, -is 100 degrees and the diameters are adjusted to produce a small reduction in metal thickness. Coined-cone dimpling is not as effective as ram-coin dimpling because the upsetting of the periphery of the hole does not begin until the dimple is almost completely formed. When the ductility of the material is low, cracking may already have taken place before the upsetting has begun. The radius at the intersection of the dimple and the sheet will generally not be as sharp as with ram-coin dimpling unless the material being dimpled has a relatively-low yield strength. This method, however, has the advantages of lower cost and longer tool life than ram-coin dimplina.

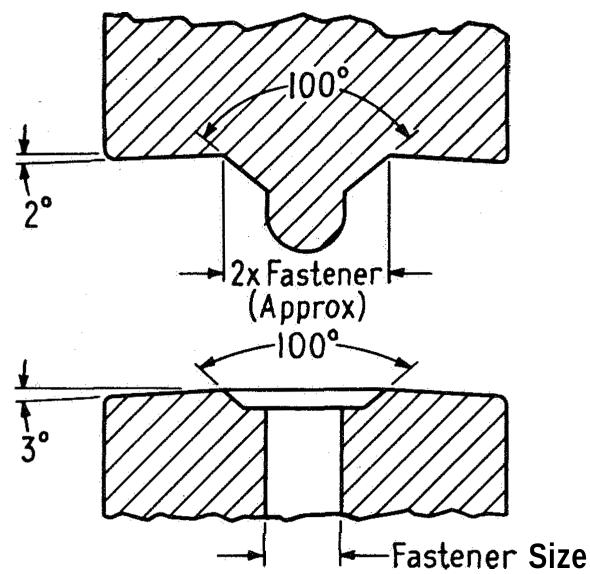


FIGURE 125. SCHEMATIC DRAWING OF TOOLING FOR COINED CONE DIMPLING (Ref. 79)

PRINCIPLES OF RAM-COIN DIMPLING

Figure 126 is a sketch of the dimpled area in a sheet. As would be expected in a press-die forming operation of this kind, the permissible deformation depends on the ductility of the sheet. The amount of stretching required to form a dimple, e, varies with the head diameter, D, of the fastener, the rivet diameter, 2R, and the bend angle, α, according to the relationship (Ref. 80)

$$e = \left(\frac{D}{2R} - 1\right)\left(1 - \cos\alpha\right) . \qquad (40)$$

If the ductility of the material is insufficient to withstand forming to the intended shape, cracks will occur radially in the edge of the stretch flange or circumferentially at the bend radius, as is shown in Figure 127. The latter type of failure is more prevalent in thinner sheets. Radial cracks are more common in thick stock. The harder tempers of stainless steels may edge crack unless they are dimpled only to certain limiting dimensions.

The general equation developed by Wood and his associates (Ref. 69) for predicting ram-coin dimpling limits from the parameters indicated in Figure 144 is

$$\frac{H}{R} = \frac{0.444(\epsilon_{2.0})^{0.253}}{1 - \cos\alpha} . \qquad (41)$$

The value $\epsilon_{2.0}$ in the equation is the elongation in a 2-inch gage length for the material at the temperature of interest (e.g., $\epsilon_{2.0} = 0.5$ for 50 percent elongation).

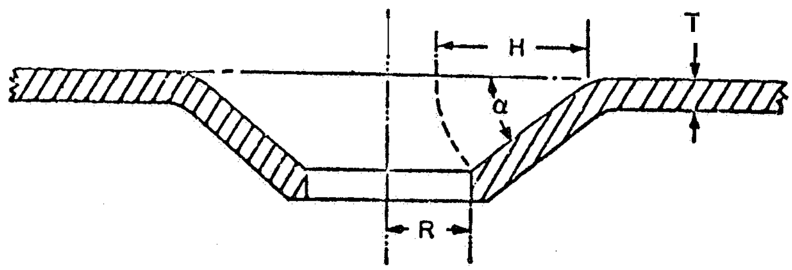


FIGURE 126. PARAMETERS FOR DIMPLING (Ref. 80)

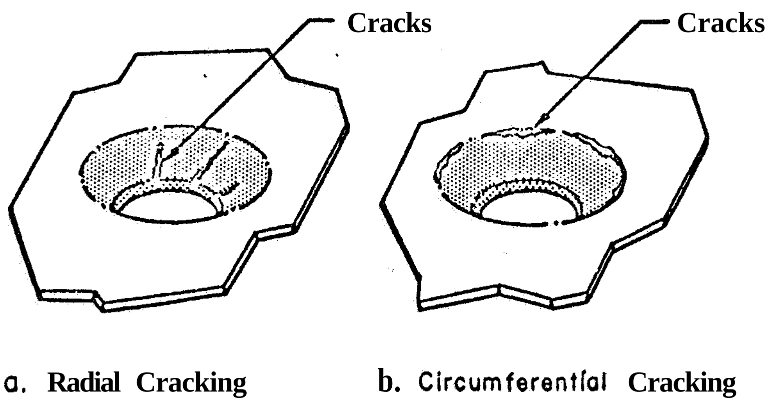


FIGURE 127. MAJOR FAILURES IN DIMPLING (Ref. 69)

The standard aircraft dimple angle, α, in Figure 126 is 50 degrees although other angles may be used for special purposes. Dimpling requires a considerable amount of ductility. Most of the stainless steels are sufficiently ductile at 100-degrees for flush screws and rivets up to 1/4-inch diameter to be dimpled. These forming limits are obtainable at room temperature in all tempers and sheet thicknesses up to 0.062 inch. The annealed stainless steels can usually be dimpled from punched holes; the harder tempers require drilled holes that are carefully deburred, Warming of the ferritic grades such as Types 430, 442, and 446, in the temperature range of 250 to 400F increases their impact toughness and may prove helpful in the dimpling of these materials.

The essential features of ram-coin dimpling are illustrated in Figure 128. In this process, a pressure in excess of that required for forming is applied to coin the dimpled area and reduce the amount of springback. The five positions shown in Figure 128 for a triple-action ram-coin dimpling machine are the approach, preform, coining, end of stroke, and retraction.

Equipment. The choice of size of ram-coining-dimpling equipment depends on the pressures needed to deform the sheet. A guide in choosing size ranges for dimpling machines needed to produce dimples for various rivet and screw sizes is tabulated below:

3/32- to 1/8-inch rivets	Up to 10,000 lb
5/32-inch rivet	10,000 - 20,000 lb
3/16-inch rivet and screw	15,000 - 25,000 lb
1/4 -inch rivet and screw	18,000 - 40,000 lb
5/16-inch screw	25,000 lb and up

The capacities of four commercially available dimplers are given in Table XLII. Such machines can easily be converted to riveting by changing the dies. Figure 129 is a photograph of the Chicago Pneumatic Model

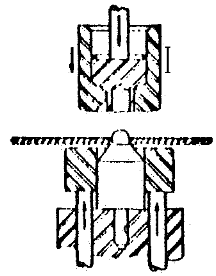
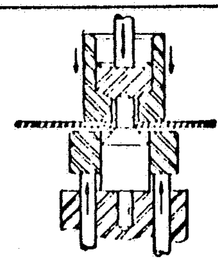
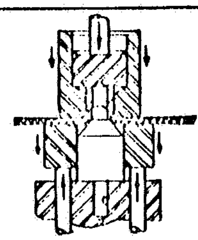
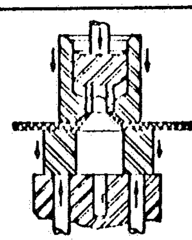
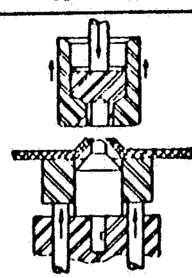
Position I		a. Approach Sheet Is positioned, with punch pilot in pilot hole and die assembly is coming down to contact position; loading farce on coining ram Is ot preselected value
Posi ion 2		b. Preform Die assembly has just contacted work, and timed heating stage is beginning; controlled preforming pressure is increasing to partial-ly farm dimple and to further accelerate heat tronsfer
Position 3		c. Coining Timed "Preform* stage has ended, and final coining stage begun; downward movement of die assembly is creating flrm gripping action between die and pad faces In area around dimple, preventing outward flow of material os dimple Is coined; coining rum controls hole stretch and balances internal strains, eliminating radial and internal shear crocks
Position 4		d. End of Stroke Dimple Is now fully farmed; the confining action of pod face, die face, and coining ram has forced material into exact con-formation with tool geometry
Pbsit ion 5		e. Retraction As die assembly retracts to starting pasitlan, load on pressure pad raises pressure pod to starting position and strips dimple from punch cone f. Result Minimum sheet stretch, minimum hale stretch, maximum definition, improved nesting

FIGURE 128. SEQUENCE OF OPERATIONS IN TRIPLE-ACTION RAM-COIN DIMPLING .

Courtesy of Convair, General Dynamics Corporation, San Diego, California.

TABLE XLII. CAPACITIES AVAILABLE IN SELECTED COMMERCIAL DIMPLING MACHINES

Model No.	Dimpling Pressure Capacity, lb	Manufacturer
CP450EA	20,000	Chicago Pneumatic Tool Co.
AT256S	30,000	Aircraft Tools Company
CP640EA	40,000	Chicago Pneumatic Tool Co.
AT260A	100,000	Aircraft Tools Company

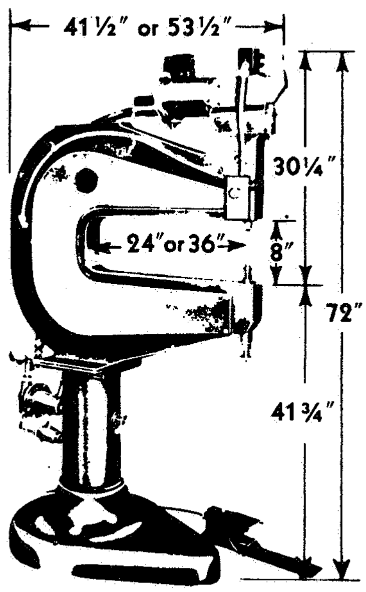


FIGURE 129. CP-450-EA DIMPLING MACHINE

Courtesy of Chicago Pneumatic Tool Company, New York, New York.

CP-450-EA compression riveter and dimpler. The dimensions on the photograph show the size of one type of this machine. Such machines are electric and air operated and manually controlled. Within a single model, there are a number of variations on types available. Such variations would include the depth of the yoke (reach) and also the total yoke gap. Equipment manufacturers should be consulted for specific information on models, sizes, and other features available.

Tooling. Since the stainless steels can generally be dimpled at room temperature, there are no unusual problems with tooling. Die materials for dimpling must be capable of resisting shock. Shock-resistant tool steels such as the hardened chromium-vanadium grades are suitable for use as both punches and dies. The coining ram may be made of materials such as case-hardened SAE 4620 steel.

Where elevated temperature dimpling is required, tool steels may be used up to about 1200F. Both resistance and induction methods are available for heating the tooling for such elevated-temperature dimpling applications.

Lubricants. No lubricants are required for room temperature or elevated temperature dimpling.

Calculated Dimpling Limits. The general theoretical predictability equation for ram-coin dimpling (Equation 41) was derived by Wood and his associates (Ref. 69). The value of $e_{2.0}$ in the equation is the elongation in a two-inch gage length for the material at the temperature and temper of interest. Calculations based on Equation 41 are used to construct a dimpling formability curve of the type shown in Figure 130 for any of the stainless steel materials and tempers. The

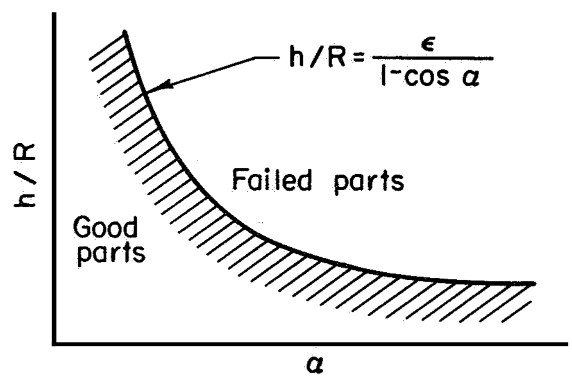


FIGURE 130. DIMPLING FORMABILITY CURVE (Ref. 69)

value of such curves is to predict if a given temper of stainless steel can be dimpled at a specified temperature and dimpling bend angle.

For such calculations, it is always desirable to experimentally determine the elongation, $\epsilon_{2.0}$, for the specific material under consideration using the proposed dimpling conditions. When such data cannot be obtained readily, data on elongations found in the literature may be used with reservations. Table XLIII gives typical room-temperature elongation values in a 2-inch gage length for selected stainless steels in various conditions of cold work or temper.

Post Dimpling Treatments. Since the stainless steels normally are dimpled after having been fabricated into parts, no heat treatments subsequent to dimpling are required. The dimpled parts should not require flattening or straightening if the dimpling was performed properly.

Flash often occurs at the edges of the dimples especially during ram-coin dimpling. The ram-coined dimpled holes generally will need to be redrilled and deburred after dimpling. Figure 131 illustrates these post dimpling operations on one side of a dimpled hole. The deburring may be done with a special facing cutter equipped with a microstop tool. The width of the flat surface on the back side of the dimple should be about 1/2 the material thickness. However, when deburring sheet 0.060 inch thick and thicker, the flat width should not exceed 0.030 inch.

Dimpling Experience. Dimpling of stainless steels in industry is being done in a routine manner. The Columbus Division of North American Aviation makes extensive use of dimpling of the austenitec stainless steels (Types 301 and 321) in the fabrication of fire curtains and shrouding (Ref. 124). They have dimpled stainless steel sheet at room temperature ranging

TABLE XLIII. TYPICAL ROOM-TEMPERATURE VALUES OF ELONGATION IN A 2-INCH GAGE LENGTH FOR SELECTED CONDITIONS OF A NUMBER OF TYPES OF STAINLESS STEELS[(a)]

Stainless Type	Condition	Elongation, percent, 2-inch Gage Length
201, 301	Annealed	50
	1/4 Hard	25 (Minimum)
	1/2 Hard	15 "
	3/4 Hard	10 "
	Full Hard	8 "
	Extra Hard	1 "
302	Annealed	67
	10 Percent Cold Reduction	43.5
	20 " " "	31.0
	30 " " "	19.5
	40 " " "	14.0
	50 " " "	10.5
	60 " " "	7.0
304	Annealed	54.5
	10 Percent Cold Reduction	36.5
	20 " " "	24.0
	30 " " "	15.5
	40 " " "	12.0
	50 " " "	9.0
	60 " " "	6.0
304L	Annealed	58.0
	5 Percent Cold Reduction	43.0
	10 " " "	35.0
	20 " " "	24.0
	30 " " "	15.0
	50 " " "	4.8
305	Annealed	62.3
	10 Percent Cold Reduction	45.5
	20 " " "	30.3
	30 " " "	17.5
	40 " " "	11.0
	50 " " "	7.5
	60 " " "	7.3

TABLE XLIII. (Continued)

Stainless Type	Condition	Elongation, percent, 2-inch Gage Length
309	Annealed	45.0
310	Annealed	44.0
316 (b)	Annealed	54.0
321 (b)	Annealed	52.0
347 (b)	Annealed	46.0
405	Annealed	31.3
	15 Percent Cold Reduction	8.3
	30 " " "	4.8
	45 " " "	3.3
	60 " " "	2.5
414	As Rolled	6.0
	Annealed	20.0
430	Annealed,	32.0
	15 Percent Cold Reduction	8.5
	30 " " "	3.0
	45 " " "	2.5
	60 " " "	1.5
446	Annealed	25.5
	10 Percent Cold Reduction	21.0
	20 " " "	4.0
	40 " " "	3.5
	60 " " "	2.0

(a) Data taken from Allegheny Metal Blue Sheets on Stainless Steel, Allegheny Ludlum Steel Corporation, Pittsburgh, Pennsylvania

(b) Data from a commercial rolling facility on the averages of many heats of each grade.

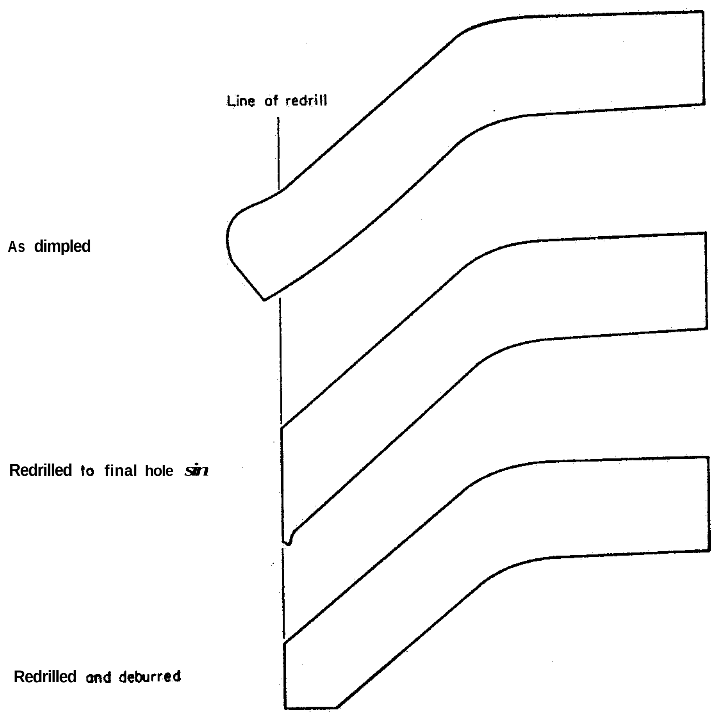


FIGURE 131. ENLARGED SECTION OF DIMPLE SHOWING POST-DIMPLING OPERATIONS

Courtesy of Zephyr Manufacturing Company, Inc., Inglewood, California.

in thickness from about 0,020 to 0,070 inch to accept flush head fasteners ranging in diameters from 3/32-inch rivets to 3/8-inch flush head screws. Most of the dimples were made for 100 degree (2α) flush-headed fasteners. The bulk of the materials that were dimpled were in the annealed condition. Some materials in the harder tempers also have been dimpled.

The North American Aviation experience in dimpling the stainless steels appears typical of that found generally in industry. The austenitic grades, such as Types 301 and 302, are readily dimpled at room temperature without difficulty (Ref. 125). At times it may be necessary to use elevated temperatures to satisfactorily dimple the mortensitic grades of stainless steel. When such is the case, the'heat required for dimpling may be supplied either by a resistance heating machine such as is supplied by Zephyr[a] or an induction heating machine as is supplied by Aircraft Tools[b].

(a) Zephyr Manufacturing Company, Inc., Inglewood, California.

(b) Aircraft Tools, Inc., El Segundo, California.

SIZING.

Introduction. Sizing is a final forming operation used to bring formed or preformed parts to specific tolerances. When the form tooling has been properly designed to compensate for the predictable springback in the stainless steels, very little sizing is required. Tolerances of about ± 0.030 inch usually are obtained in forming the stainless steels. A sizing operation usually is required when tolerances closer than the ± 0,030 inch are required.

Sometimes a number of preformed parts of the austenitic stainless steels are welded together to form a larger assembly. After annealing, the assembly is sized in a restriking or sizing die at room temperature to obtain the desired tolerances and shapes. Sizing or restriking operations also are used to produce smaller die radii and deeper parts than can be achieved in a single forming step. Such parts usually are annealed and trimmed prior to the final sizing operation. As a general principle, it is advisable to fill or set a sharp corner or produce a sharper bend radius in sizing by pushing the metal into the desired area rather than to stretch the metal across a bend, The metal frequently tears when stretched during sizing. Sometimes sizing must be performed in more than one step if the parts are very complicated.

Parts made of the austenitic and ferritic stainless steels are nearly always sized at room temperature. It may be necessary to use elevated temperatures to size parts of the martensitic grades. For all of the stainless steels, it is desirable to anneal the preformed parts prior to sizing. Recently, a rather new process called cryogenic sizing or forming was developed to produce tank-like shapes from the austenitic grades, expecially Type 301. Such tanks reportedly have higher strength than are obtained by other forming methods.

The stainless steels can be sized by benching, by cold or hot sizing in suitable fixtures or dies, or by cryogenic or subzero sizing.

Benching. Benching is the simplist, least expensive, and the most commonly used method of sizing. It is a hand-forming operation used to bring parts produced by other aeformation processes to the aesired tolerances. Benching consists of placing a preformed part over a male aie of the desired dimensions at room temperature and beating the part with lead strips. The term benching is used because the work generally is carried out with the die lying on a bench.

Unless they have been annealed, stainless steel parts are usually quite hard when benched. Therefore, a considerable amount of benching time may be required to bring the part to the desired dimensions. Sometimes formed parts fracture during benching. Because of this, it is advisable, whenever possible, to anneal the formed or preformed part after forming but prior to benching. Martensitic stainless steels may be heat treated after benching to obtain the aesired properties. The austenitic and ferritic stainless steels cannot be hardened by heat treatment and generally are used in the work-hardened condition after bench sizing. Sizing in dies may be accomplished by restriking parts in matched dies at room temperature or by clamping the parts in matched dies at an elevated temperature.

Sizing in Dies, Sizing performed at elevated temperatures utilizes the creep-forming principle to produce parts accurately to specified dimensions by the controlled application of pressure and heat. 411 that is generally required to size preformed parts of the austenitic stainless steels at room temperature is a matched set of dies and a suitable source of pressure such as a mechanical or hydraulic press. The pressure is nearly always applied in a vertical direction. The horizontal forces result from reaction with the rigid tooling. Forces that approach the yield strength of the material are required. The minimum pressure should be used that will size the part considering the sheet thickness, amount of cold work in the part, and the stainless steel grade. This will insure maximum life from the sizing dies.

Sizing the stainless steels at elevated temperatures instead of room temperature reduces the forces required and the possibility of tooling damage. Hot sizing may be done in a press with heated platens or in wedge-type fixtures that are heated in conventional furnaces. The latter method is simpler and less expensive than sizing in presses with heated platens. Both of these methods are described in detail for the sizing of the precipitation-hardenable stainless steels (Ref. 126).

Subzero Sizing and Forming. Subzero or cryogenic sizing and forming involves the mechanical working or forming of alloys at subzero temperatures. In addition to improving the dimensional tolerances, the method also produces higher strengths in selected austenitic stainless steels than have been produced by conventional forming methods. These higher strengths probably result from a combination of the following three metallurgical influences that occur during subzero sizing and forming (Ref. 127):

(a) The stainless steels are strengthened by work hardening.

(b) The stainless steels are strengthened by transformation of part of the austenite to a low-carbon martensite. This probably produces the majority of the increased strength resulting from cryogenic forming.

(c) Aging at elevated temperatures after cryogenic sizing further increases the strength.

To date it appears that a greater increase in strength is obtained from Type 301 stainless steel than from other austenitic stainless steels when cryoformed and aged. High-strength pressure vessels have been produced for use as fuel tanks for rockets and missiles, Typical hoop strengths for such vessels are shown in Table XLIV for Type 301 stainless steel welded tanks both before and after aging following cryogenic sizing (Ref. 128). Yield strengths greater than 300,000 psi are obtained.

A process known as "ARDE forming" has been developed in which undersized high-strength, welded tanks are first fabricated and then expanded under pressure at -320 F. A schematic drawing of the process is shown in Figure 132. The tank first is welded generally using hydrospun ends. The side walls are produced by roll bending techniques. Figure 133 illustrates a typical preformea tank. The tank must be equipped with a pressure fitting or boss so that it can be pressurized during the sizing operation. The cryogenic stretch forming or sizing operation then is carried out in an open pit in the ground. The forming aie is a cylindrical

TABLE XLIV. TYPICAL HOOP STRENGTHS FOR CRYOGENIC STRETCH FORMED PRESSURE VESSELS (Ref. 128)

	Cylinders[b]		Spheres[c]	
	Un-aged	Aged	Un-aged	Aged
Yld Str, 1000 psi	240	300	210	270
Burs! Str, 1000 psi	260	310	220	280

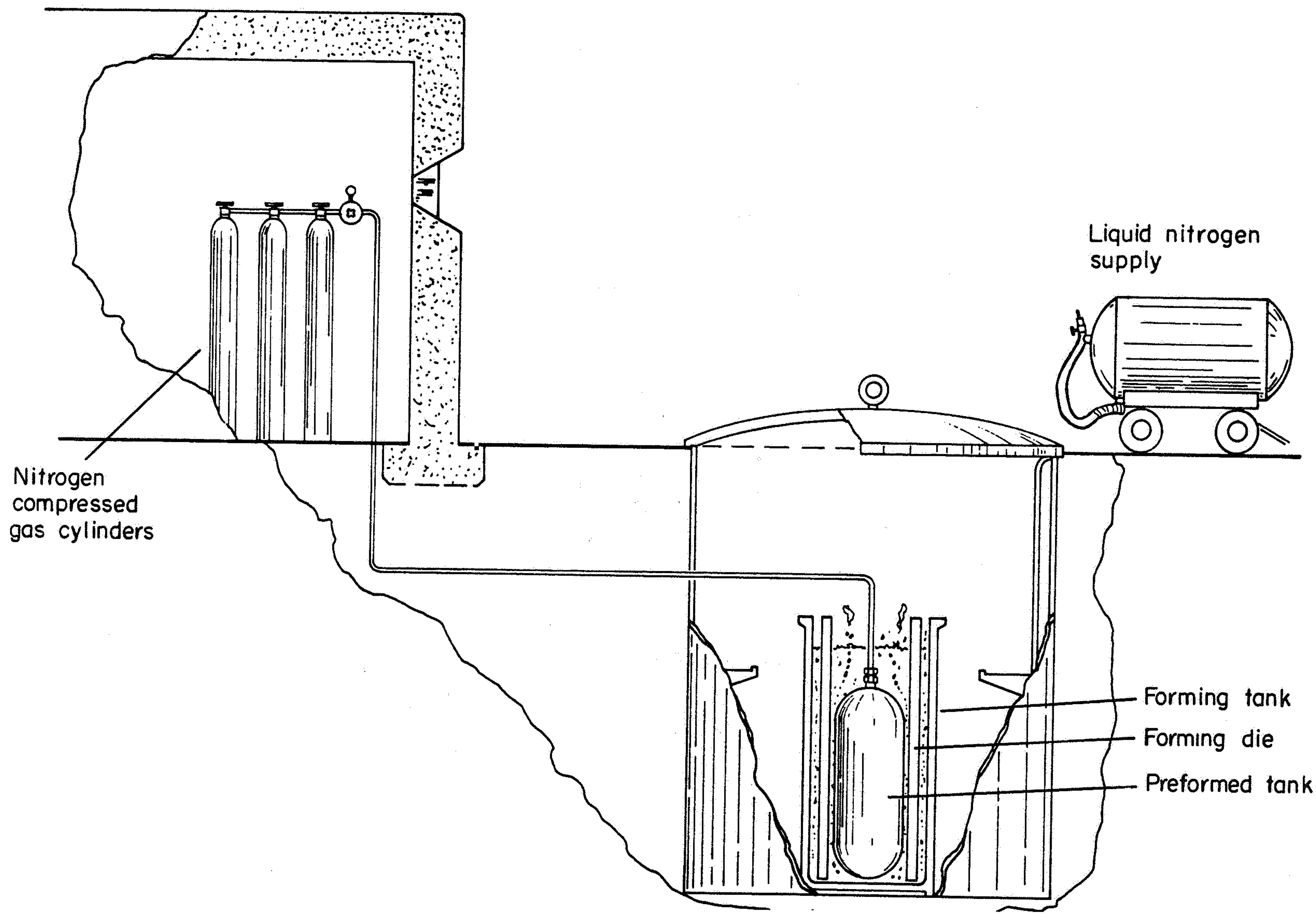


FIGURE 132. SCHEMATIC OF "ARDE FORMING" PROCESS (Ref. 129)

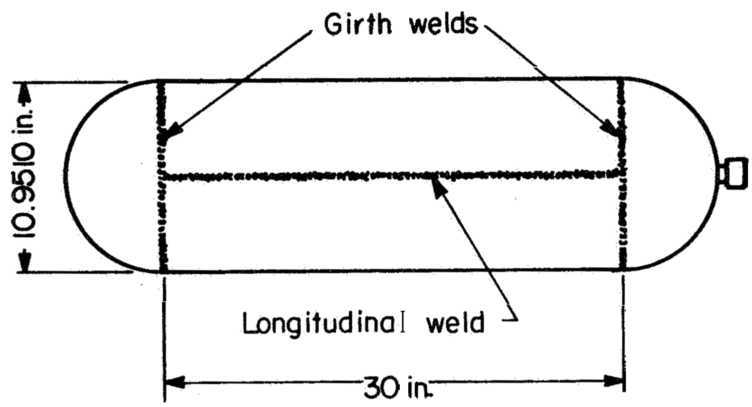


FIGURE 133. TYPICAL PREFORM (Ref. 127)

tube having a wall thickness six times that of the cylinder to be stretched. The following equation can be used to calculate the inside diameter of the die:

$$D_d = \left(\frac{0.85S_c}{E} + 1\right) D_Y \qquad (42)$$

where

D_d = the inside diameter of the die

D_Y = the outside diameter of the preformed cylinder

S_c = the stress in the cylinder wall when it just contacts the die

E = the modulus of elasticity

Stainless steel is a suitable die material since it will not become brittle at the forming temperature. The bottom edge of the die usually is scalloped to allow liquid nitrogen to escape as the welded preform expands.

For a typical subzero sizing or stretch-forming operation by the ARDE forming technique, the following sequence of operations is followed.

1. The forming tank in the pit is filled with liquid nitrogen. Usually this tank is suitably insulated on the outside diameter to conserve liquid nitrogen.

2. The die is inserted into the tank and then the undersized welded preform is inserted and filled with liquid nitrogen. The liquid nitrogen must completely cover the preform.

3. The high pressure line is attached and when the tank has cooled to -320 F, it is pressurized to expand it to the diameter of the die. The pressurizing gas is nitrogen.

Springback when the pressure is released permits the tank to be removed from the die without difficulty. The tanks also can be stretched by free forming without the use of a die. The ends of the tank are free formed even when a cylindric21 die is used to constrain the side walls of the tank. Usually preformed tanks are stretched in the range of 5 to 15 percent by ARDE forming. Table XLV gives permissible stretch values for thin-wallea sections of Type 301 stainless steel in various tempers.

The design of the preform depends on the strength of the material to be stretched cryogenically. Equations that have been used for preform design for subsequent ARDE forming are summarized in Ref. 127.

TABLE XLV. PERMISSIBLE STRETCH VALUES FOR THIN-WALLED SECTIONS OF TYPE 301 AUSTENITIC STAINLESS IN VARIOUS TEMPERS (Ref. 79)

Temper	Permissible stretch, Percent
Annealed	20 (up to 30 percent €or symmetrical and rigid sections)
1/4 hard	15 to 20
1/2 hard	5 to 10
3/4 hard	2
Full hard	2

Table XLVI compares the properties obtained in Arde-formed Type 301 stainless steels with those of other typical aerospace materials. The strength to density ratio of the cryostrained and aged Type 301 stainless steel is surpassed only by those of the two aged titanium alloys. However, stainless steel is amuch less costly material than titanium alloys.

Figure 134 shows a number of shapes of stainless steel tanks that have been sized by cryogenic forming. The shapes range from nearly cylindrical to almost spherical. Figure 135 illustrates a welded preform used to produce

TABLE XLVI. COMPARISON OF TYPE 301 STAINLESS STEEL WITH OTHER TYPICAL AEROSPACE MATERIALS AT AMBIENT TEMPERATURES (Ref. 127)

Alloy	Condition	Density, lb/in.^{3}	Ultimate Tensile Strength, 1000 psi	Strength-Density Ratio, 1,000,000 in.
Type 301 Stainless Steel	Strained 12 percent at -320°F	0.29	250	0.86
Type 301 Stainless Steel	Cryostrained + aged	0.29	300	1.02
17-4PH Stainless Steel	Aged 1 hr at 900°F	0.282	200	0.71
17-7PH Stainless Steel	CH-900 sheet	0.277	262	0.95
18Ni (250) Maraging Steel	Aged 3 hr at 900°F	0.29	260	0.90
18Ni (300) Maraging Steel	Aged 3 hr at 900°F	0.29	290	1.00
2014 Aluminum Alloy	T6	0.101	70.2	0.70
7178 Aluminum Alloy	T6	0.102	90.0	0.88
Ti-6Al-4V Alloy	Aged 8 hr at 900°F	0.160	165	1.03
Ti-8Al-1Mo-1V Alloy	Aged 8 hr at 900°F	0.156	170	1.09

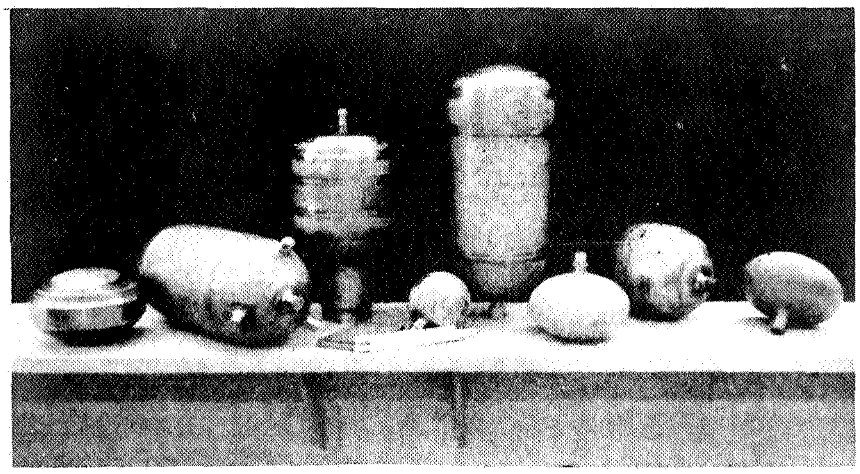


FIGURE 134. CYLINDRICAL AND SPHERICAL PRESSURE VESSELS FORMED BY CRYOGENIC STRETCHING (Ref. 128)

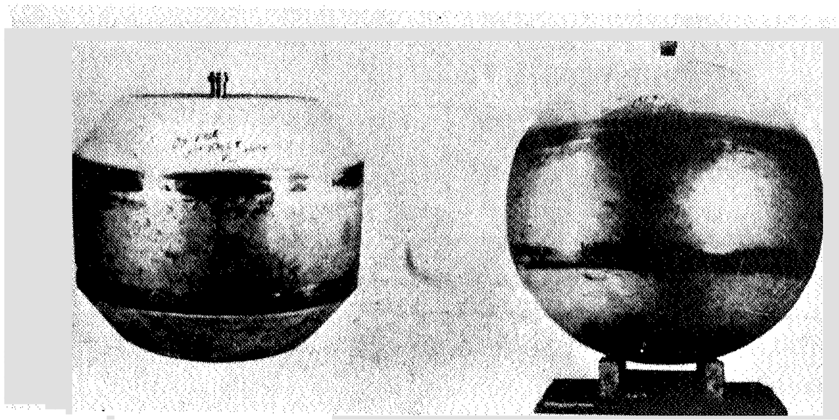


FIGURE 135. PRESSURE VESSEL BEFORE (LEFT) AND AFTER (RIGHT) CRYOGENIC STRETCHING

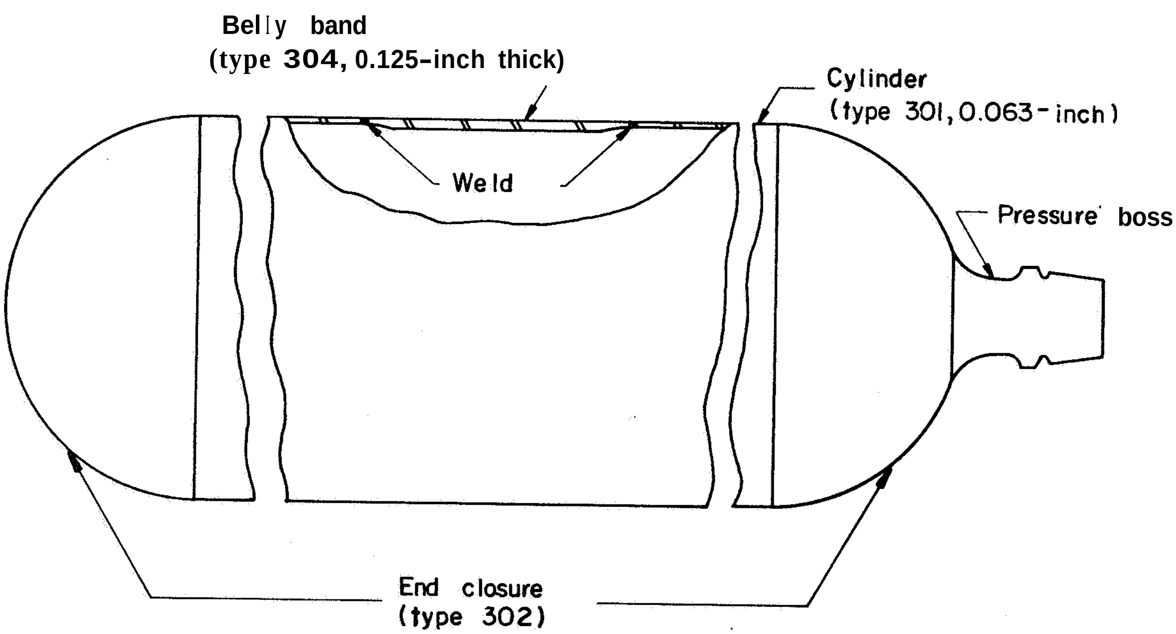


FIGURE 136. SPARROW ROCKET MOTOR–CASE PREFORM (Ref. 127)

a spherical tank. Sometimes tanks produced by cryogenic sizing and forming techniques are fabricated from several types of stainless steel as is illustrated for the Sparrow rocket-motor-case preform shown in Figure 135.

CONCLUSIONS AND RECOMMENDATIONS

One of the major problems in deformation processing of stainless steels is the variation of properties between heats of the materials. The springback from forming might vary between 5 and 40 percent while the yield strength of annealed material may vary by 30,000 psi. Research to determine the effect of metallurgical and processing variables on the properties and forming characteristics of stainless steels should be undertaken. Such studies could be used as a basis for setting closer specifications for control of chemistry and processing methods.

A large variety of stainless steels are commercially available and the steel companies are continuously developing new alloys that can be produced at a lower cost. Other alloys are under development which give superior performance in specific corrosion applications or high temperature applications, As new alloys are developed, however, the methods of fabrication are left mainly to the metal fabricators, Consequently there is considerable duplication of effort throughout the fabrication industry in the development of processing practices for new alloys. Development of fabrication data or performing mechanical property evaluations which are useful in predicting formability at a single source would result in rapid introduction of new alloys and would result in considerable reduction of trial and error type forming by the fabricators.

Types 200, 300 and 400 stainless steels are widely used throughout industry. In order to reduce fabrication costs of large components wide sheets are required. Rolling equipment or techniques for making wider sheet with smaller dimensional variations and more consistent properties throughout the sheet are required. Techniques such as pack rolling to obtain thin sheets should be investigated. Better methods for surface treatment to limit the amount of conditioning required during rolling or forging would reduce the cost of production.

New methods for using stainless steel as a cladding material and fabrication of the clad materials should be investigated.

Basic studies in the theoretical behavior of metals during rolling, forging, extrusion, or wire arawing would be of benefit in increasing the formability of stainless steels. Similarly, studies in friction and lubrication should advance the forming technology of these materials.

The stainless steels show only slight increases in formability with increasing forming temperature until the hot working range is reached. The sensitizing temperature range, which reduces the corrosion resistance of the material, also limits the utility of elevated temperature forming. Cryogenic forming on the other hand has shown considerable promise for developing high strengths in the stainless steels. The difficulty in using this type of forming result mainly from the higher strength of the material at low forming temperatures ana the special facilities requirea for forming. Some benefit has also been obtained in forming sheet, plate, ana tubing at high velocities. Research in both high-velocity forming and trapped-rubber impact forming would be expected to give significant benefits.

As with other materials, the collection of information on the mechanical properties that control the performance of sheet and plate in forming operations is necessary. It is unfortunate that the tests necessary to determine formability are not commonly performed and have not been conducted on the commercial graaes of stainless steels. Tests that will give significant data on the most important parameters in metalforming should be undertaken. The routine tension and compression tests, although useful, do not give sufficient information to make reliable prediction of formability limits.

Collection of data on the stainless steels should be relatively easy since generally only room-temperature values are required.

Development of sizing techniques in conjunction with thermal and mechanical processing of these materials should be undertaken. More reliable parts with closer tolerances and possibly higher mechanical properties could be expected from these stuaies. Variations in the thermal and mechanical processing history of stainless steels also should be studied to ascertain their effects on formability.

Development work should also be directed toward improving equipment and tooling for forming stainless by conventional processes. Major improvements in forming some part shapes, such as sheet and tubing, may result from applying a counterpressure to minimize tensile stresses developed at the surface during forming. Tube bulging, drawing, and flanging operations are likely examples. Advances are taking place in the use of polyurethane dies. Work should continue in the development of dual-hardness pads for increased formability and improved tolerances.

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DEFORMATION PROCESSING OF STAINLESS STEEL

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This document has also been reviewed and approved for technical accuracy.

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