

STAINLESS STEEL INFORMATION SERIES

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development association

COLD FORMING OF STAINLESS STEEL

Cold forming stainless steel is generally different to processing low-alloy and plain carbon (mild) steels, primarily because stainless steels are stronger, harder and more ductile, work harden more rapidly and must maintain their inherent corrosion resistance. These characteristics necessitate greater power requirements, an allowance for a greater wear rate of processing equipment and the application of working procedures that will avoid surface damage and contamination or impairment of corrosion resistance. The grade of stainless steel being processed will generally dictate the type of process to be used.

Specific grades of stainless steel are usually chosen on the basis of specific inherent properties such as corrosion or heat resistance, strength, ductility etc. The response of the steel to work hardening and the subsequent effect on the mechanical properties will play a significant part in selecting a steel for formability. The formability of a steel is largely determined by the rate at which the yield strength approaches the ultimate tensile strength as the material is cold worked.

Figure 1. shows a narrowing of the band between the yield strength and the ultimate tensile strength curves as the material is cold worked indicates that the formability is limited for grades such as 430. The narrowing shows that most of the available yielding is expended and any further deformation will result in rupture. On the other hand, for steels that do not show a great convergence such as grade 301, a tendency for greater work hardening is indicated and, together with a higher ductility for the same degree of cold work, will permit severe deformation during forming.

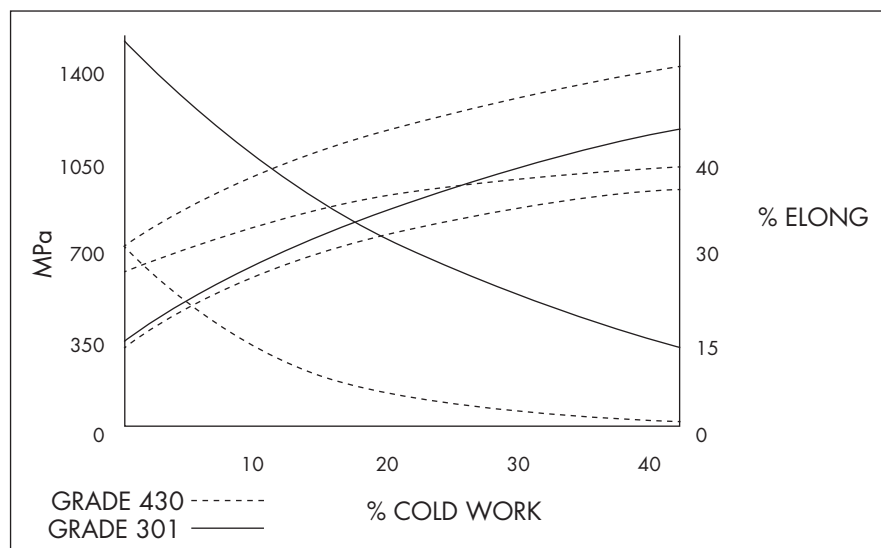


FIGURE 1 Effect of cold work on mechanical properties

FORMABILITY OF STAINLESS STEEL AUSTENITIC STAINLESS STEEL

These are the chromium nickel (Cr/Ni) and chromium, nickel manganese (Cr/Ni/Mn) stainless steels the 300 and 200 series respectively.

Nickel (Ni) and manganese are the alloying elements which promote the formation of, and stabilise, the austenitic crystal structure. The higher the Ni:Cr ratio the more stable the austenite, and hence a difference in mechanical properties and response to work hardening both of which in turn affect the formability.

Grade 301 has the lowest nickel (6.5%Ni) content of the austenitic stainless steels and has thus the highest rate of work hardening. Although having a fully austenitic microstructure in the annealed condition the lower nickel content results in a greater proportion of martensite being formed during plastic deformation which helps the metal resist necking and assists in a more uniform deformation. An advantage of the high work-hardening rate is that appreciable increases in strength and stiffness can be achieved which are useful for cold-formed structural sections. Similar properties are seen in many of the

200 series. The higher nickel grades such as 304DDQ and 305 (10-13% Ni) work harden the least of the austenitic grades. The lower work hardening rate is characteristic of a more pronounced convergence of the ultimate tensile stress and yield stress curves with cold work. This convergence means that the total deformation prior to fracture would be less than for a work-hardening grade such as grade 301. A reduction in thickness is hence not so effectively countered by a higher developed strength in the location of the thinning. A lower yield stress, as with grade 305, means that much less force is required to initiate deformation.

The cold forming operations used for austenitic stainless steels are the same as those used for ferritic stainless steels. However, the forming conditions differ. The austenitic stainless steels are capable of greater deformation due to their high ductility and thus a greater amount of reduction in a single given operation can be tolerated. Among the austenitic stainless steels, the greatest deformation in a single operation can be withstood by the more rapidly work-hardening grades such as 301 or 304. The formability of cold-worked austenitic stainless steels is adequate to permit >



cold forming operations without prior annealing. However, during a sequence of operations, the extent of cold work achieved may necessitate intermediate annealing, to return the steel to its original ductility

The better formability of the austenitic stainless steels is particularly apparent in such processes as stretch bending where a greater tensile deformation will be sustained, and in severe drawing operations where a high ductility is required.

However, because of the higher annealed strengths and response to work hardening, greater forces are required for austenitic stainless steels compared to ferritic stainless steels. Not only are higher deformation forces necessary, but the initial force must be increased as the metal deforms to accommodate the effects of work hardening.

In general, the austenitic stainless steels are more difficult to form as the nickel (Ni) content decreases, as in grade 301 (approximately 6.5% Ni). The presence of stabilising elements such as titanium (Ti), niobium (Nb) and tantalum (Ta) as well as higher carbon (C) contents have an adverse effect on the forming characteristics of the stabilised grades. This is due to the formation of second phase particles in the microstructure such as titanium carbides, carbo-nitrides etc. Forming of grades 321 and 347 is thus less favourable than grades 302, 304 and 305.

The 200 series austenitic stainless steels (i.e. those in which nickel (Ni) is partially replaced by manganese (Mn) require more power due to their greater initial strength and a high response to work hardening. They also suffer a greater degree of springback than the equivalent 300 series.

FERRITIC STAINLESS STEELS

These are plain chromium stainless steels which have low carbon (C) contents (< 0.1% C). They are contained in the 400 Series.

The mechanical properties of the ferritic stainless steels compared with the plain carbon (mild) steels indicate that different cold forming methods are required for these materials.

The higher yield strength of ferritic stainless steel implies that more power is required for a given amount of deformation; the high ultimate tensile strength indicates that higher loads can be applied before rupture;

and the lower elongation means less plastic deformation can be tolerated prior to fracture. Although higher initial deformation forces are required, the force/load does not need to be increased as deformation progresses, because ferritic stainless steels do not work harden to the same extent as the austenitic stainless steels. The poor notch ductility of the ferrite stainless steels in heavy sections requires that the speed at which the load is applied will have to be slower than for low alloy or plain carbon (mild) steels. Ferritic stainless steels will tend to fracture under shock loads at low temperatures.

As can be seen in Figure 1, the yield strength for grade 430 converges rapidly to the ultimate tensile strength as the cold work progresses. Since the yield point must be exceeded for plastic deformation (and hence for cold forming) to occur the close convergence of the yield and ultimate tensile stresses is conducive to rupture. This response is typical of the ferritic stainless steels. This effect, plus the rapid drop in ductility with increasing cold work, necessitates the use of fully annealed sheet together with intermediate annealing, where necessary, during processing.

Severe bending should always be carried out transverse to the rolling direction due to directionality of the as-rolled microstructure.

The decreasing ductility with increasing work of the ferritic stainless steels requires more inter-annealing steps than is necessary for plain carbon (mild) steels when spinning or roll forming. Nevertheless, grades such as 409, 441 and 430 are often used for applications that require forming by blanking, bending, drawing or spinning.

MARTENSITIC STAINLESS STEELS

These are plain chromium stainless steels which have relatively high carbon (C) contents (0.15-1.2% C). They are also contained in the 400 Series.

The forming characteristics of grades 403, 410 and 414 (the lower carbon grades) in the fully annealed condition may very similar to those of the ferritic stainless steels.

The remaining martensitic grades with higher carbon contents are not recommended for cold forming.

DUPLEX STAINLESS STEELS

These steels have excellent resistance

to stress corrosion cracking. They have a two-phase (duplex) microstructure consisting of about equal proportions of austenite and ferrite.

Duplex stainless steels can be readily cold formed by the same methods used for austenite stainless steels.

Duplex stainless steels have higher proof strengths than the conventional austenitic stainless steels and therefore more power is required to initiate forming. When forming grades such as 2101, 2304 and 2205, the capacity of a press brake will be reduced by 50% when compared to austenitic stainless steels, although once the yield stress has been attained, the duplex stainless steels flow as easily as the austenitic stainless steels.

Because of the higher proof stress of the duplex stainless steels, greater springback can be expected. Over-bending by approximately 10% on a 90° bend should compensate for this. Hydraulically operated presses are preferred.

Duplex stainless steels such as 2101, 2304 and 2205 require larger inner bend radii — typically 3 to 4 times plate thickness. Severe bending should always be carried out transverse to the rolling direction due to directionality of the as-rolled microstructure.

Where heavy cold forming has been done, consideration should be given to heat treatment — particularly if severely corrosive service conditions are to be expected.

POWER REQUIREMENTS

Power requirements for forming stainless steels, mainly because of the high yield strength, are greater than for equivalent thicknesses of low alloy and plain carbon (mild) steel.

As a general rule, approximately twice as much power is required for forming stainless steels. Not only is more power required initially, but because the austenitic and duplex stainless steels work harden rapidly, increasingly more power is required as forming proceeds. Most of the ferritic grades behave in a similar manner to the carbon steels with regard to work hardening, although more power is required to initiate the forming process, due to the higher initial yield strength of the ferritic stainless steels.

LUBRICATION

The lubrication requirements for forming stainless steels are more >



TABLE 1

	FATTY OILS	SOAP-FAT PASTES	WAX-BASED PASTES	HEAVY DUTY EMULSIONS	C FILM	SULPHURIZED OR SULPHO-CHLORINATED OILS	HIGH VISCOSITY CHLORINATED OILS	LOW VISCOSITY CHLORINATED OILS	GRAPHITE MOLYBDENUM DISULPHIDE
PRESS BRAKE FORMING	☆	✖	☆	✖	☆	☆	✖	☆	✖
PRESS FORMING	✖	✖	☆	☆	☆	☆	☆	☆	✖
MULTIPLE SLIDE FORMING	☆	☆	☆	☆	✖	☆	✖	☆	✖
DEEP DRAWING	✖	☆	☆	☆	☆	✖	☆	☆	✖
SPINNING	☆	☆	☆	☆	☆	✖	✖	✖	✖
CONTOUR ROLL FORMING	☆	☆	☆	☆	✖	☆	☆	☆	✖
EMBOSSING	☆	✖	☆	☆	☆	☆	✖	☆	✖
TABLE 1	☆ BEST			☆ GOOD		✖ NOT RECOMMENDED			

critical than in forming plain carbon (mild) and low alloy steels.

This is due to the necessity of preserving the high quality surface on stainless steels. In addition, stainless steels have higher strength, greater hardness, lower thermal conductivity and higher coefficients of friction. Galling and scoring may also be expected, especially where high pressures are to be employed. The selection of a particular lubricant for a forming process is based on two primary considerations:

- the lubricant must be efficient ie: to assist in the forming process and minimise scrap and excessive scoring.
- the lubricant must maximise the tool life, which is determined by wear and pick-up.

In addition, a suitable lubricant is not determined solely by the particular forming operation, but also by other factors such as material and tool surface roughness.

For medium and severe forming, a pickled surface after cold rolling and annealing (i.e. 2D finish) has been found to be the most suitable. The relatively rough surface retains lubricants better than a smooth or polished surface and lubricant is thus drawn in between the contacting surfaces.

It is also important to consider the ability and ease of removal of the lubricant after forming, particularly if the part is to be subsequently exposed to high temperature (eg: an annealing or stress relief heat treatment). If lubricants are not totally removed,

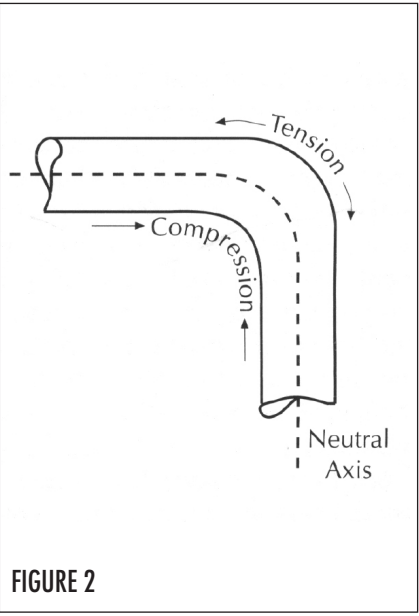
carbon can diffuse into the steel and cause sensitization, with subsequent impairment of corrosion resistance.

Table 1 lists the suggested lubricants for a particular forming process.

- Mineral oils, soap solutions and water emulsions or general purpose soluble oils are omitted since they are ineffective in most stainless steel forming operations.
- Regardless of the operation being performed, selection of a lubricant can affect both quality and cost of the formed product. The lubricant must have the properties required for the job, but use of a heavier duty lubricant than is required is poor economy because of the cost incurred in its removal.

SPRINGBACK

In any bending operation that produces



a permanent deformation of the workpiece, the metal on either side of the neutral axis suffers either compressive or tensile plastic deformation. Refer to Figure 2.

On either side of the neutral axis, plastic stresses remain in those parts of the material that have passed the elastic limit (yield point) and those parts lying nearer the neutral plain that have not reached the elastic limit may have residual elastic stresses. These residual elastic stresses cause “springback”, i.e. the tendency of a deformed piece of metal to return partway to its original shape.

Springback increases if:

- The elastic limit of the material increases (due to cold work - refer to the austenitics).
- The plastic strain increases (due to the increased amount of plastically deformed material in the workpiece).
- The amount of plastic strain involved depends on both the thickness of the workpiece and the radius of the bend, not the total bend angle. Thus the amount of springback per degree of bend increases as the ratio of bend radius to sheet thickness increases. There will therefore be less springback in a given thickness sheet when it is bent through a small radius than when it is bent through a large radius. Springback can be controlled by reducing the punch radius or by slightly overbending.

BEND RADII

The smallest radius for any given metal that can be formed without cracking is called the minimum bend radius. It is generally found that the minimum bend radius increases almost in proportion to the sheet or strip thickness.

In extremely soft metals or ductile steels such as annealed austenitic stainless steels, it may be possible to form a bend with zero radius when the seams are bent through 180° to form an interlocking joint along the edges of two sheets. This can be done provided the tool edges are not sharp, otherwise the die will cut the steel while forming the bend.

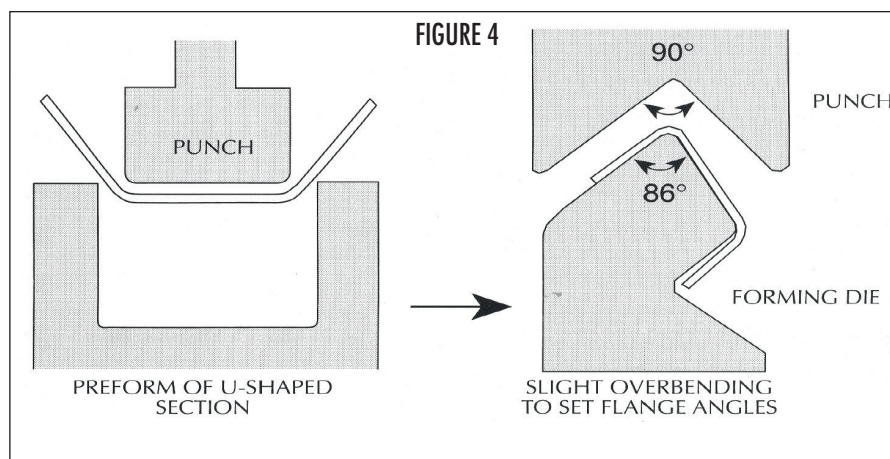
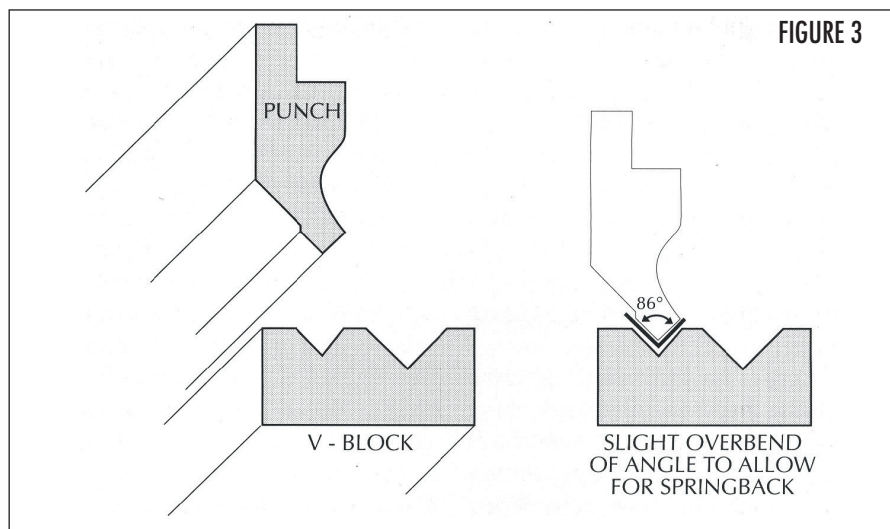
Generally, for annealed material, a bend radius (R) equal to the material thickness (T) will meet most engineering requirements. Cold worked material however, will require larger bend radii, eg:

- 1/4 Hard tempers $R = 1 - 1.5T$
- 3/4 and Full Hard tempers $R = 3 - 6T$

The bend radius selected must be done with the grade of steel in mind ie. some steels such as duplex stainless steels, require larger radii.

FORMING PROCESSES

A brief overview of some different forming processes is given below:



PRESS BRAKE FORMING

Stainless steel sheet, strip and plate of virtually all types and tempers are formed in press brake equipment. This method of forming is usually limited to small quantities and relatively simple parts. Press brakes are generally equipped with standard or sharp Vee dies, as shown in Figure 3. Springback is controlled by adjusting the angle of the dies.

All of the austenitic stainless steels in the annealed condition can be bent 180° over one stock thickness (1T), but need up to 50% more power to form than plain carbon (mild) steels. Springback must be allowed for as it is more severe in the austenitic stainless steels.

The plain chromium (400 series) stainless steels vary in their response

to press brake forming, but like the austenitic stainless steels require more power to initiate the bend.

For ordinary press brake forming, lubricants are generally not used, although the use of lubricants or pvc films may reduce scoring on sensitive finishes.

fracture because of the greater forces employed.

■ Die materials used for long service in mass production include high strength aluminium bronze, high quality tool steels and carbide tools.

The austenitic stainless steels are generally more easily press formed than other grades of stainless steel. Their work hardening characteristics which result in higher strength are often used to advantage in press formed components, the greater stiffness giving an improved resistance to fatigue. Stainless steels, and the austenitic grades in particular, have high ductility but are susceptible to wrinkling in press forming if the workpiece is stressed in compression. It is therefore recommended that in terms of metal flow, the part be stretched rather than compressed.

Press forming of the ferritic stainless steels can be improved by slightly warming the blanks to about 120-200°C. At this temperature the metal is more ductile, so less power is required for forming and, in addition, the tendency for the workpiece to crack is lowered.

Chlorinated lubricants are often used in press forming because the viscosity and activity can be adjusted over a wide range. These are also easily removed with solvents and degreasers.

A typical press-formed austenitic stainless steel component is illustrated in Figure 5 (on the following page). The severe forming induces work hardening that will increase the rigidity and fatigue resistance.

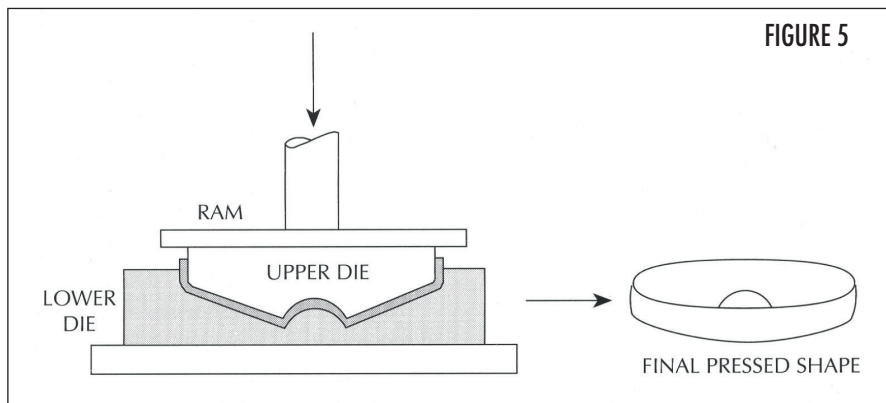
SPINNING

Stainless steel components such as cups, cones and dishes can be readily formed by manual or power spinning. Again, more power is required than for low carbon (mild) steel.

Manual spinning can be carried out

GRADE	MAX STRETCH(%)	GRADE	MAX STRETCH(%)
301	25	316	35
302	40	316	35
304	40	410	20
305	45	430	30

on all the 300 series stainless steels. The lower work hardening grades such as 304 and 304 DDQ enable greater reductions before inter-annealing becomes necessary. All annealing operations must be followed by >



pickling to restore the clean, smooth surface and to remove any carbon steel contamination.

The approximate maximum limits of stretch in manual spinning are:

The amount of stretch is not necessarily uniform over the entire component, as it varies with the shape of the form. A second stretch after annealing of approximately 8% less than the initial stretch can be attained.

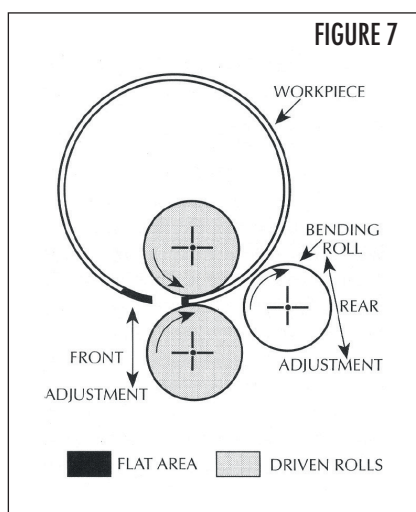
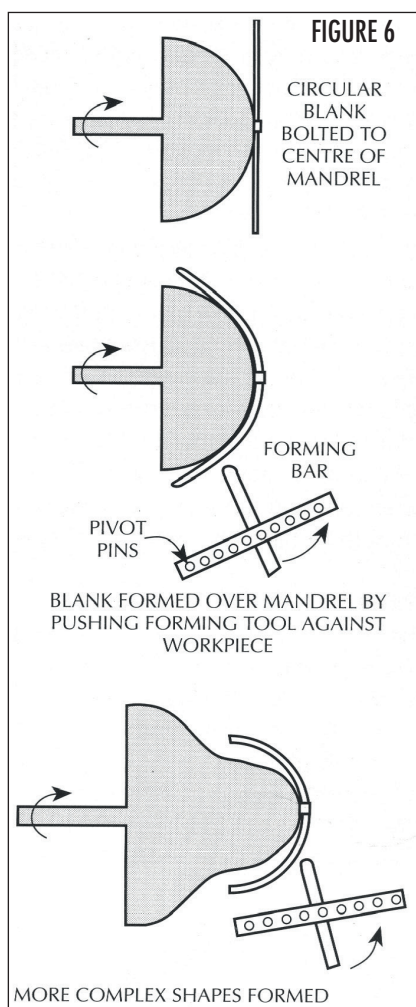
A typical sequence of operations for manual spinning of a cone is illustrated in Figure 6. The process starts with the drilling of a hole in the centre of a blank for location of the centre mounted on a tailstock. The blank is then mounted on a wooden (or metal) mandrel and the forming process accomplished by applying pressure to the surface with a bar or roller-type spinning tool.

The 400 series ferritic stainless steels, because of their relatively low ductility, do not lend themselves to manual spinning. The high pressure of the forming tool causes severe local deformation of the workpiece resulting in early thinning and fracturing.

Power spinning of the 300 and 400 series stainless steels is readily carried out with the low work hardening types being superior. Much larger reductions of type 430 can be made by this method of spinning.

Cracking at the edge of austenitic stainless steel blanks during spinning is a major problem. This is due to the localised work hardening and minute imperfections induced in the cut edge. Dressing the cut edge by grinding prior to spinning will overcome the problem. Cracking and distortion can be prevented by keeping a narrow flange on the workpiece. This flange can be trimmed off in the last operation if it is incompatible with the component design/function.

The surface of a power-spun form is rough and requires extensive finishing



to make it smooth and bright. The roller usually imparts a helical or spiral groove to the surface of the workpiece which may detract from the aesthetic appeal of the finished component.

Lubricants are used to reduce friction, minimise galling and tool drag, and also to provide cooling. For manual spinning, firmly adherent lubricants are preferred, whilst for power spinning the cooling action of the lubricant is more important. Chlorinated or sulphurised lubricants are usually avoided as they are difficult to remove and traces left on the steel could have harmful, corrosive effects.

THREE-ROLL FORMING

There are different configurations of three-roll forming machines but the principles are similar – see Figure 7.

The position of the top roll is fixed while the bottom roll adjusts vertically to compensate for material thickness. The rear roll is adjustable angularly and this determines the diameter of the cylinder formed. Usually two rolls are driven although in some machines all three rolls can be driven.

Springback can be a major problem during rolling of the austenitic and duplex stainless steels due to the large radii involved and work hardening of the steel during the forming process. It is therefore advantageous to have the equipment set up so that the desired curvature can be achieved in one pass.

Lubricants are not generally used in this type of roll forming.

CONTINUOUS ROLL FORMING

This is a process used for production of long lengths of formed sheets, such as roof sheeting, cable racking, components for rail carriages, tube forming, etc. The process involves the passage of the steel from a coil through a number of rotating rolls, each forming the material gradually in succession until the final form is achieved.

Most of the grades of stainless steel can be roll formed successfully, but care should be taken with the duplex and ferritic grades as directionality in the rolling direction can result in cracking if tight bend radii are used.

As with many of the other forming operations, tool wear and scoring of the stainless steel surfaces are an issue, and correct selection of tool materials and lubricants is critical.

STRETCH FORMING

Stretch forming is the forming of sheet, bars and rolled sections over a block of the required shape while the workpiece is in tension. The workpiece is stretched just beyond its yield point (usually 2-4% elongation) to retain the contour of the form block.

EXPLOSIVE FORMING

Explosive forming is a method of changing the shape of a metal blank by the instantaneous high pressure that results

Stainless steels may not behave the same in a high-energy, high rate forming method as when formed at a slower, more conventional rate. In some instances, certain grades of stainless steel can be accurately formed into intricate shapes without cracking by explosive forming, whereas the same grades would crack if subjected to the equivalent severity in conventional processes. The converse may also be true.

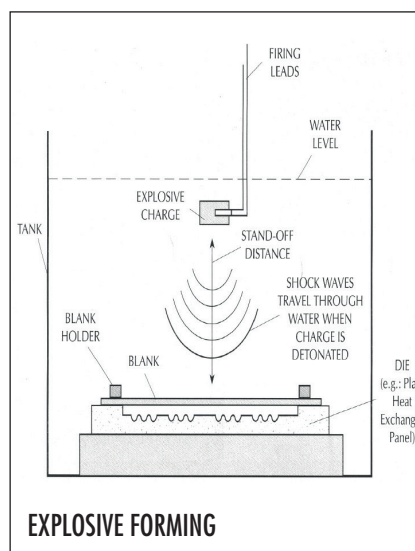
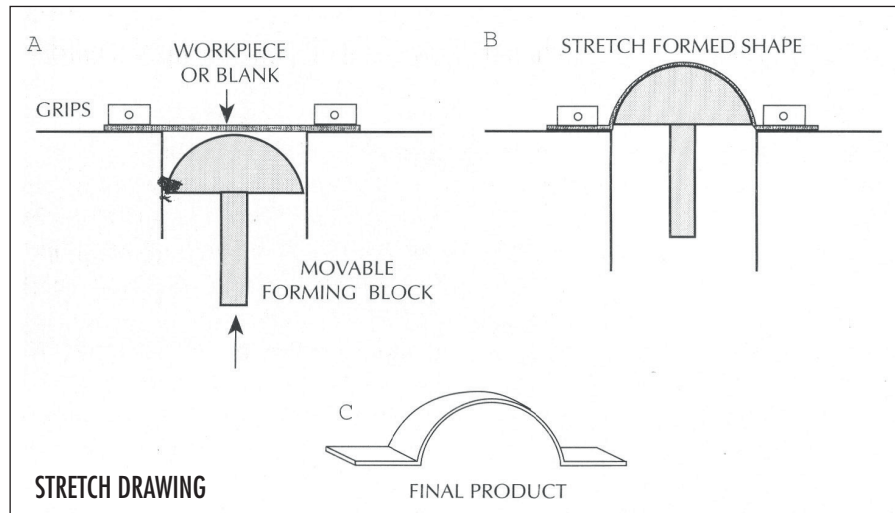
TUBE BENDING AND FORMING

Equipment similar to that used for carbon (mild) and low alloy steels is used for stainless steels although, again, greater power is needed. austenitic stainless steel tubes can be bent to a centre-line radius of 1.5 times the tube diameter. As the ratio of the tube diameter to wall thickness ($D:t$) increases, it becomes more important to provide both internal and external support to prevent wrinkling, buckling and flattening.

Numerical controlled or robotic operations are regularly used for high volume tube bending operations, such as in auto exhaust pipe production. Mandrel lubricants should be fairly heavy, viscous oil-based lubricants with emulsifiers for easy removal. Very light chlorinated mineral oil can be used in some bending operations between the wiper die and the tube.

Tubing can be flared to increase the diameter 25-30% if in the annealed condition. The diameter can be reduced by rotary swaging or increased by bulging or beading. Rubber punches are often used for this purpose.

AUSTENITIC STAINLESS STEELS, WITH THEIR HIGH DUCTILITY, CAN BE PRESSED OR FORMED INTO COMPLEX SHAPES.



Tube spinning can be used to reduce the wall thickness of tubes and to increase their strength. Producing specific shapes from tubing is a major function of tube spinning, eg. flanges can be spun at substantial savings compared with other processes such as machining. The lower work hardening grades such as 304 and 305 are more suited to spinning.

COLD-HEADING

This method of forming is used to form a head-like shape on the one end of a wire or rod blank. Cold-heading is usually associated with the production of nails, screws, bolts, rivets and other fasteners or more elaborate parts such as ball studs, pinion shafts etc. Heading is fast, scrap free and produces strong, uniform parts and is best suited to high volume production.

The amount of metal moved determines the severity of the forming process and is usually referred to as the number of diameters in the upset. In cold-heading, a diameter is a length of wire/rod equal to its diameter and hence the severity of an operation is measured in diameters, or the volume of metal deformed to the length of rod deformed.

With the exception of the free machining grades such as grade 303 and the higher carbon martensitic grades such as 420 and 440, virtually all of the 300 and 400 grades can be headed to a severity of 1.5 diameters in one or two blows.

In two or three blows, most grades can be cold-headed to a severity of about 1.7 diameters. More severe heading may require the blank to be heated.

For cold upsets as severe as 2.25 diameters, grade 430 is the only 400 series grade that can be considered. Of the austenitic types, grades 304 and 305 are best suited to cold-heading.

For mild upsets up to 1.5 diameters, ordinary machine oil applied to the die usually will suffice. For the most severe upsets a solid lubricant such as copper plating or dry lime on the stock together with machine oil is recommended.

CONCLUSION

The austenitic, ferritic and duplex stainless steels can be readily formed in all of the conventional cold forming equipment.

The austenitic stainless steels, with their high ductility, can be pressed or formed into complex shapes.

Careful selection of lubricants and attention to the extra power requirements will result in the achievement of uniform, high quality products. **SS**