# STAINLESS STEEL INFORMATION SERIES

sassda
southern africa stainless steel development association

**PULL OUT**
**PART 10**

# FORGING OF STAINLESS STEEL

The art of forging has existed from prehistory, when man first began to work with metal. Until comparatively recently it was, with few exceptions, the only method of shaping solid metal into forms such as swords, axes, eating and cooking utensils, coinage and jewellery.

Forging may be defined as the process of shaping metal by the controlled amount and direction of plastic deformation using impact or pressure.

It is usually done hot, but cold forging is also carried out.

The advantages of forging include:

- Virtually all metals and alloys can be forged.
- A wide range of sizes and shapes can be produced.
- The forgings are of near net shape.
- Excellent refinement of the microstructure takes place, particularly in that a continuous grain flow consistent with the shape of the forging occurs, which results in enhanced mechanical properties.

In recent times, forging equipment has increased in size and power, and precise controllability has been developed. Forging may now be considered as an art under scientific control.

## STAINLESS STEEL

Stainless steel is not a single material, but a family of different classifications and grades, based on alloying chromium (Cr) with iron (Fe). A chromium content in excess of ±11 % Cr imparts to stainless steel its natural built-in corrosion resistance due to the formation of an extremely thin but continuous and stable chromium oxide film on its surface.

This has been covered in detail in previous modules in this series.

**TABLE 1:** The Nominal Composition of Grades of Stainless Steel

**MARTENSITIC STAINLESS STEELS — AS TYPIFIED BY THE AISI 400 SERIES**

| GRADE | C%(1) | Cr% | Ni% | Mo% | Other % and Remarks |
|---|---|---|---|---|---|
| 410 | 0,15 | 11,5-13,5 | | | |
| 416 | 0,15 | 12-14 | | | S0,15 P 0,06 Mn 1,25 / Free-Machining |
| 416Se | 0,15 | 12-14 | | | S 0,06 P0,06 Mn 1,25 Se0,15 / Free Mach |
| 420 | >0,15 | 12-14 | | | |
| 431 | 0,20 | 15-17 | 1,3-2,5 | | |
| 440A | 0,60-0,75 | 16-18 | | 0,75 max | |
| 440B | 0,75-0,95 | 16-18 | | 0,75 max | |
| 440C | 0,95-1,20 | 16-18 | | 0,75 max | |

**FERRITIC STAINLESS STEELS — AS TYPIFIED BY THE AISI 400 SERIES**

| GRADE | C%(1) | Cr% | Ni% | Mo% | Other % and Remarks |
|---|---|---|---|---|---|
| 430 | 0,12 | 14- 18 | | | |
| 430F | 0,12 | 14- 18 | | | S0.15 P 0,06 Mn1,25 / Free-Mach |
| 446 | 0,2 | 23-27 | | | N 0,25 max |
| (•) 3CR12 | 0,03 | 11-12 | | | |

**AUSTENITIC STAINLESS STEELS — AS TYPIFIED BY THE AISI 300 SERIES**

| GRADE | C%(1) | Cr% | Ni% | Mo% | Other % and Remarks |
|---|---|---|---|---|---|
| 301 | 0,15 | 16-18 | 6-8 | | |
| 302 | 0,15 | 17 19 | 8-10 | | |
| 303 | 0,15 | 17- 19 | 8- 10 | | S0,15 P0,12 / Free-Machining |
| 303Sc | 0,15 | 17- 19 | 8- 10 | | S0,06 P0,12 SeO,15 / Free-Machining |
| 304 | 0,08 | 18-20 | 8-12 | | |
| 304L | 0,03 | 18-20 | 8- 12 | | |
| 309 | 0,20 | 22-24 | 12- 15 | | |
| 310 | 0,25 | 24-26 | 19 22 | | |
| 316 | 0,08 | 16 18 | 10- 14 | 2-3 | |
| 316L | 0,03 | 16- 18 | 10- 14 | 2-3 | |
| 316F | 0,06 | 18 | 13 | 2,25 | S0,15 P0,13 Mn1,5 / Free-Machining |
| 317L | 0,03 | 18-20 | 11-15 | 3-4 | |
| 321 | 0,08 | 17- 19 | 9- 12 | | Ti (5 x % C) min / Stabilised |
| 347 | 0,08 | 17- 19 | 9-13 | | Nb + Ta (10 x % C) min / Stabilised |

**DUPLEX STAINLESS STEEL — TYPICALLY AVAILABLE AS PROPRIETARY GRADES**

| GRADE | C%(1) | Cr% | Ni% | Mo% | Other % and Remarks |
|---|---|---|---|---|---|
| (•) | 0,03 | 23 | 4 | | N0, 10 |
| (•) | 0,025 | 22 | 5,5 | 3,0 | N0.15 |
| (•) | 0,025 | 18,5 | 4,7 | 2,7 | |
| (•) | 0,03 | 22 | 6 | 2,5 | N 0,05 Cu 1,75 |

**PH STAINLESS STEEL — TYPICALLY AVAILABLE AS PROPRIETARY GRADES**

| GRADE | C%(1) | Cr% | Ni% | Mo% | Other % and Remarks |
|---|---|---|---|---|---|
| (•) | 0,07 | 16 | 4 | | Cu 3,5 Nb+Ta 0,15-0,45 |
| (•) | 0,05 | 12,5 | 8 | 2,5 | Al 1,1 |
| (•) | 0,07 | 17 | / | | Al 1,2 |
| (•) | 0,10 | 16,5 | 4,3 | 2,7 | N 0,1 |
| (•) | 0,10 | 17 | 11 | | P0,3 |

Notes: (1) % max unless indicated as minimum or range
(•) Indicates Proprietary Alloy - Nominal composition given
All steels will contain normal amount of Si, P, S, except where specifically indicated
C = Carbon; Cr = Chromium; Ni = Nickel; o - Molybdenum; Si - Silicon; S = Sulphur;
P = Phosphorus; Mn = Manganese; Se - Selenium; Ti = Titanium; N = Nitrogen; Cu - Copper

## PRODUCTION OF STAINLESS STEEL FORGINGS

A great variety of stainless steel forgings of different size and shape are produced, ranging from medical instruments weighing only a few grams to massive forged heads and cylindrical shells of nuclear pressure vessels which weigh several hundred tons.

Production is carried out by:

- The steelmakers, i.e. conversion of steel made in their own steel plant; either as limited quantities of forgings of large size required for specific applications, or as larger quantities of standard forgings .
- In-House Forge Plant, i.e. conversion of purchased steel into forgings specifically for the company's own range of products, and which will usually be of large quantities falling within a narrow range of size, mass, and shape.
- "Jobbing" Forge Plant, i.e. conversion of purchased steel to meet a wide variety of individual user requirements, normally consisting of a small quantity of forgings of diverse size, mass, shape, and types of steel (plain carbon, low alloy, tool and die, stainless steels etc.).

## FORGING EQUIPMENT

The equipment used to produce forgings varies with respect to:

The forging processes which can be carried out:

- The method of applying the force.
- The size.

The different types of forging equipment include:

- Hammers
- Presses
- Upsetters
- Forging Rolls
- Ring Rollers
- Swaging Machines

Forging Processes

The shaping of the metal is normally done using two different techniques:

- Open Die Forging
- Closed Die Forging

In the production of some forgings a combination of both techniques may be used.

## OPEN DIE FORGING (ODF)

The forging is shaped between two flat (or simply contoured) surfaces by the repeated application of the forging force (hammering or pressing). Manipulation of the workpiece is needed to obtain the desired final shape, and therefore can be highly dependent on the skill and experience of the smith.

- Much forging done in "Jobbing" forge plants use this process.

## CLOSED DIE FORGING (CDF)

The final shape and size of the forging is produced between dies into which the impression (shape) has been machined.

- Preliminary shaping by the workpiece is often necessary before the final shape is forged. - This is often carried out by ODF or a combination of ODF and CDF.
- Single or repeated application of the forging force may be used dependent on the material being forged, the forging equipment employed, and the complexity of the shape.
- Higher forging forces are required, which increase as the degree of confinement and complexity increases. - This is due to the friction between the workpiece and the die, and the surface of the workpiece being chilled by the die. - Die lubricants, which are usually mixtures of graphite and mineral oils, should be judiciously used. Excessive use may lead to the carburisation of the surface layers thereby decreasing the corrosion resistance of some grades of stainless steel.
- Die design, including size, draft (the taper on the side walls of the impression), the formation and accommodation of the flash, and the location of the parting line are important due to the greater high temperature strengths of Stainless steels, and hence their higher resistance to metal flow. - A die used for the forging of plain carbon and low alloy steels may well prove to be unsuitable for the forging of the same component in stainless steel. - The die life when forging stainless steels is much less than would be obtained when forging plain carbon and low alloy steels. - Dies can vary from being very simple to extremely complex, from small to large, and also to the grades of tool steel from which they are made.
- Most of the high quantity repetitive production of identical forgings as done by Production and In-House. - Forge Plants is done using CDF.

Different forging processes include:

- Drawing Out
- Upset Forging
- Upsetting
- Ring Forging and Ring Rolling
- Die Forging
- Piercing and Core Forging

These forging processes are briefly described below, but many variations of the techniques used, and the number and sequence of operations employed to produce the required final forged component. Forging is still as much an art as a science and each smith has his own techniques.

## DRAWING OUT

Increasing the length of the workpiece by reduction of the workpiece thickness as it is progressively fed between the forging surfaces.

- The workpiece is drawn out on the square by frequently rotating it through 90°. - Rounding up of round bar is only done once the square cross section is that of the diameter. The comers are first rounded and then frequent applications of force of lower intensity are given as the workpiece is rotated through small angles. Improved size tolerance and surface finish is obtained if final forging is done between swage blocks. Dies can vary from being very simple to extremely complex, from small to large, and with respect to the grades of steel from which they are made.
- It is an Open Die Forging technique.
- The commonly used forging equipment are steam hammers and hydraulic presses.

*(Note: The piston of steam hammers used to be driven by steam; hence the name. Compressed air is now normally employed, but the term steam hammers is still used).*

- Common products include round, square, flat and hexagon bars; stepped shafts.

## UPSET FORGING

This is compression of the workpiece along its longitudinal axis where its length (height) is decreased and its diameter increased.

It is a very severe forging process.

- The deformation is non-homogeneous. The metal at and near the centre is deformed to a great extent. This forces the metal located near the circumference outwards causing moderate deformation in these areas. The metal in contact with the forging surfaces undergoes little deformation.

- The metal which is to be upset must therefore be of prime quality, having a homogeneous microstructure with no central segregation and a defect free surface.

The maximum length/height which can be upset is limited. The length/height (H):cross section (D) is dependent on the material being forged.

- For plain carbon and low alloy steels H:D can be up to 3:1. - Due to the greater high temperature strength of stainless steels H:D is limited to usually 2:1, and a maximum of 2.7:1. - Attempting to upset forge longer lengths will often result in buckling of the workpiece before any bulging is attained.

The commonly used forging equipment includes steam hammers, mechanical and hydraulic presses.

Common products include discs, blind flanges, slip-on flanges weld neck flanges, gear blanks, tube plates.

- Upset forging is often the initial forging process used to form the blank required for the forging of rings.

## UPSETTING

This is compression forging in which only a portion (short length) of the workpiece is upset; either at the end of, or at a location within the length of the workpiece.

The factors as outlined in Upset Forging apply:

- The upset is general performed with a single application of the forging force. In some cases a preform upset may need to be performed in one set of dies, and then subsequently upset to final shape/size in another set of dies.
- For small components the upsetting may be done cold, i.e. without any heating of the workpiece (e.g. the heads of screws and bolts).
- Only CDF technique is used. The forging equipment used is Upsetters, or special purpose mechanical/hydraulic presses which operate in the horizontal plane. Common products include fasteners (screws, hex head bolts, eye bolts), valve stems, spindles, hub, gear blanks, stub axles, small rings and flanges (by first heading and then piercing).

## RING FORGING AND RING ROLLING

The initial forging process is upset forging to produce a blank that is punched and pierced to make a central hole.

### RING FORGING

The pierced blank is forged over a mandrel, rotating the blank by small amounts for repeated applications of forging force. This progressively increases the outside diameter (OD) and decreases the wall thickness (WT). This operation is often referred to as Ringing-Up.

- It is an Open Die Forging technique.
- The commonly used forging equipment is steam hammers and hydraulic presses.
- It is well suited to produce small quantities of different sizes of rings. Bushes and sleeves can also be produced.
- Common products are rings, bushes and sleeves which then find application as various components, e.g. flanges, hubs, gear rings, gear blanks, bearing housings, bearing rings, trunions, sockets.

### RING ROLLING

This is not truly a forging process, but it is being increasingly adopted by forge shops to convert the forged and pierced blank to larger rings of the required final dimensions. High production rates (cf ring forging) are attained.

- Rolling of the ring as a continuous "flat bar" takes place, the OD increasing and the WT decreasing as the idler roll is brought closer to the drive roll. The width is controlled by edging rolls.
- The range of sizes which can be produced depends on the configuration of the equipment. - The width that can be produced is dependent on the length of the idler and drive roll. The ability to produce bushes and sleeves may therefore be limited. - As the WT increases the process is progressively less suitable, as the force and dimensional control which the edging rolls can exert may be limited. - Special profiles can be produced by suitably shaped contours machined in either the drive or idler rolls.

## DIE FORGING

This is the forging of the component in fully closed impression dies (i.e. CDF). Pre-shaping of the workpiece may be done by ODF and/or CDF using one or more of the forging processes.

- The commonly used forging equipment is Single Action and Steam Hammers, Mechanical and Hydraulic Presses.
- Common products include hooks, surgical and dental instruments, offset shafts, crankshafts, conrods, valve bodies, pipe fittings, injection nozzles, turbine vanes, pump components, shackles, swivels, turnbuckles, cable clamps.

## PIERCING AND CORE FORGING

Piercing is the forging of hollow shaped components by forcing a punch into the workpiece which is contained in a die. The metal flow can either be:

- Radial, i.e. diameter increases but length remains the same.
- Rising, i.e. diameter remains virtually constant but the length increases along the length of the punch.

In piercing, the OD of the workpiece is not usually contoured.

Core forging increases the OD of the workpiece and also forges the metal into the containing die cavity to produce a contoured OD on the workpiece.

- Both are Closed Die Forging techniques.
- The commonly used forging equipment used is Mechanical and Hydraulic Presses.
- Products include cylindrical and conical components, pipe fittings, valve bodies, cups, sleeves.

## STARTING STOCK FOR FORGING

The starting stock for forging may be

- Cast Ingot
- Continuously Cast Strand/Billet
- Semi finished Products (Semis) such as rolled billet
- Finished product such as Bar

### CAST INGOT

The forging of cast ingot is usually only carried out by the steelmakers themselves to produce either forgings, or semi- finished product for sale as re-forging stock.

Prior to forging, the cast ingot must be surface conditioned (usually by heavy duty grinders) to remove surface defects, and cropped to eliminate any areas of shrinkage (pipe) and gross segregation.

Breakdown of ingot is done by drawing out. The initial forging is by light reduction to break down the coarse cast granular structure, and to effect initial refinement and consolidation. Once this stage of fragility has been passed subsequent breakdown with heavier reductions can be accomplished.

- Complete consolidation and refinement of the internal structure will require a reduction of cross-sectional area of between 4 and 6:1, depending on the melting, refining and ingot pouring techniques which have been used.
- The upset forging of cast ingot may be considered as virtually impossible. Failure during forging will usually result due to the unrefined and unconsolidated structure being unable to accommodate the severe and non-homogeneous deformation which takes place.

### CONTINUOUSLY CAST BILLET

Breakdown is done by drawing out. Continuously cast strand/billet has an internal structure which is superior to that of cast ingot.

- Therefore, for complete consolidation and refinement of the internal structure less reductions in cross-sectional area is needed. - Continuously cast billet should not be taken and simply rounded up to produce forged bar of similar cross section. Inferior mechanical properties will result. - If upset forging is to be done, prior consolidation and refinement must be effected (reduction of cross-sectional area by ± 3:1).

### SEMIFINISHED PRODUCTS such as ROLLED BILLET

Semi-finished products (billets) are bought from steelmakers by the forging industry for subsequent forging into finished products.

Production of billet is either by rolling (in cogging/blooming mills) or by forging the original cast material to the smaller cross-sectional sizes of billet.

- Billet which has been forged tends to have a better internal consolidation and refinement of the microstructure than does rolled billet (especially in the larger sizes of >±200mm).

In ordering such billet, either by forge shops or by steel merchants/stockists, it should be specifically stated in the order "BILLET FOR REFORGING PURPOSES", and if upset forging is to be effected this should also be stipulated.

- The steelmaker should therefore produce such material with sufficient reduction to ensure refinement/consolidation, and condition the surface, so that it may be successfully converted provided the necessary precautions and good working practices are applied during heating, forging and post forging operations.

### FINISHED PRODUCT such as BAR

Finished product (usually round bar) is used for forging operations in which stock of highest integrity and accurate size is required (such as upsetting, die forging where no blocking is carried out, core forging).

- The bar supplied is usually rough machined to fairly close size tolerances so that the exact volume can be cut for the required forging, or the exact length for the required upset in upsetting can be indexed. - Rough machining will also ensure a defect free surface.
- When ordering such material, it is still advisable to state on the order" BAR FOR REFORGING PURPOSE", and also to stipulate the forging process which is to be employed.

## HEATING FOR FORGING

- Heating requirements which are suitable for plain carbon and low alloy steels are NOT applicable for Stainless steels. Care must be taken to ensure that the appropriate heating parameters are applied. Shortcomings will lead to a high failure rates during forging.

Stainless steels have a low Coefficient of Thermal Conductivity (particularly the austenitic stainless steels) compared to plain carbon and low alloy steels. Therefore, longer times are needed to attain the required forging temperature uniformly throughout the workpiece.

- Typical heating time from ambient to the required forging temperature can vary from 40-90 minutes per 25mm of nominal section thickness. - Larger cross-sections will require longer heating times per 25mm of nominal thickness than smaller cross sections. - The type of furnace will also have an effect.

Because of these longer heating times the temptation may be to run the furnaces with a relatively high degree of superheat. This should not be done because:

- Rapid heating of the surface layers occurs which results in a differential in expansion between the hot surface layers and the cooler interior. Internal cracking may result, termed "klinking", which will open and progress to the surface in the subsequent forging operation. (This is more prone to occur in heating of cast material).
- The undesirable high temperature crystal structures (such as delta ferrite) may form in the surface layers of some grades of Stainless steel. As this crystal structure has lower transverse ductility, cracking within the surface can occur in the initial stages of the subsequent forging operation.
- Gross overheating of the surface layers may occur, resulting in "burning" (incipient melting) taking place at the grain boundaries. When the forging force is applied the workpiece cracks or disintegrates along the grain boundaries which are "lubricated" by molten metal.

The following additional factors should also be borne in mind.

- The workpiece should be frequently turned during heating. Otherwise the area of the workpiece in contact with the hearth will take too long to, or may not, attain the correct forging temperature. - Placing the workpiece on bearer bars assist in more uniform heating.
- The atmosphere should be controlled to be slightly oxidising in nature. If too highly oxidising, Cr depletion may occur. If reducing, C pick-up (carburisation) can occur in the surface layers, with a reduction of the corrosion resistance.
- No flame impingement onto the workpiece should occur.
- Refinement of the microstructure which results from the heating of the workpiece to the high temperatures necessary for forging is an important objective of the forging process. The temperature to which the workpiece is heated depends on the amount and rate of the deformation which will be effected. The higher temperatures should only be used if a large amount of deformation is required. If more than one excursion to the forge is required to accomplish the necessary shaping of the workpiece, lower initial and reheat temperatures may be needed as the amount of deformation during each excursion is usually of a lesser amount.
- High rates of deformation during

forging can maintain or even raise the temperature of the workpiece. If this is to be the case the temperature to which the workpiece is heated should be modified accordingly.

- Soaking at the forging temperature must be avoided as the longer times will cause high temperature induced changes to the microstructure, which are more difficult to refine or may cause forging difficulties.

## COOLING AFTER FORGING

Stainless steel must be suitably cooled after forging dependent on the chemical composition (classification/type) and on the size/section thickness.

### FORGING

Forging parameters vary for each classification/type of stainless steel, and sometimes (to a lesser degree) for the different grades in the same classification.

However, in general, the following apply in the forging of all stainless steels.

- Due to their greater strength at high temperatures Stainless steels need more force (forging pressure) or a larger number of blows to cause the required amount of plastic deformation (cf plain carbon and low alloy steels).
- If surface defects/tears occur the forging operation should be stopped immediately otherwise they will progressively get larger/deeper. The defect may be then dressed out of the workpiece. - Either whilst hot by gouging/ cutting (usually confined to small defects only). - Or by grinding after cooling the workpiece in the appropriate manner dependent on the grade of stainless steel. The heating of the surface layers by heavy localised grinding is high and care must be taken with the martensitic grades that this does not cause heat checking of the ground surface which would again initiate defects during subsequent forging. (Preheating or thorough flooded cooling while grinding are suggested in order to prevent this).
- Intense and rapid deformation can cause an increase in the temperature of the workpiece. Further, if this occurs in a localised area, the heat will not dissipate into the workpiece due to the low thermal conductivity. - Overheating can therefore result with associated formation of undesirable crystal structures (delta ferrite), and possibly even incipient grain boundary melting, both of which seriously impair the forging properties. In addition, the required refinement will not take place (or be non-uniform) which will detract from the properties of the forging.
- Forging should be finished at as low a temperature as possible to maximise the refinement of the microstructure.
- If more than one forging operation is required the amount of deformation which occurs in each should not be on a random basis, but be planned to optimise the grain refinement.
- The free-machining grades of Stainless steel have additions of Sulphur (S) or Selenium (Se). - These both impair the forging properties due to the formation of stringers within the microstructure. Se has a lower tendency to do so, and therefore is the preferred free-machining addition in Stainless steels which are to be forged.
- The suggested forging temperature range for the different grades of Stainless steel are given in the sections below. - Reference to alternative sources of forging data will most certainly give different values. Therefore, the suggested temperatures given should be used as a guide until experience dictates otherwise.

## MARTENSITIC STAINLESS STEELS

This classification of stainless steel is extensively used to produce forged components due to the properties (strength/hardness, abrasion resistance) which can be developed by heat treatment.

The main factor in forging these steels is to exercise close control of the maximum forging temperature attained (both in the heating and during the forging of the workpiece) due to their tendency to form delta ferrite at temperatures in the range of ±1100°-1250°C.

- A composition which gives a high Chromium Equivalent will result in delta ferrite formation at the lower temperatures within this range, and correspondingly the lower maximum forging temperatures must be used. - The Chromium Equivalent may be determined by using the Schaeffler-DeLong diagram as for predicting the crystal structure of weld metal *(Refer to the module on Stainless Steel Welding)*.

When heating martensitic grades for forging:

- It is advisable to preheat certain grades (particularly if the workpiece has a large cross-sectional thickness) to an intermediate temperature, and equalise the temperature throughout before charging the workpiece into the furnace to heat to the higher temperatures required for forging.
- Forging of martensitics must not be carried out at temperatures below that at which crystal structure change occurs, (±810°C termed the altotropic transformation temperature). However, forging is usually finished at the higher temperatures as given below because deformation becomes increasingly more difficult at lower temperatures.

Cooling after forging is a very important factor in the forging of martensitics. Due to their hardenability, especially the high C grades, they must be carefully cooled.

- As a minimum requirement the forging must be held in a dry warm insulating material immediately after forging is completed, and allowed to cool to below 550ºC after which it can be removed and allowed to cool in air. It is preferable to cool the higher Cr and high C grades (e.g. Grades 420; 440A,B,C) by slow furnace cooling at ±25°C/hr. Such slow continuous cooling of the high C grades can result in an unacceptable excessive formation of grain boundary carbides. To overcome this, a modified cooling sequence is required - air cool to ±250°C (taking great care to ensure that lower temperatures are not attained), and then immediately "tempering" at 650°-680°C before finally allowing to cool freely in air to ambient temperature.
- For complex forgings which have large and/or sudden changes in thickness of cross-section it may prove necessary to carry out a full annealing process immediately after forging.

A further aspect related to cooling is that during the actual forging rapid cooling of the workpiece must be avoided (e.g. indiscriminate use of water sprays, chilling of the surface layers by contact with the die) as this" quenching" could cause incipient cracking within the surface layers of the workpiece.

### FERRITIC STAINLESS STEELS

These are plain chromium stainless steels which have a low C content. They cannot be hardened/strengthened by heat treatment. The poor weldability is an inhibiting factor which limits the application of the standard ferritic stainless steels.

The main factor in forging these steels is their susceptibility to excessive grain growth at the high temperatures employed for forging. This is due to their single phase crystal structure. They must therefore be heated with care.

Heating involves two stages:

- First to an intermediate temperature of ± 850°C and then, once the workpiece has uniformly attained this temperature, heated as quickly as possible to the forging great care to ensure that lower temperatures are not attained).
- And then immediately "tempering" at 650°-680°C before finally allowing to cool freely in air to ambient temperature.

For complex forgings which have large and/or sudden changes in thickness of cross-section it may prove necessary to carry out a full annealing process immediately after forging.

A further aspect related to cooling is that during the actual forging rapid cooling of the workpiece must be avoided (e.g. indiscriminate use of water sprays, chilling of the surface layer to overcome this a modified cooling sequence is required, viz air cool to ±250°C (taking note of the cooling effect) as this "quenching" could cause incipient cracking within the surface layers of the workpiece.

Take care to ensure that lower temperatures are not attained, and then immediately "tempering" at 650°-680°C before finally allowing to cool freely in air to ambient temperature.

A further aspect related to cooling is that during the actual forging rapid cooling of the workpiece must be avoided (e.g. indiscriminate use of water sprays, chilling of the surface layers by contact with the die) as this" quenching" could cause incipient cracking within the surface layers of the workpiece and greater resistance to deformation at lower temperatures may induce mechanical failure by tearing.

The standard grades can, depending on C content, begin to sensitise if the temperature falls below ±850°C. This is seldom a factor as forging is finished at higher temperatures because deformation becomes increasingly more difficult at lower temperatures.

- Soaking at the forging temperature must not occur (i.e. to minimise the extent of grain growth).
- The forging temperature must correspond to the amount of deformation which will take place in order to optimise the refinement which will occur during forging. - This is particularly important if two or more excursions to the forge are necessary. Especially in the final excursion sufficient deformation must take place, and forging must finish at as low a temperature as possible.

**TABLE 2:** Forging of Martensitic Stainless Steel

| GRADE | PREHEAT (°C) | MAX FORGING Temp Range (°C) | MIN FORGING Temp (°C) |
|---|---|---|---|
| 410 | | 1100-1200 | 900 |
| 416Se | = | 1150-1225 | 925 |
| 420 | +-775 | 1100-1200 | 900 |
| 431 | = | 1150-1200 | 900 |
| 440A,B,C | +-775 | 1040-1150 | 925 |

**TABLE 3:** Forging of Ferritic Stainless Steel

| GRADE | PREHEAT (°C) | MAX FORGING Temp Range (°C) | MIN FORGING Temp (°C) |
|---|---|---|---|
| 405 | +-850 | 1040-1110 | 900 |
| 430 | +-850 | 1040-1110 | 820 |
| 446 | +-850 | 1040-1120 | 800 |
| 3CR12 | +-850 | 1040-1100 | 800 |

## AUSTENITIC STAINLESS STEEL IS CONSIDERED TO BE "FRIENDLY" IN FORGING TERMS

If the coarse grain size is not refined the material will exhibit inferior properties, e.g. in respect of toughness, ductility and fatigue.

- It is therefore advisable not to use ferritic stainless steels for the production of forgings of such shape/size that would result in any portion of the workpiece being heated to the forging temperature, and not subsequently subjected to sufficient deformation during forging to fully refine the microstructure.

The suggested forging temperature ranges of some of the ferritic grades of stainless steel are given in the table above.

Cooling after forging should be by cooling freely in still air.

### AUSTENITIC STAINLESS STEELS

This classification of stainless steels is extensively used to produce forged components due to their excellent corrosion resistance and, additionally, the broad scope of their related properties.

In general forging terms, the austenitic stainless steels may be considered as "friendly".

- Most of the grades may be forged at higher temperatures without associated shortcomings. This compensates for their greater high temperature strengths and facilitates their deformation during forging. - However the compositions (e.g. 309S, 310S) which give a higher Chromium Equivalent tend to result in the formation of delta ferrite at high temperatures. The upper forging temperature for such grades is accordingly limited.

The stabilised grades (321 and 347) may contain stringers/segregates of carbides/carbonitrides which can initiate rupture during forging.

Grade 347 is less susceptible, and is thus often the preferred/specified grade of stabilised steel for forging purposes.

**TABLE 4:** Forging of Austenitic Stainless Steel

| GRADE | MAX FORGING Temp Range (°C) | MIN FORGING Temp (°C) |
|---|---|---|
| 304 and 304L | 1150-1250 | 925 |
| 304N | 1150-1250 | 975 |
| 303 and 303Se | 1150-1250 | 925 |
| 309 and 309S | 1150-1180 | 975 |
| 310 and 310S | 1150-1180 | 975 |
| 316 and 316L | 1150-1250 | 925 |
| 321 | 1150-1250 | 925 |
| 347 | 1150-1225 | 925 |

- The high forging temperatures employed will induce a degree of grain growth. - Heating times must compensate for the lower thermal conductivity of austenitic stainless steels, but soaking for times longer than that required to uniformly attain the forging temperature throughout the cross-section of the workpiece must be avoided. - The top temperature to which the workpiece is heated must correlate to the amount of deformation/ reduction which is to be carried out (i.e. to effect optimal refinement).

Forging should finish at as low a temperature as possible.

- The higher alloyed grades (e.g. 309, 310) and grades alloyed with Nitrogen(N) have greater high temperature strengths. Therefore, the finishing temperature is higher because their greater resistance to deformation at lower temperatures may induce mechanical failure by tearing = the standard grades can, depending on C content, begin to sensitise if the temperature falls below ±850°C. This is seldom a factor as forging is finished at higher temperatures because deformation becomes increasingly more difficult at lower temperatures.

Austenitic stainless steels can develop a greater resistance to deformation as the amount of deformation increases, especially as the temperature of the workpiece falls to the lower temperatures within the forging temperature range (i.e. a "work-hardening" effect) = increased forging pressure or number of blows should therefore be expected and allowed for in the final stages of a forging sequence.

Forging temperature ranges for some of the austenitic grades of stainless steel are given above.

- Preheating to an intermediate temperature of ±925°C is advisable for the heating of workpiece of cross- section thickness >175 mm.

Cooling after forging MUST be immediate (by quenching in water).

- This is necessary for ALL grades, including the "L" and the stabilized grades.

## DUPLEX STAINLESS STEELS

This classification is being used to an increasing degree to produce forged components for applications which necessitate its higher resistance to pitting and stress corrosion cracking in chloride environments. Their higher strength (cf austenitic stainless steel) is also an advantage

Most of the duplex stainless steels available are proprietary grades as produced by different manufacturers.

- Therefore details regarding the forging parameters should be obtained from the manufactures as specific requirements may apply.

However, in general terms the following factors are pertinent.

- These are dual phase alloys of a mixed Ferrite/austenite crystal structure.
- The maximum forging temperature must be such as to induce a minimum coarsening of the ferrite fraction and, due to the high Chromium Equivalent, the formation of delta ferrite and sigma phase. - The temperature to which the workpiece is heated must correlate to the amount of deformation/ reduction which is to be carried out (i.e. to effect optimal refinement). - Soaking at the forging temperatures for times longer than necessary to attain uniform temperature throughout the workpiece must be avoided. - Heating time are ±10-20% less than those required for austenitic stainless steels of equivalent cross-section.
- Forging should finish at as low a temperature as possible, but must not be below 900°C = care must be exercised to prevent any section of the forging cooling at a higher rate, or being chilled, to below this temperature.
- Initial forging should be effected without major reductions or change of shape. Once the material starts to "flow" progressively more deformation/reduction can be accomplished. - The workpiece may be prone to failure by cracking/ tearing during rapid deformation forging processes (e.g. single blow CDF operation). It is beneficial if the workpiece can be given some initial deformation before being set in the dies for the CDF operation.
- The indicative forging temperature range is:

  Max Forging Temp 1150°C
  Min Forging Temp 925°C

Preheating to an intermediate temperature of ±900°C may prove to be of benefit in the heating of workpieces of large cross-section (>200mm).

- Cooling after forging should be rapid, usually by cooling freely in still air.

## PRECIPITATION HARDENING (PH) STAINLESS STEELS

This classification of stainless steels is used in applications which demand the combination of high corrosion resistance and high strength, and which are often for a specific application of a critical nature.

- Therefore the production of forgings may be considered to be of a "specialised" nature.

Most of the precipitation hardening stainless steels are available as proprietary grades.

- They are complex materials which can have specific forging parameters related to each grade, and the final properties are highly dependent on the thermo-mechanical procedures employed.

Because of varying forging procedures and parameters which apply, full details should be obtained from the manufacture of the specific grade which is to be forged.

## POST FORGING REQUIREMENTS

### Inspection and Testing Requirements

The purchasing requirements which cover forged components will set out any inspection and testing required to validate their integrity and mechanical properties. Machining and the development of the optimal aqueous corrosion resistance must be borne in mind.

## HEAT TREATMENT

Heat treatment is required to produce the required mechanical properties and the optimal corrosion resistance for all types of stainless steel forgings.

### MARTENSITIC STAINLESS STEELS

These are usually annealed (fully softened) to render them amenable to machining. Different annealing parameters apply to each grade.

After machining the steel is then hardened and tempered to produce the desired mechanical properties of strength, hardness, ductility and toughness. Again, each grade requires different quenching temperatures/ rates, and tempering temperatures.

The best aqueous corrosion resistance of the Martensitic Stainless steels is attained in the hardened and tempered condition.

### FERRITIC STAINLESS STEELS

These steels are machined and used in the annealed condition. Different annealing parameters will apply to each grade.

### AUSTENITIC STAINLESS STEELS

These steels are machined and used in the fully solution annealed condition which is essential to develop their optimal aqueous corrosion resistance.

- An equivalent annealing process is used for all austenitic stainless steels, viz heat to 1050°-1060°C and rapidly cool by quenching in water.

### DUPLEX STAINLESS STEELS

These steels are machined and used in the fully solution annealed condition which is essential to develop their optimal corrosion resistance.

- The annealing process requires quenching in water from an annealing temperature which varies for the different grades.

### PRECIPITATION HARDENING STAINLESS STEELS

These steels require to be solution annealed for machining purposes. This treatment also takes all the constituent alloying elements uniformly into solution.

- The temperature used, the time at this temperature, and the subsequent quenching rate will vary for the different grades.

To develop the mechanical properties further heat treatment is required.

- This is the precipitation hardening heat treatment which is carried out at lower intermediate temperatures.
  - It is time-temperature related, which varies for each grade and depends on the mechanical properties.

Full details should be obtained for each steel from the manufacturers.

## MACHINING

Stainless steels are not the easiest of materials to machine, and are therefore less tolerant of any shortfalls in machining technique.

## OPTIMAL CORROSION RESISTANCE

In addition to the development of optimal aqueous corrosion resistance by heat treatment as outlined above, the passivity of the surface must be ensured.

Scaling of the surface will result from high temperature exposure during forging and heat treatment. This scale impairs the corrosion resistance and must be properly treated as the final operation before the forging is placed in service. Often the forging is machined before entering service, so this process is unnecessary.

- Scale may be removed by mechanical or chemical (pickling) methods, or a combination of both.
- If mechanical methods are used, contamination of the surface of the Stainless steel by Iron(Fe) or steel particles MUST be avoided. Mechanical methods of scale removal should be followed by a passivation Treatment.
- Pickling is the preferred method of scale removal.

Forgings which are to be used in high temperature application (>±600°C) do not need to be pickled and/or passivated.

## CONCLUSION

Although the tonnage of stainless steel forged is relatively small compared to other wrought products, it nevertheless constitutes a vital and indispensable sector of the industry.

The forging of stainless steel is essentially not difficult. But it is different, and often vastly so, from the forging of plain carbon and low alloy steels. Further, Stainless steel cannot be considered as a single material for forging purposes as the forging properties of the various classifications differ substantially.

The main factors of difference which must be catered for are:

- The heating of the stock for forging.
- The higher strength at high temperatures.
- The forging temperature ranges.
- Thorough refinement in the forging operation.
- Cooling after forging.