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PULL OUT PART 9

CASTING OF STAINLESS STEEL

Casting is a method of manufacturing complex shapes that are not easily or cost effectively fabricated. Casting involves heating the material to above its melting point and introducing the material into a mould where it solidifies into the required shape

In this paper, we will not be covering the detailed mechanics of the casting processes, but rather focusing on specific aspects which relate to stainless steels.

CASTING OF STAINLESS STEELS

In broad terms, it may be said that castings are produced by pouring molten metal of the required composition into a hollow mould. The metal solidifies into the shape of the hollow cavity.

It is therefore possible, on a reproducible basis, to manufacture complex shapes that need a minimum of post-solidification operations to obtain a component of the required shape and dimensions.

The range of chemical compositions utilised for stainless steel castings are different from, and more varied, than those for wrought products. The composition is not limited by the necessity that the metal must be capable of being reduced in section (or shaped) by hot and/or cold working processes, for example rolling, forging.

Thus, castings can have properties that often render them more suitable for, and resistant to, the conditions associated with some applications.

However, the properties are largely dependent on the cast microstructure that results from simple solidification. They are not developed or modified, as in wrought products, by the refinement which occurs during the hot or cold work processes after solidification; but may be developed and modified to a certain extent by heat treatment.

Nominal, representative or typical values will be used to illustrate the different compositions and properties. These must not be used as guaranteed values for specification or design purpose.

THE MANUFACTURE OF STAINLESS STEEL CASTINGS

The production of stainless steel castings encompasses a large variety of different compositions and shapes with individual castings weighing from less than 1kg up to several tons. However, the greater majority of stainless steel castings produced weigh between 2-100kg each.

It is therefore impractical to melt large quantities of metal, and most of the furnaces used are of relatively small capacity (usually ±1000kg).

MELTING

Induction furnaces are best suited for melting such quantities and are most frequently used.

Briefly the features of an induction furnace are:

- A refractory “pot” (to hold the molten charge) which is surrounded by water cooled copper coils.
- An alternating current (usually of high frequency) is passed through the copper coils.

This makes and breaks a magnetic field, which in turn sets up eddy currents in the metallic charge. These result in the heating and melting of the charge.

- A molten slag blanket is used to cover and protect the molten metal.
- However, a negligible amount of refining is possible when using induction furnaces.

The selection and grading of the scrap charge and the purity of any alloys used (for example low carbon ferrochrome) is of critical importance, especially in the case of stainless steel castings of low carbon(C) content.

FACTORS THAT AFFECT CASTABILITY

Not all shapes are castable.

This is mainly as a result of the inherent problems associated with the solidification of molten metal. Factors include the condition of the molten metal and the design and the shape of the casting (and hence the moulds used).

The shape of the casting can be modified and placement of risers to induce directional solidification, and delay the freezing of sections of the casting through which molten metal has to flow to feed another location may be used. Directional solidification is also induced using chills and insulators.

Contraction after solidification must also be catered for. If sections of the casting are restrained, the shrinkage stresses can cause hot tears, particularly at changes of section size and profile. This problem is best overcome by:

- Modifying the shape of the casting to allow for:
  - A gradual change of cross section
  - Large radii at change of profile
- Inducing directional cooling.

CASTING PROCESSES

Casting processes are designated according to the different methods which are used to make the moulds. The most common processes used in the production of stainless steel castings are:

- Sand Casting
- Shell-mould Casting
- Investment Casting
- Ceramic Mould Casting

There are varying aspects relating to each process, for example the following:

- Mass, size, thickness and shape limitations
- Surface finish
- Dimensional accuracy
- Production rate
- Cost

Common factors of the different casting processes include:

- The moulds are destroyed with each casting produced
- Within the mould and appended to the actual casting cavity are risers, and the feeder system.

THE CHEMICAL COMPOSITION OF STAINLESS CASTINGS

The principal effect of alloying chromium (Cr) in iron (Fe) is the increased resistance which develops to both aqueous (wet) corrosion and high temperature gaseous and dry corrosion (for example oxidation/scaling). A chromium content of over 11-12% Cr renders the steel passive due to the formation on the surface of an extremely thin, continuous and stable chromium oxide film.

The surface is thus inert in many environments which imparts to stainless steel its natural corrosion resistance.

A secondary benefit of the Cr content is an increase in high temperature mechanical properties. The nominal chemical compositions of the more commonly used standard "C" and "H" series stainless steel castings are given in **Table 1.**

It is stressed that there are many additional chemical compositions to which stainless steel castings are produced, either with specific limitations or modifications within the standard grade composition, or as special purpose or proprietary grades.

TABLE 1: The Nominal Composition of Stainless Steel Casting

CAST GRADE COMPOSITION (Max c/o unless range given)

Designation	C%	Cr%	Ni%	Mn%	Si%	P %	S%	Other %	Wrought Grade
CA-6NM	0,06	11,5-14	3,5-4,5	1,0	1,0	0,04	0,04	0,4-1,0 Mo	
CA-15	0,15	11,5-14	1,0	1,0	1,5	0,04	0,04		410
CA-15M	0,15	11,5-14	1,0	1,0	0,65	0,04	0,04	0,15-1,0Mo	
CA-40	0,2-0,4	11,5-14	1,0	1,0	1,5	0,04	0,04		420
CB-30	0,3	18-22	2,0	1,0	1,5	0,04	0,04		431
CB-7Cu	0,07	15,5-17	3,6-4,6	1,0	1,0	0,04	0,04	2,3-3,3 Cu	17-4PH
CC-50	0,5	26-30	4,0	1,0	1,5	0,04	0,04		446
CD-4MCu	0,04	25-26,5	4,75-6,0	1,0	1,0	0,04	0,04	1,75-2,25 Mo: 2,75-3,25 Cu	SAF 2205
CE-30	0,3	26-30	8-11	1,5	2,0	0,04	0,04		
CF-3	0,03	17-21	8-12	1,5	2,0	0,04	0,04		304 L
CF-8	0,08	18-21	8-11	1,5	2,0	0,04	0,04		304
CF-20	0,2	18-21	8-11	1,5	2,0	0,04	0,04		302
CF-3M	0,03	17-21	9-13	1,5	1,5	0,04	0,04	2,0-3,0 Mo	316 L
CF-8M	0,08	18-21	9-12	1,5	2,0	0,04	0,04	2,0-3,0 Mo	316
CF-8C	0,08	18-21	9-12	1,5	2,0	0,04	0,04	(8xC%)-1,0 Nb	347
CF-16F	0,16	18-21	9-12	1,5	2,0	0,17	0,04	1,5 Mo: 0,2-0,35 Se	303
CG-8M	0,08	18-21	9-13	1,5	1,5	0,04	0,04	3,0-4,0 Mo	317
CG-12	0,12	20-23	10-13	1,5	2,0	0,04	0,04		
CH-20	0,20	22-26	12-15	1,5	2,0	0,04	0,04		309
CK-20	0,20	23-27	19-22	2,0	2,0	0,04	0,04		310
CN-7M	0,07	19-22	27,5-30,5	1,5	1,5	0,04	0,04	2,0-3,0 Mo: 3,0-4,0 Cu	
CN-7MS	0,07	18-20	22-25	1,5	2,5-3,5	0,04	0,04	2,5-3,0 Mo: 1,5-2,0 Cu	
HA	0,2	8-10		.0,35-0,65	1,0	0,04	0,04	0,94-1,2Mo	
HC	0,06	26-30	4,0	1,0	2,0	0,04	0,04	0,5 Mo	446
HD	0,05	26-30	4-7	1,5	2,0	0,04	0,04	0,5 Mo	
HE	0,2-0,5	26-30	8-11	2,0	2,0	0,04	0,04	0,5 Mo	
HF	0,2-0,4	19-23	9-12	2,0	2,0	0,04	0,04	0,5 Mo	302B
HH	0,2-0,5	24-28	11-14	2,0	2,0	0,04	0,04	0,5 Mo 0,2 N	309
HI	0,2-0,5	26-30	14-18	2,0	2,0	0,04	0,04	0,5 Mo	
HK	0,2-0,6	24-28	18-22	2,0	2,0	0,04	0,04	0,5 Mo	310
HL	0,2-0,6	28-32	18-22	2,0	2,0	0,04	0,04	0,5 Mo	
HN	0,2-0,5	19-23	23-27	2,0	2,0	0,04	0,04	0,5 Mo	
HP	0,35-0,75	24-28	33-37	2,0	2,0	0,04	0,04	0,5 Mo	
HT	0,35-0,75	15-19	33-37	2,0	2,5	0,04	0,04	0,5 Mo	
HU	0,35-0,75	17-21	37-41	2,0	2,5	0,04	0,04	0,5 Mo	

THE AMOUNT OF IRON DETERMINES IF THE CASTING IS A STAINLESS STEEL OR STAINLESS ALLOY CASTING. ALLOY CASTING USUALLY ALSO CONTAINS A HIGHER NICKEL CONTENT

Virtually all the "C" grades, but only four "H" grades have similar or related wrought grades but it should be noted that the chemical compositions of the cast stainless steels and stainless alloys are NOT exact equivalents of the corresponding wrought grade.

Seemingly small but nevertheless significant modifications have been made to the compositions to produce stainless steel castings to compensate and cater for the loss of some elements by oxidation during the casting process, due to it being a fairly slow process, and as a result of the relatively large surface areas which are created by the greater degree of segregation and non-uniformity which results from the solidification of the molten metal.

Although heat treatment of castings will bring about a degree of improvement, the refinement (homogenization) which occurs during the hot/cold reduction in cross section of wrought material does not take place

The necessary fluidity of the molten metal to enable it to flow into and fill the sometimes small and complex cavities of the mould also requires a modification of chemistry.

Stainless steel castings are, in general, those which contain more than ±50% Fe and less than 50% alloying elements. Most the "C" series are therefore stainless steel castings.

Stainless alloy castings are, in general, taken as those which contain less than +50% Fe and more than ±50% alloying elements. In the "H" series there are approximately an equal number of stainless steel and stainless alloy grades. A significant feature of the stainless alloy grades is the higher nickel (Ni) content, which in most cases exceeds the chromium (Cr) content.

GRADE DESIGNATIONS OF STAINLESS CASTINGS

Grade designation is according to a standard format for both the "C" and "H" series.

The second letter in the grade designation indicates the nominal chromium-nickel (Cr-Ni) content

2ND LETTER EXAMPLES

F = Cr-Ni content of 20% Cr, 10% Ni.

L = CrNi content of 30% Cr, 20% Ni.

NUMBERS EXAMPLES

3 = Carbon content of 0,03% C max.

16 = Carbon content of 0,16% C max.

-Last letter.

M = Molybdenum (Mo) is a specified alloying addition.

F = An addition of Selenium (Se) to give free-machining properties.

THE EFFECT OF THE ALLOYING ELEMENTS

The crystal structure, corrosion resistance, mechanical and physical properties of stainless castings are affected by the different alloying elements. These effects are similar, but not exactly equivalent to those which result in the wrought stainless steels – for details of this refer to previous modules in the series.

THE MICROSTRUCTURE OF STAINLESS CASTINGS

Both the grain and crystal structure of castings is of a non-uniform, non-homogenous nature in the "as-cast" condition.

- This is due to the (usual) considerable amount of non-uniformity and segregation which occurs during the freezing of the molten metal, brought about by variations in
    - The temperature of the molten metal from the beginning to the end of casting.
    - Freezing and cooling rates in different parts of the casting.
    - Section thickness (and often sudden change from light to heavy section) in different parts of the casting.
- Any lower melting point phases or intermetallic compounds tend to advance ahead of the freezing front and therefore concentrate in that section of the casting which is the last to freeze.
- The cast microstructure does not undergo refinement resulting from the reduction of cross section during hot cold working as is the case with wrought steels.

The alloying elements, and the relative amounts of each element in the final composition of the molten metal will nevertheless affect the crystal structures which develop.

However, compositions which, in wrought stainless steel, would result in a fully austenitic crystal structure, will not do so in the stainless castings. For example, grade CF8 (18-20%Cr, 8-11 %Ni) and grade CF8M (18-21%Cr, 9-12%Ni, 2-3%Mo) may be termed austenitic, but their crystal structures will contain relatively large amounts of ferrite (up to 20%), and thus be noticeably magnetic.

By balancing the composition of the molten metal within the specified limits the foundry can influence the final crystal structure to best suit the requirements for the conditions of the intended application.

"H" SERIES

In the "H" series the phase stability and the mechanical properties at the high operating temperatures involved are the factors of primary importance.

Therefore, the aim (for both Fe-Cr-Ni and Fe-Ni-Cr grades) is usually to attain a fully austenitic crystal structure with as little ferrite as possible.

- The compositional balance to attain this is not as critical with the Fe-Ni-Cr grades as compared to the Fe-Cr-Ni grades.

The adverse effects of ferrite at high temperatures include:

- A lower high temperature strength
- Poor creep properties at >±600°C
- High temperature embrittlement due to the transformation of ferrite at ±600°-870°C to the brittle sigma or chi crystal structures.
    - This results in low toughness at normal ambient temperatures (for example during shut-down).
- Inferior resistance to thermal fatigue and thermal shock
- A possibility of preferential high temperature corrosion of the ferrite network by certain molten salts.

The high carbon contents of the "H" grades is a major contributing factor to their excellent creep resistance at high temperatures. This is due to the formation of uniformly finely dispersed carbides within the crystal structure.

- For example, the cast microstructure of grade HK can accommodate

higher loads with far less resultant deformation than the similar wrought grade 310.

"C" SERIES

In the "C" series the aim is to attain the most corrosion resistant microstructure. Therefore, in addition to the control of the compositional balance, it is normal practice for "C" series stainless castings to be heat treated to modify the "as cast" micro-structure. Heat treatment will also develop the required mechanical properties.

Ferrite will have a lower tendency to form in the Fe-Ni-Cr grades, but will usually be present to a significant degree in the Fe-Cr-Ni grades.

The Ferrite fraction can result in both beneficial and inferior effects, viz

- If exposed to temperatures of 450°-650°C, carbide precipitation will tend to take place within the ferrite pools in preference to at the austenite grain boundaries. This can lower the susceptibility to sensitization.
- The ferrite fraction can result in an improved resistance to stress corrosion cracking in chloride media.
- The strength at ambient temperatures is improved.
- The weldability is improved.
- The ductility and toughness are decreased.
- If the Ferrite pools form a continuous interlinked network corrosion can penetrate and proceed along this network.
- The instability of the Ferrite at elevated and high temperatures (>430°C).

HEAT TREATMENT OF STAINLESS CASTINGS

Heat treatment of Stainless Castings will modify (to a degree) the "as-cast" micro-structure and thereby develop both the required corrosion resistance and mechanical properties.

"H" SERIES

The "H" series stainless castings are normally not heat treated, being placed in service in the "as-cast" condition. The Fe-Cr-Ni and Fe-Ni-Cr Grades will, under the high temperature service conditions, develop the uniformly finely dispersed carbides which result in the required high temperature strength and creep resistant properties.

"C" SERIES

The "C" series stainless castings are normally heat treated to develop optimum corrosion resistance and mechanical properties.

The chemical composition will determine the heat treatment process, the temperatures employed, and the response thereto. Typical heat treatment processes are given below.

THE FE-CR PLAIN CHROMIUM "MARTENSITIC" GRADES

E.g. CA6NM, CA15, CA40. Anneal to soften (e.g. for machining purposes).

- Slow furnace cool from temperatures between 800°-900°C.
- Harden to develop mechanical properties and corrosion resistance.
- Either oil or air quench (dependent on size/cross-section) from temperatures between 980°-1060°C).
- Quenching must be immediately followed by tempering.
    - Tempering at 290°-315°C results in the best strength and corrosion resistance.
    - Tempering between 590°-800°C

TABLE 2: Nominal(*) Mechanical Properties for Stainless Castings at Ambient Temperature

Description of Cast Material	Tensile (MPa)	0,2% Yield (MPa)	Elong (%)	Hardness (HBN)
Fe-Cr "MARTENSITIC" "C" GRADES Hardened (i.e. Q & T). Properties depend on Composition and Tempering Temperature	820/1500	690/1130	24/1	269/470
Fe-Cr "FERRITIC" "C" GRADES Annealed	655	420	16	200
Fe-Cr-Low Ni "DUPLEX" "C" GRADES Solution Annealed	740	550	25	250
Fe-Cr-Low Ni "PRECIPITATION HARDENING" "C" GRADES Solution Annealed + Aged	1300	1140	12	400
Fe-Cr-Ni "AUSTENITIC" "C" GRADES Solution Annealed	535	250	50	160
Fe-Ni-Cr- "AUSTENITIC" "C" GRADES Solution Annealed	470	215	45	135
Fe-Cr "H" GRADES As Cast	650	445	22	180
Fe-Cr-Low Ni "H GRADES" As Cast	400/700	250/500	16	-
Fe-Cr-Ni "H GRADES" As Cast	560	310	15	-
Fe-Ni-Cr "H GRADES" As Cast	485	275	10	-

(*) NOTE: It is stressed that the Nominal Values must ONLY be used for relative/indicative purposes. For specified values reference must be made to the actual Code or Specification.

will improve the Ductility and Toughness (impact resistance), but lowers the strength and slightly lowers the corrosion resistance

- Tempering in the range 350°-550°C should be avoided as this results in temper embrittlement (i.e. low and erratic toughness [impact resistance]).

THE FE-CR PLAIN CHROMIUM "FERRITIC" GRADES

E.g. CB30, CC50.

- Anneal to optimise both the formation of a uniform crystal structure and the corrosion resistance.
- Heat to 790°-860°C and either slow furnace cool or air cool.

These grades are not able to be hardened by heat treatment

THE FE-CR-LOW NI "DUPLEX" GRADES

E.g. CD4MCu.

- Solution anneal for complete solution of any Chromium Carbides existing in the "as-cast" condition.
- Heat to ±1120°C and hold for ±3 hours. Then slow cool to 960°-1040°C, hold for 1/2 hour, Then rapidly cool by quenching in water, oil or air (depending on size and cross section).

THE FE-CR-NI AND FE-NI-CR "AUSTENITIC" GRADES

E.g. CE30, CF3, CF3M, CF8, CF8C, CF8M, CF16, CG8M, CH20, CK20, CN7M

- Solution anneal for complete solution of all Chromium Carbides existing in the "as-cast" condition.
- Heat to temperatures between 1040° and 1150°C (dependent on composition), and rapidly cool by quenching in water, oil or air (dependent on size and cross section).
  - Grade CF8C is then given a subsequent "stabilizing" treatment, by heating to 870°-900°C. At this temperature Niobium Carbides are preferentially precipitated. This fully "stabilized" microstructure is preferred if the casting is to operate in the sensitization temperature range of 450°-850°C.
  - Under some conditions it may be acceptable for Grade CF8C to be applied in the "as-cast" condition.

MACHINING OF STAINLESS CASTINGS

In general terms, stainless castings have a lower machinability than that of the similar wrought Stainless Steels.

This is due to factors which include

- The internal cast microstructure of castings which typically exhibit a higher degree of segregation, mixed crystal structures, variations in grain size and grain orientation.
- The tendency for castings to contain oxide inclusions, and have fine particles of mould material entrapped on the surface. Such hard particles can rapidly blunt the tool cutting edge.

Stainless castings normally require lower cutting speeds and, to a lesser degree, tower feeds.

WELDING OF STAINLESS CASTINGS

All grades of stainless castings may be welded. However, the Fe-Cr-Ni and Fe-Ni-Cr (austenitic) grades have better weldability than the Fe-Cr (plain chromium martensitic and ferritic grades.

The reasons for welding include:

- The incorporation of a casting into a component fabricated from wrought material.
- The joining of two (or more) castings to produce a complex shape, the geometry of which would have been extremely difficult or impossible to make as a single casting.
- The repair of castings (e.g. cracks, hot-tears, porosity, shrinkage cavities etc.).

If welding is to be employed, it is preferable to carry out the required heat treatment after welding. This removes any deleterious effects of welding and optimizes the properties within the weld zone.

If welding is done on heat treated (solution annealed) "C" Series castings (e.g. grades CF8, CF8M) sensitization may occur. To rectify this re-heat treatment is necessary.

Avoid welding at locations where high restraint will result. For example thick to thin sections, at areas of large or rapid change of cross-section, at corners.

WELDING CONSUMABLES

The welding consumables employed are of a matching type that is equivalent to the composition of the casting.

MECHANICAL PROPERTIES OF STAINLESS CASTINGS

Typical ambient temperature mechanical properties for some grades of stainless castings are given in **Table 2**.

The results so obtained can only be considered as "representative". This is due to the non-uniform and non-homogenous nature of castings. Differences in section size in complex castings (and the associated cooling rates thereof) can result in mechanical properties at various locations in the casting being different, both from each other and to those determined from the test blocks.

Further, the ambient temperature properties of the "H" series stainless castings are of little significance, as it is the properties at high temperatures which are of primary importance.

The high temperature properties for some grades of the "H" series stainless castings are given in **Table 3**.

STAINLESS CASTINGS OFFER ATTRACTIVE AND VIABLE SOLUTIONS FOR SMALL AND LARGE PROJECTS WITH COMPLEX SHAPES AND DESIGN REQUIREMENTS

THE APPLICATION AND USE OF STAINLESS CASTINGS

Stainless castings have a tremendously wide scope of application resulting from the ability to produce components of both complex shape and of compositions which afford excellent corrosion resistance and high temperature properties. However, cognisance must be taken of the fact that both mechanical properties and corrosion resistance may differ to those of the "equivalent" wrought grades.

CONCLUSION

Stainless castings offer an attractive viable solution in many applications.

The advantages include the ability to produce in relatively small batches (both quantity and total mass), complex shapes of near net shape on a reproducible basis, a wide variety of compositions to fulfil a wide range of required properties by utilizing different compositions and heat treatments applied thereto.

For the selection and design of stainless castings to perform to optimum levels it is vital that full and detailed information regarding the intended application be given to the foundry.

TABLE 3: Indicative High Temperature Creep/Rupture Properties for some "H" Grade Stainless Castings

Description of Cast Material	Temp (°C)	Limiting Stress for Creep Rate of 0,0001 % /hr (MPa)	Limiting Stress for Rupture Time (MPa/hours)
Fe-Cr Grade HA	535	110	185/1 000
Fe-Cr-Low Ni Grade HC	760	8,9	15,5/1 000
	980	2,5	4,3/1 000
Grade HD	760	24	48/1 000
Fe-Cr-Ni Grade HE	760	27,5	76/100 17/100
	980	9,7	
Grade HF	760	47	63/1 000 30/1 000
	870	27	
Grade HH (Partly Ferritic)	760	21	45/1 000 14,5/1 000
	980	7,5	
Grade HH (Fully Austenitic)	760	43	55/1 000 11,5/1 000
	980	14,5	
Grade HK	760	70	83/1 000 61/10 000
	980	17	19/1 000 12/10 000
	1040	9,7	13/1 000 7,5/10 000
Fe-Ni-Cr Grade HP	980	19	25/1 000 15/10 000
	1090	6,9	10/1 000 4,1/10 000
Grade HT	760	55	83/1 000 58/10 000
	980	14	19/1 000 12/10 000
	1090	3	9/1 000
Grade HH	980	15	20/1 000 12,5/10 000

NOTE: (i) Cyclic Temperature will result in lower values (ii) For complete data, reference should be made to published data e.g. Alloy Casting Institute Division).