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Welding of Duplex Stainless Steels

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ABSTRACT:

The duplex stainless steels are now receiving increasing attention as materials of construction for several critical hostile service environments such as in oil and natural gas production. The superior corrosion properties and yield strength render them suitable for such applications. In India though the cast materials have been in use for quite sometime, use of wrought products for fabrication of equipment is on the increase in the recent past. Naturally, welding of these duplex stainless steels is gaining importance. The welding of these steels requires proper selection of filler materials, use of carefully formulated welding procedure so as to ensure that the weldment possesses the desired toughness and corrosion properties. This paper reviews the available technical data on welding of duplex stainless steels and deals with the Indian scene in this field with particular attention to availability of welding consumables and the applications of this class of stainless steel.

1.0 INTRODUCTION:

There has been an ever increasing attention towards the development of materials to resist the corrosive attack in different environments. This has resulted in a number of special grades of materials particularly stainless steels. The common grades of stainless steels, as we all know, can be classified into three well known groups viz. the martensitic, the ferritic and the austenitic depending on their room temperature structure. Each group has characteristic properties and are suitable for resisting the corrosive attack of several environments. But the ever expanding industrial scene has offered certain environments, viz. the environments like offshore structures in which stress corrosion cracking is possible, in which all the above three groups have certain draw backs. The work towards the development of materials to suit these environments has resulted in the development of a new series of stainless steel materials viz. the duplex stainless steels. These steels contain a 50-50 austenitic-ferritic structure combining the best properties of both the phases. Because of the excellent mechanical and corrosion properties of these duplex stainless steels, they are increasingly being used for various applications.

In India, these steels have recently engaged the attention of the fabricators particularly for the offshore applications. The coming years will therefore offer the welding fraternity a new challenge in fabricating these materials. It is with this view, an attempt has been made in this paper, to present in a concise form the available data which can form an useful reference to the welding personnel.

2.0 DUPLEX STAINLESS STEELS:

The duplex austenitic-ferritic stainless steels were developed to combine the following advantages of the above phases[1]

(i) Austenite for imparting toughness and general corrosion resistance.

(ii) Ferrite for imparting strength and resistance to stress corrosion cracking.

The duplex structure i.e. 50% austenite and 50% ferrite is achieved by suitably adjusting the percentages of alloying elements like chromium (18-26%) Nickel (5-6%) Molybdenum (1.5-3.5%) and with addition of nitrogen etc. Table 1 gives the various grades of duplex stainless steels, their chemical composition and mechanical properties. It can be observed that the yield strength of these grades are substantially higher than that of the 300 series of stainless steels.

2.1 Properites of Duplex Stainless Steels:

The properties of duplex stainless steels can be discussed under two broad heads. They are

(i) Mechanical properties

(ii) Corrosion properties

In a detailed review[2] the properties of the duplex stainless steels have been compared with other candidate materials like normal austenitic stainless steels, particularly for offshore applications. The salient properties can be summarised as follows:

(i) The duplex stainless steels have higher yield strength than the austenitic stainless steels, super austenitic grades and Alloy 825.

(ii) The thermal expansion coefficient is closer to carbon steels unlike austenitic stainless steels and hence facilitates easier fabrication between themselves and to carbon steels.

(iii) The duplex stainless steels are susceptible to high temperature embrittlement due to sigma formation. The ferrite in the duplex stainless steels gets converted to sigma phase and there also exists an embrittling temperature range 315°C to 595°C. Hence duplex stainless steels are not recommended for use above 315°C[11].

(iv) The low temperature properties of duplex stainless steel are good. But however it is dependant on several factors like composition, microstructure, heat teratment and manufacturing route. Fig. 1 shows a typical curve for one of the duplex stainless steels.

The duplex stainless steels possess excellent corrosion properties also.

(i) Excellent general corrosion resistance particularly to wet CO_2 atmosphere.

(ii) Moderate crevice corrosion resistance.

(iii) Excellent pitting corrosion resistance (Fig. 2)

(iv) Excellent resistance to chloride SCC particularly above 50°C where the 18/8 grades are susceptible. Figs. 3-5.

(v) Resistance to H_2S cracking

(vi) Intergranular stress corrosion cracking: The duplex stainless steels are resistant to sensitisation and hence the resistance to this type of corrosion. Another point is that duplex stainless steels have so far been rarely used under aggresive highly oxidising conditions in which the effects of sensitisation may be most pronounced.

Another review[11] indicates that

(i) Duplex stainless steels are subjected to cracking in $MgCl_2$ SCC tests but are more resistant in NaCl tests. Even in NaCl tests their resistance can be impaired by distribution of austenite and ferrite.

(ii) Duplex stainless steels are fairly resistant to aqueous chloride media. However their resistance is reduced by high temperature, low pH the presence of H_2S and high applied tensile stress.

The pitting and SCC resistance of some duplex stainless steels as compared to the normal stainless steels and other alloys is shown schematically in Fig. 6 and the cost comparison is shown in Fig. 7.

3.0 WELDING OF DUPLEX STAINLESS STEELS:

In welding of duplex stainless steels care should be exercised in all aspects of welding to achieve the following ultimate goals;

(i) Sound welds of sufficient strength

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(ii) HAZ and welds should have good toughness

(iii) The weld joint should possess good corrosion resistance.

Duplex stainless steels can be welded by the common welding processes like SMAW, TIG, MIG, SAW etc. and all of them have given sound welds when proper welding procedure, consumables are used.

3.1 Microstructural Changes During Welding :

Essentially during welding, the HAZ undergoes transformation to ferrite, with grain growth at high temperature followed by austenite reformation on cooling at grain boundaries and within grains[3]. The matching composition weldmetal solidifies to ferrite followed by austenite formation at lower temperatures. These changes and the final structure are dependant on

(i) The material composition

(ii) The cooling rate.

Consequent to these changes, the weldmetal, the HAZ may differ appreciably from the base material in the

(i) Proportion of the microstructural phases

(ii) Morphology of the structure

which can affect the service behaviour of the weld joints.

Reviewing the microstructural changes during welding of Duplex stainless steels, N Stephenson[5] brings out clearly the disadvantages of high as well as low heat inputs when using matching composition weldmetal.

High heat input : It promotes excess grain growth, excess width of HAZ although beneficial reversion to gamma phase is facilitated.

Very low heat input : Fast cooling rates, inhibits grain growth, precipitation and reversion to gamma phase.

Figure 8 shows the CCT diagram indicating the influence of cooling rate on the transformation.

3.2 Selection of Welding Consumables :

The properties of the commonly used welding consumables are shown in Table 2. It can be observed that the Ni percentages in the weldmetal are relatively higher. The higher nickel content ensures a higher percentage of austenite in the weldmetal and an increased toughness (Fig. 9) which is not so easily obtainable with matching weldmetals.

3.3 Welding Procedure :

The duplex stainless steels are normally welded in the annealed condition. As said earlier the coefficient of thermal expansion of duplex stainless steels is nearer to the carbon steels and very much less compared to the stainless steels. Therefore the distortion that can be expected in duplex stainless steels is much less as compared to the stainless steels. The design of jigs and fixtures should be done keeping this aspect in mind. Available data[2 5] highlight the following points in the welding procedure :

a) This material does not require preheating and only warming is recommended during welding.

b) The maximum interpass temperature should be 150°C.

c) The heat input should be in the range of 0.5-2.5 kJ/mm; some cases are reported with higher heat input of 6kJ/mm also.

d) In gas shielded processes, the mixing of hydrogen in the shielding gas is not recommended as it may lead to HIC.

e) There is no need for PWHT; but fabrications subjected heavy coldworking i.e. more than 15%, a solution annealing treatment can be done at 1040-1150°C.

S Budgifvars[7] has presented in detail the welding procedure for the duplex stainless steels and has obtained satisfactory results.

4.0 PROPERTIES OF WELDED JOINTS :

As seen earlier, the weldmetal and the HAZ are likely to have a different metallographic structure which is dependant on the welding conditions and hence have different properties as compared to the base material especially the toughness and the corrosion properties. The other mechanical properties like the YS, UTS etc. seem to be achievable without much of a problem.

4.1 The Toughness of Weld Joints :

The toughness of the weldmetal, HAZ is sensitive to the percentage of ferrite and arc energy[7]. The toughness decreases with increased ferrite and increases with increasing arc energy. In the weldmetal as seen earlier, increasing the nickel content increases the toughness of the weldmetal. According to Tadao Ogawa et al[10] with reference to SMA weld joints, the weldmetal containing 70% ferrite showed fairly low impact energies with a clevage like brittle fracture at -40°C, while the one containing 40% ferrite showed rather higher values with mostly ductile dimpling fracture. Increased nickel content from 6% to 9% led to a rise in the impact energies by about 50J at -40°C and improved brittle ductile transition temperatures below -40°C. Analysing the toughness of the welds, John Street[2] indicates that the weldmetal toughness is more important than the HAZ because the HAZ toughness, although difficult to measure, is always higher. The weldmetal toughness according to him is influenced by (a) grain size, (b) ferrite content and (c) inclusion (oxygen) content. The use of higher nickel content helps in achieving better toughness.

4.2 Corrosion Properties :

The duplex stainless steels are intended to resist a variety of service environments and hence several corrosion tests are conducted to assess the suitability of the weldmetal and the weld joint.

4.2.1 Stress Corrosion Cracking Resistance :

The duplex stainless steels, though have been used to replace the austenitic stainless steel in SCC medium the data on the performance of welded duplex stainless steels is very little[3]. From the available data, it has been observed that when reduction in SCC arises, it is most commonly associated with

(a) predominantly ferrite HAZ and weld metals OR

(b) the use of Ni base consumables.

Therefore, the modern steels, where a higher percentage of austenite is ensured in the HAZ and weldmetal, should exhibit more resistance. The use of Ni based consumables should be avoided atleast in chloride environments. This area requires further study so that an optimum phase balance can be prescribed for the weldmetal since

(a) in general the Ferrite percentage has to be kept below 50% to ensure adequate toughness and this is being achieved by increasing the Ni percentages in the weldmetal.

(b) on the basis of the work on austenitic stainless steels, low ferrite content might lead to higher sensitivity to chloride stress corrosion.

Further research is also required so that the extent of practical hazard can be gauged and recommendations can be made to optimise material analysis and welding procedures. It is interesting to note that welded duplex stainless steels have been employed in a range of media and no major problem of weld SCC has been reported probably because environments were harmless, with duplex being employed as replacement to austenitics.

4.2.2. Intergranular Corrosion :

Before dealing with the intergranular corrosion of weldmetals, it is interesting to study the sensitising behaviour of the duplex stainless steels base material when heated to around 600°C (Ref. 8)

(a) as Cr diffusion rate is around 1000 times higher in delta ferrite, $M_{23}C_6$ begins to precipitate in the boundaries δ - δ rather than γ - γ boundaries and Cr depleted zone is formed in δ - γ phase boundaries.

(b) The diffusion rate in δ phase is high and so C is supplied quickly there and C in δ phase is exhausted immediately. The carbide forms with C from γ phase and Cr in δ phase and a part of Cr from γ phase. Therefore although small Cr depleted zone is formed in δ - γ phase boundaries at γ phase side, Cr depleted zone is hardly formed at γ - γ boundary.

(c) As the depleted zone is small, it recovers fast. This phenomenon is shown schematically in Fig. 10., Thus the duplex stainless steels are resistant to sensitisation unlike austenitic stainless steels.

The matching weldmetal is expected to have a good resistance to; sensitisation. But however detailed data on the sensitising behaviour of weldmetal is not available. The modern duplex stainless steels are welded with higher Ni weldmetals. The resistance to intergranular corrosion is tested by A262 practice E & C and consumable manufacturers make this data available. It should be noted that practice C is much more severe. It has been reported[2] that

(i) In practice E no sensitisation has been detected even while using high arc energies upto 6KJ/mm

(ii) In Practice C the base material (SAF 2205) shows corrosion rates below 1.0mm/year and negligible effects of increasing arc energies (upto 6kJ/mm) on the corrosion rates of all weld deposits and bead on tube welds.

The corrosion data for a weldmetal are given in Table 3.

4.2.3 Pitting Corrosion :

Figure 11 shows the effect of ferrite on chloride pitting corrosion resistance where the ferrite content was varied with nickel percentage. It can be seen that an optimum range exists for the ferrite for maximum pitting corrosion resistance[10]. The effects other variables can be summarised as follows :

(a) Increasing carbn content decreases the pitting corrosion resistance of weldmetals.

(b) Nitrogen contents increase the pitting resistance of weldmetals.

(c) Increased Molybdenum is not preferable in weldmetals as in case of base metals.

(d) Increased Cr contents are beneficial as long as it did not modify the ferrite content.

(e) Heat input has little effect on the pitting resistance. But however, high arc energies (upto 6KJ/mm) improve pitting resistance of weldmetal & HAZ[2].

(f) Addition of Nb, Ti, Cu deteriorated pitting corrosion resistance of weldmetals.

5.0 HOT CRACKING :

When welding thick sections of cast duplex stainless steels under severe restraints it was observed[1] that the weldmetal is prone to cracking. At this stage the matching weldmetal was used. This hot cracking was found to be associated with the low intrinsic toughness of the deposited weldmetal combined with high restraint. The low toughness is associated with a slightly higher ferrite content than in the parent metal. By increasing the nickel content of the weldmetal considerable improvements were made in the toughness of the weldmetal which solved the problem.

Basic research studies on hot cracking conducted by DE Nelson et al[9] using varestraint tests have revealed that the susceptibility of the commercial duplex stainless steels is associated with a low melting liquid film enriched in copper and phosphorus.

6.0 MEASUREMENT OF FERRITE :

It can be observed that these duplex stainless steels have more than 28% ferrite making measurement of ferrite using the normal instruments impossible since the maximum limit in these instruments is only 28%. In order to overcome this problem, an extended ferrite number (EFN) system has been fomulated by D. J. Kotecki[12] in which by changing the counter weights in the magna gauge instrument, the entire range of duplex as well as ferritic stainless steels can be measured.

7.0 DEVELOPMENTS IN INDIA :

The cast duplex alloys like CF8M etc. have been in use in India for quite sometime and are being welded using matching composition electrodes. The wrought alloys particularly the UNS 31803 has appeared only recently. This is one of the popularly used duplex stainless steels. Indigenous electrodes have been developed, meeting the chemical composition requirements. The consumables for the other processes are not available indigenously. Even in the case of electordes it cannot be said with certainty that they have the requierd properties particularly the corrosion resistance in different media. Efforts are still in progress to establish suitable facilities to generate the desired data for the welding consumables.

8.0 CONCLUSION :

In conclusion, this topic can be summarised as follows :

(i) Duplex stainless steels possess a duplex ferritic-austenitic structure in equal proportion combining the best properties of both.

(ii) They exhibit good toughness and excellent corrosion resistance.

(iii) Their weldability is good and is similar to that of the austenitic stainless steels.

(iv) The duplex stainless steels have good resistance to sensitisation.

(v) Matching compositon filler metals cannot produce good mechanical, corrosion properties and hence it is desirable to have weldmetals having more Ni than base metal.

(vi) While the data on corrosion properties of the base material covers a wide range, only limited data is available on the weldments and further work is necessary to evaluate the effects of welding on corrosion properties and to arrive at an optimum chemistry of weldmetal to achieve best services performance.

(vii) In India the wrought materials have come into use only recently. Suitable indigenous welding consumables with the desired weld chemistry are available but are without the supporting data for their corrosion behaviour in various tests which will ensure their satisfactory performance in actual service condition.

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Table 1

Specification	Designation	C max	Ni	Cr	Mo	N	Others	Tensile Strength Min.N/mm²	Yield Strength, Min.N/mm²	Elongation in 50mm, Min.%
ASTM A182 ASTM A240 ASTM A789 ASTM A790	UNS S31200	0.030	5.50-6.50	24.0-26.0	1.20-2.00	0.14-0.20		690-900 690 690 690	450 450 450 450	25 25 25 25
ASTM A182 ASTM A240 ASTM A789 ASTM A790 ASTM A815	UNS S31803	0.030	4.50-6.50	21.0-23.0	2.50-3.50	0.08-0.20		620 620 620 620 620	450 450 450 450 450	25 25 25 25 25
ASTM A240 ASTM A479	UNS S32550	0.04	4.50-6.50	24.0-27.0	2.0-4.0	0.10-0.25	Cu 1.5-2.5	760	550	15
ASTM A789 ASTM A790	UNS S32550	0.040	4.50-6.50	24.0-27.0	2.90-3.90	0.10-0.25	Cu 1.5-2.5	760	550	15
ASTM A240	UNS S32900	0.08	2.50-5.0	23.0-28.0	1.0-2.0			620	485	15
ASTM A744	CD-4MCu	0.04	4.75-6.00	24.5-26.5	1.75-2.25		Cu 2.75-3.25	690	485	16
ASTM A789 ASTM A790	UNS S31500	0.030	4.25-5.25	18.0-19.0	2.50-3.00			630	440	30
ASTM A789 ASTM A790	UNS S31250	0.030	5.50-7.50	24.0-26.0	2.50-3.50	0.10-0.30	Cu 0.20-0.80 W 0.10-0.50	630	440	30
Wr No 1.4460	X 8 CrNiMo 275	0.10	4.00-5.00	26.0-28.0	1.30-2.00			640-900	490	25
Wr No 1.4582	X 4 CrNiMo Nb 257	0.06	6.50-7.50	24.0-26.0	1.30-2.00		Nb(min)= 10x%C	640-900	490	25

Table 2 **Welding Electrodes for Duplex Stainless steels**

Property		Various electrodes	
	A	B	C
Chemicl composition (Typical)			
C	0.030 max.	0.03	0.03
Mn	1.20	1.2	0.5-1.2
Si	1.0	0.80	0.4-0.90
Cr	19.0	19.0	21-23
Ni	10	6	8-10
Mo	2.7	2.7	2.75-3.25
N	0.08	0.17	0.1-0.15
Ferrite %	20.0	40.0	25-40

Table 3 **Corrosion Test results obtained with electrode C**

I : ASTM 262 Practice E : Satisfactory
II : ASTM 262 Practice C : 0.3mm/year max.
III : NACE TM-01-77—Stress corrosion cracking test Load (N/mm²) 650, 550 — Time to fracture (hrs) 67.6, 720

Load (N/mm²)	Time to fracture (hrs)
650	67.6
550	720

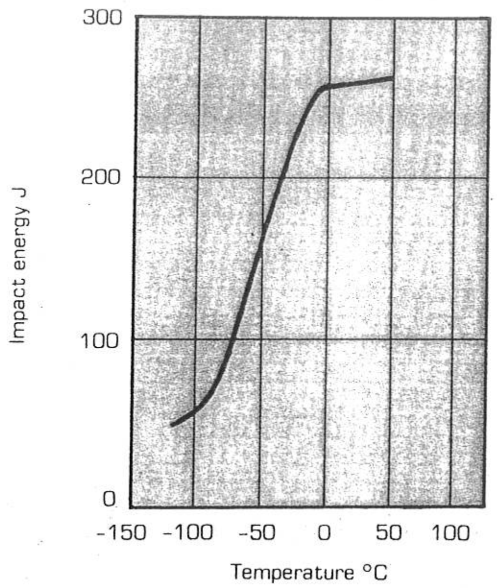

Fig. 1 Typical impact results of a duplex stainless steel-Ref. 2

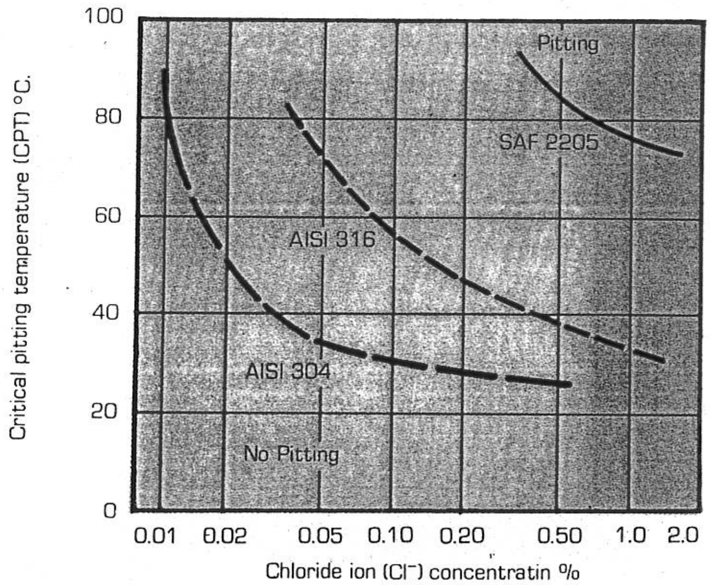

Fig. 2 Critical pitting temperatures at varying concenctraction of Sodium chloride (potentiostatic determination at+300mV pH 6.0) - Ref. 2

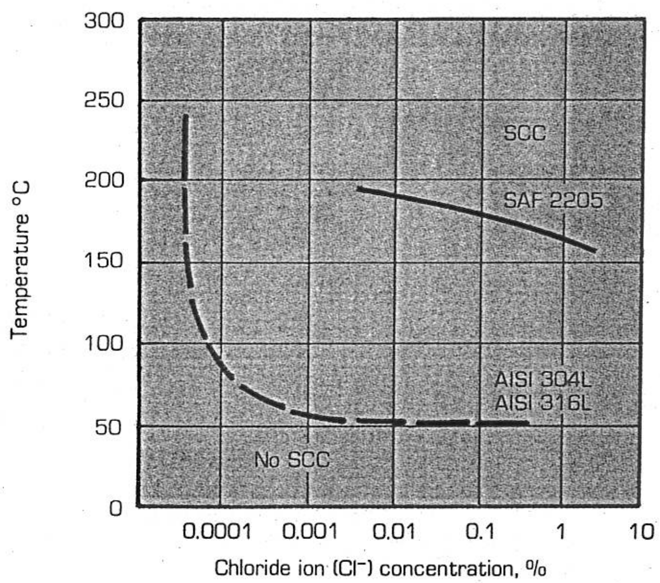

Fig. 3 Resistance to SCC laboratory test results- Ref. 2

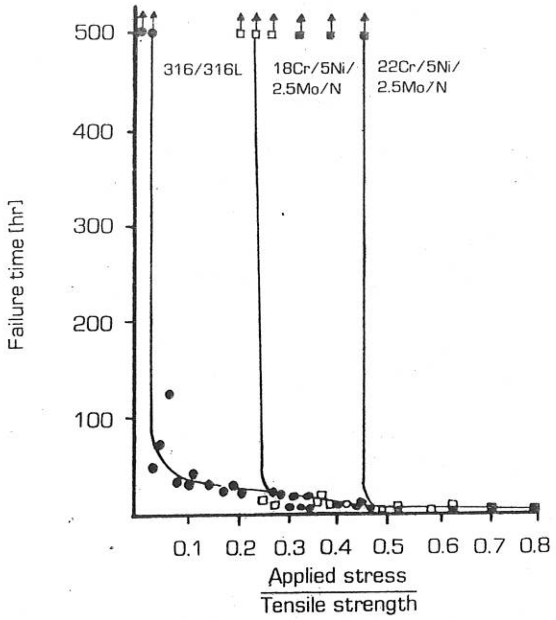

Fig. 4 SCC resistance in 45% $MgCl_2$ at 150°C- Ref. 3

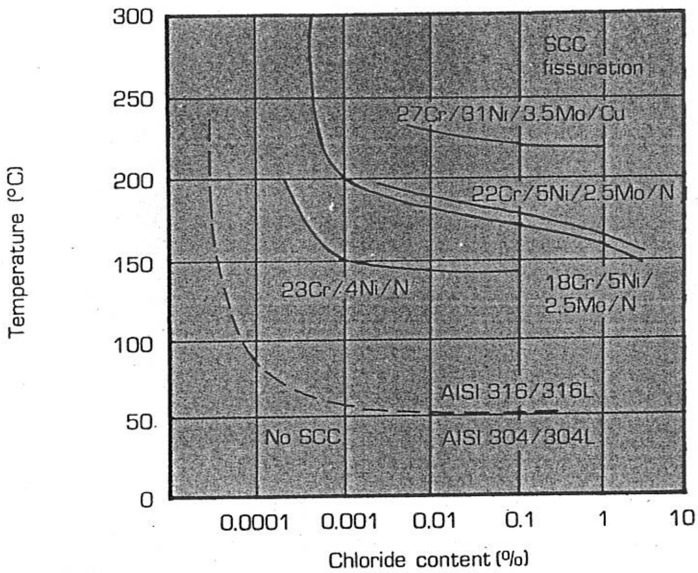

Fig. 5 Compilation of practical experience and laboratory test data for stainless steels in neutral areated aqueous chloride environments- Ref. 3

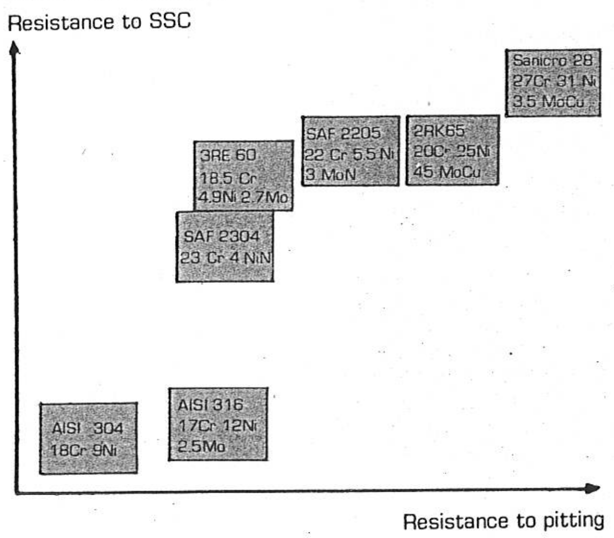

Fig. 6 Ref. 4

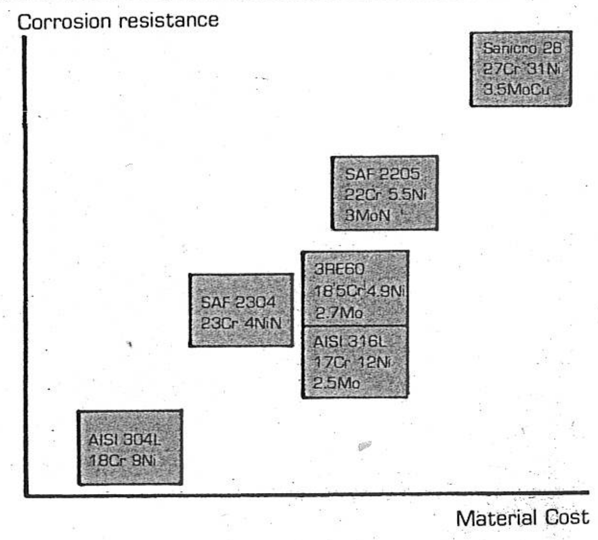

Fig. 7 Ref. 4

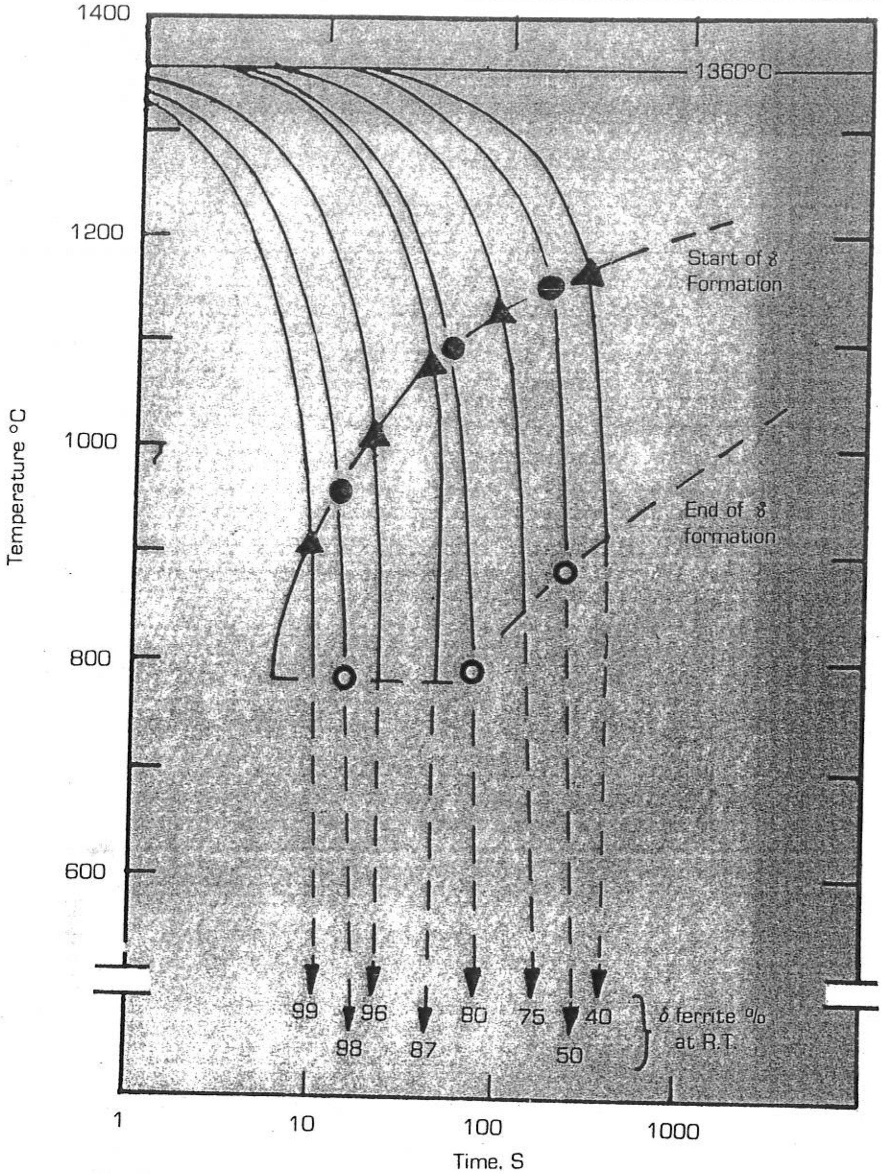

Fig. 8 CCT diagram for cast duplex stainless steel (without nitrogen)- Ref. 5

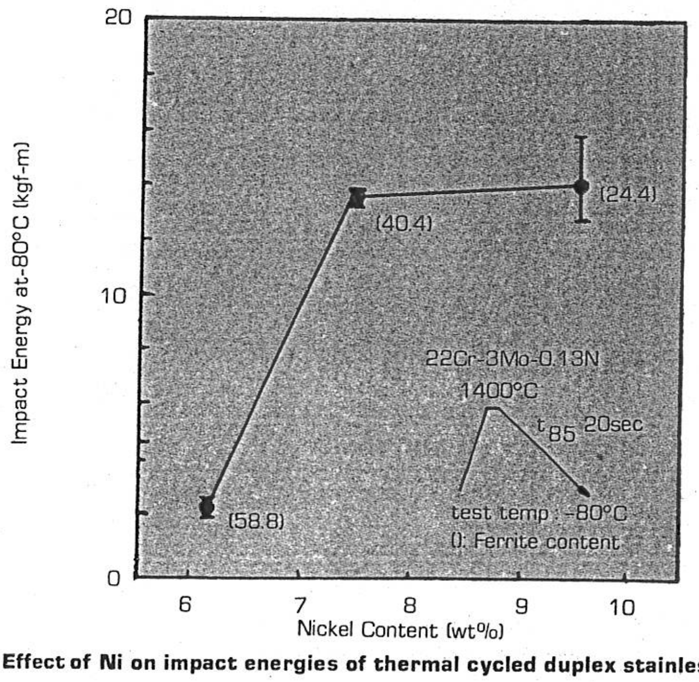

Fig. 9 Effect of Ni on impact energies of thermal cycled duplex stainless steel- Ref. 10

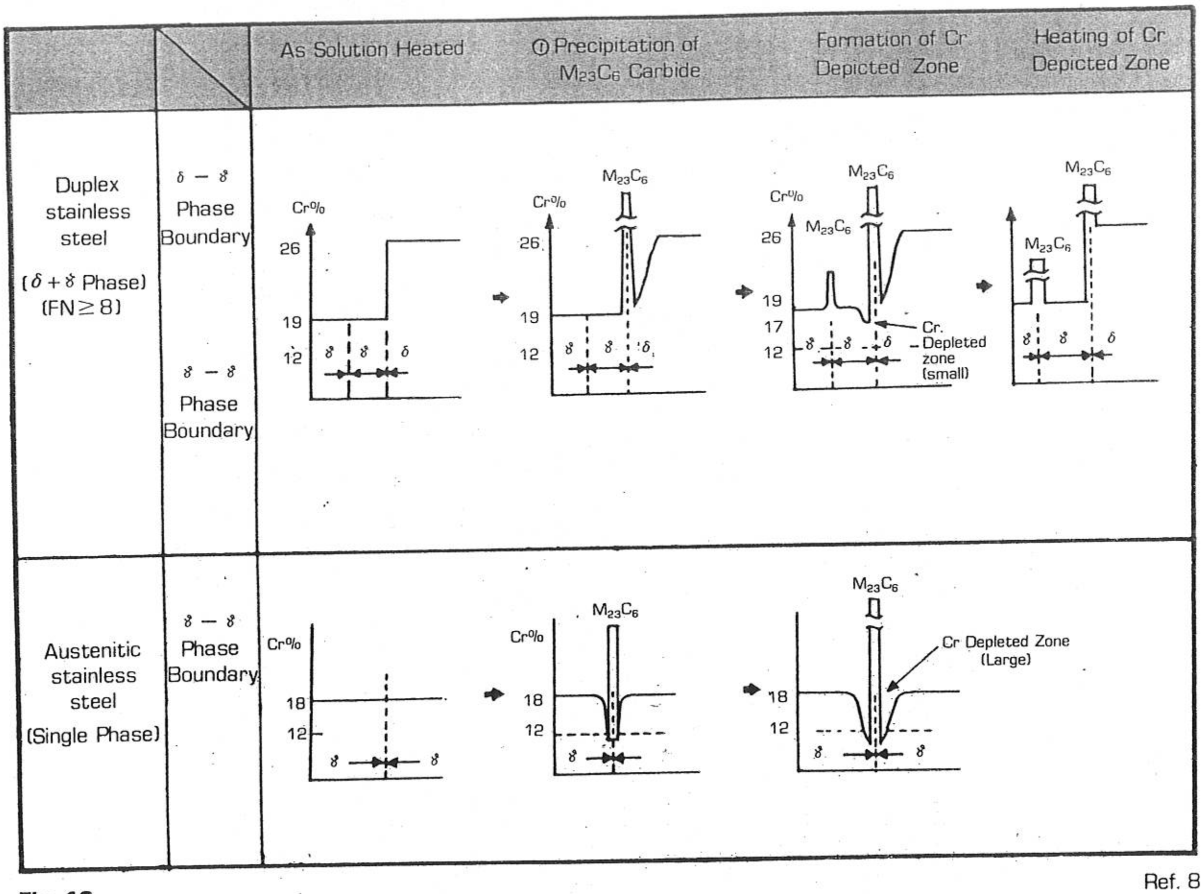

Fig. 10

Ref. 8

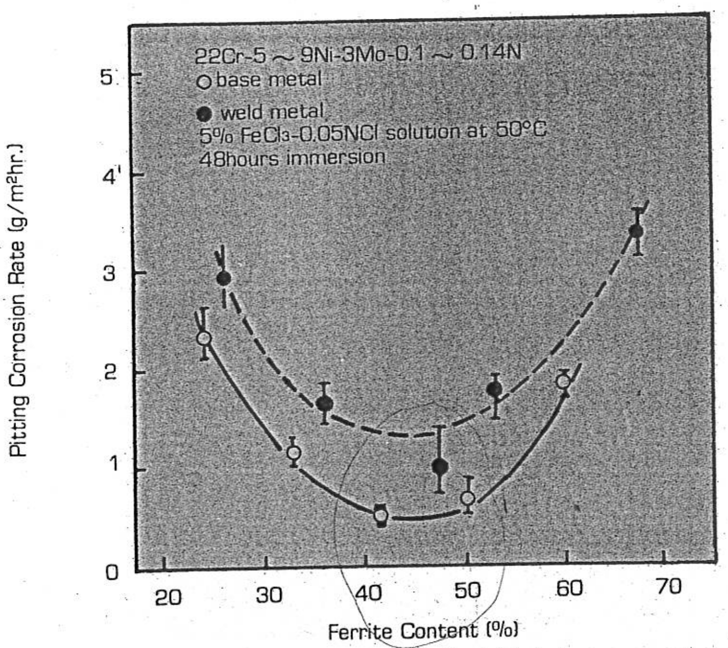

Fig. 11 Effect of ferrite content on pitting corrosion resistance of base and weldmetals Ref. 10