Welding of Duplex Stainless Steel

Jatandeep Singh[1] Nishant Goswami[2]
[1,2] Department of Manufacturing Processes and Automation Engineering
[1,2] Netaji Subhas Institute of Technology, Dwarka, New Delhi, India

Abstract— Duplex stainless steels are unrivalled in a large number of applications in the temperature range -50°C to 250°C where a combination of corrosion resistance and mechanical strength is required. The key to the unique properties is the duplex structure and the synergistic interaction between the two phases. Duplex stainless steels (DSS) have somewhat different welding requirements than those of the more familiar austenitic stainless steels. They also provide high immunity to stress corrosion cracking (SCC). The purpose of this paper is to give an overview of welding of DSS. The discussion includes the importance of balancing ferrite to austenite, reducing formation of deleterious intermetallic and non-metallic phases, effect of hydrogen on duplex stainless steel and measuring ferrite contents. [1]

Keywords: Duplex stainless steel, Metallurgy, Precipitation mechanism, GTAW, GMAW

I. INTRODUCTION

Duplex stainless steels (DSSs) are characterized by a two phase structure, which consists of approximately equal proportions of ferrite (BCC) and austenite (FCC), i.e. from 60/40 to 40/60 percent volume fractions of austenite/ferrite. DSSs combine the good mechanical properties of both austenitic and ferritic phases (high YS, UTs, work-hardening rate and ductility), some of them (YS, UTS) still increased by the small grain size, and progressively improved during recent years. Moreover, DSS possess a very good corrosion resistance. Today they are used as structural materials in large fields of industries, such as oil and gas, petrochemical, paper, and nuclear industries, also replacing even progressively the more costly 300' series austenitic stainless steels. For many engineering applications in the petroleum and refining industry, duplex stainless steels (DSS) are the preferred material. Finally, their high mechanical properties permit thickness reductions, particularly appreciated in transportation industries for instance. [2]

When DSS is welded incorrectly, the potential to form detrimental intermetallics phases drastically increases which could lead to a catastrophic failure. When comparing DSS to SS, DSS is not as resistant as ferritic SS but more resistant than austenitic to stress corrosion cracking (SCC); also if compared on the parameter of toughness, DSS is typically superior to that of ferritic SS but not as good as austenitic SS. DSS are two phase alloys based on the Iron-Chromium- Nickel (Fe- Cr- Ni) system. Maximum corrosion resistance and mechanical properties for a DSS weldment are achieved when the phase balance of ferrite to austenite is 50:50. However, achieving a 50:50 phase balance of ferrite to austenite ($\alpha \rightarrow \gamma$) in a weldment has proven to be difficult due to many variables such as weld metal chemistry, welding process and thermal history of the steel. Experience coupled with testing has shown that DSS have optimal corrosion resistance and mechanical properties when 35-60% ferrite content is maintained in the weld deposit. [3]

II. METALLURGY

The iron-chromium-nickel ternary phase diagram is a roadmap of the metallurgical behavior of the DSS. The usefulness of a phase diagram is illustrated by an isopleths diagram computed using Thermocalc5 for Cr-7Ni-4Mo-0.28N using chromium as a variable (Fig 1). The composition of SAF 2507 is indicated by a broken vertical line. At first, the steel solidifies ferritically, after which austenite is formed until, below about 1300°C, an entirely duplex structure is formed. As the phase fractions of ferrite and austenite may be calculated the relative fractions can be controlled by selecting the appropriate heat treatment temperature (see Fig 2). Moreover, the laws of thermodynamics can be used to control the heat treatment so as to give equal pitting resistance in ferrite and austenite. [8]

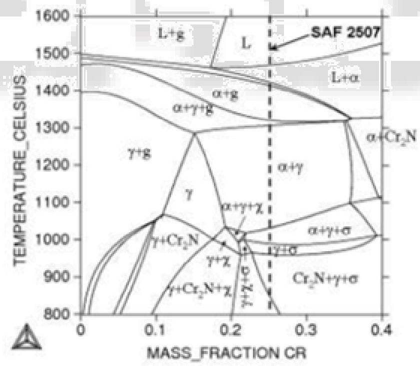

Fig 1. Phase diagram of SAF 2507 computed using the thermodynamic computer program Thermocalc. The composition of SAF 2507 is indicated by a dashed line.

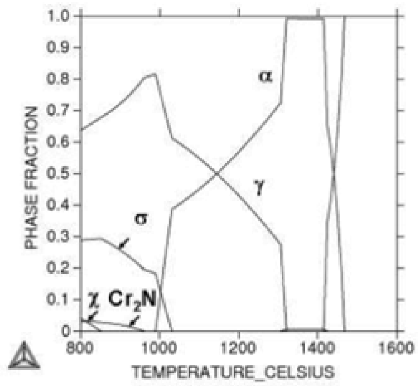

Fig 2. Phase fractions of ferrite, austenite, σ-phase, χ-phase and Cr_2N as a function of temperature in SAF 2507. Computed using Thermocalc.

By applying rule mining algorithms, frequent itemsets are generated from large data sets e.g. Apriori algorithm. It takes so much computer time to compute all frequent itemsets. We can solve this problem much efficiently by using Genetic Algorithm(GA). GA performs global search and the time complexity is less compared to other algorithms. Genetic Algorithms (GAs) are adaptive heuristic search & optimization method for solving both constrained and unconstrained problems based on the evolutionary ideas of natural selection and genetic. The main aim of this work is to find all the frequent itemsets from given data sets using genetic algorithm & compare the results generated by GA with other algorithms. Population size, number of generation, crossover probability, and mutation probability are the parameters of GA which affect the quality of result and time of calculation. (The physical metallurgy of duplex stainless steels J.-O. Nilsson and G. Chai Sandvik Materials Technology, R&D Centre, S-81181 Sandviken, Sweden)

Three basic categories of DSS are low-alloy, intermediate alloy, and highly alloyed, or Super-duplex stainless steel (SDSS) grades which are grouped according to their pitting resistance equivalent number (PREN) with nitrogen. DSS-grade 2205 and SDSS-grade 2507 are the most widely used alloys. The rich alloy content of chromium, nickel, molybdenum, and nitrogen that form austenite in a ferrite matrix are attributed for the remarkable corrosion resistance and mechanical properties of DSS. [1]

Elements	Weight Percentage (wt %)	Element Role	Alloying Characteristics
Chromium (Cr)	18 to 30 %	Ferrite former	↑ Cr will ↑ Corrosion resistance. The Ferrite content increases with ↑ Cr; however, too much Cr will ↓ optimal phase balance.
Nickel (Ni)	4 to 8 %	Austenite former	Ni influences a change in crystal structure from ferrite to austenite. Ni delays the formation of intermetallic phase.
Molybdenum (Mo)	Less than 5 %	Ferrite former	↑ pitting corrosion resistance. ↑ Tendency to form detrimental intermetallic phase if Mo content is too high.
Nitrogen (N)	Minimum of 0.14 %	Austenite former	N cause austenite to form from ferrite at elevated temperatures, allowing for restoration of an acceptable balance of austenite to ferrite after a rapid thermal cycle in the HAZ after welding. An addition of N increases pitting and crevice corrosion resistance and strength. Delays the formation of intermetallic phase. Offsets the formation of sigma phase in high Cr, high Mo steels.

Table (1): Importance of alloying elements of DSS

(Dr. Manish Samant, Mr. Kedar Godse and Dr. Manfred Rostek, February 2012, Best Practices in Welding of Duplex Stainless Steel, Seminar on Emerging Trends in Welding Industry.)

III. OPTIMUM (Α→Γ) BALANCE

The presence of ferrite in DSS imparts the superior chloride stress corrosion cracking (CSCC) resistance and high strength. It may behave similar to ferritic SS if ferrite content is increased. When the amount of austenite in DSS increases, strength will decrease while corrosion resistance and susceptibility to CSCC increases. Thus, ferrite limits should be used as a control measure and mentioned within a reasonable range. Ferrite content must be carefully controlled, whenever low temperature impact properties are required.

When the ferrite content exceeds approximately 60%, there will be a noticeable decrease in the ductile behavior and pitting resistance. To have optimum results, ferrite should be within a range of 35-60 %.

Below diagram illustrates how ferrite content affects DSS materials. The dotted curve represents the corrosion rate in chloride containing aqueous environments with respect to percentage of ferrite within the material. The solid curve represents impact energy at ambient temperatures with respect to the percentage of ferrite in DSS. Impact energy is at its greatest magnitude at lower ferritic levels right through to approximately 60% ferrite, at which point the impact energy begins significantly to decrease.[3]

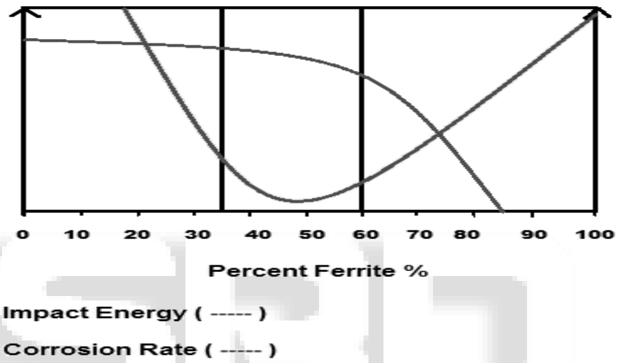

Fig. 3: Corrosion rate and impact energy vs. percent ferrite of DSS

(Duplex stainless steel welding Best practices (Part 1) Barry Messer, Andrew Wright, Vasile Oprea. Fluor Canada Ltd., Canada)

IV. DSS WELDING

A. *Base Material*

Since, corrosion resistance and mechanical properties of duplex alloys depend heavily on the phase balance and absence of deleterious microstructures, base materials should be delivered in an acceptable condition. Generally, DSS are produced by the mills with a good α→γ balance that is very close to 50:50; however, the absence of harmful intermetallic compounds or precipitates should be verified by testing. It should be noted that the test methods will not necessarily detect loses of toughness or corrosion resistance attributable to other causes. One of the good practices is that %ferrite of the base metal should be verified prior to welding. Dissimilar metal welds (DMW) between DSS and other materials must be evaluated case by case. Generally, it is possible to weld all grades of DSS to DSS, to carbon steel (CS), to alloy steel, and to austenitic SS. In some cases, to avoid PWHT of the final weld, it is necessary to use buttering techniques. [4]

B. *Welding Process*

The key for obtaining well balanced ferrite proportions within the base metal, weld-metal and HAZ is to perform

Welding Procedure Specifications (WPS) and Procedure Qualification Records (PQR) that address DSS welding issues as well as all requirements and codes for weld joints and applications. According to code requirements, a WPS and PQR must meet only the minimum requirements specified in the design code. In particular, heat inputs should be well documented in the WPS and PQR, so that welders may duplicate the original during production welding.

Availability of consumables, economics, and logistic considerations has a major role in deciding the process selection than the end desired properties. As well, it is commonly mistaken that DSS can be welded similarly to austenitic SS. For DSS, close monitoring of the narrow welding parameters and specific filler metals defined in the PQR is required to maintain a balanced microstructure. Where exceptional low-temperature toughness is required, gas-shielded processes may be specified to produce higher weld metal toughness properties than flux-shielded processes. Gas tungsten arc welding (GTAW), shielded metal arc welding (SMAW), submerged arc welding (SAW), flux cored arc welding (FCAW), gas metal arc welding (GMAW) and plasma arc welding (PAW) are commonly used with success for most DSS grades. Autogenous welding, such as electron-beam welding and laser-beam welding, is not very suitable for the welding of DSS since this process creates welds with very high ferrite content (as the base material contain lower Ni than filler metals). In these cases, a solution annealing PWHT can restore an acceptable weld and HAZ phase balance and also remove undesirable precipitates, provided ideal cooling rates are followed. [5]

C. GMA Welding of Duplex Stainless Steel

Hot tapping is now a well-established technology both onshore and offshore subsea in connection of branch pipelines to production pipeline systems without stopping production. The majority of the onshore hot taps is based on welding the branch pipe to the pipeline with subsequent tapping by using hydraulic drilling. The fully remote hot tapping will be done using gas metal arc welding (GMAW), which represents a new situation in the Norwegian oil and gas industry.

Following diagram shows the microstructure of 2 work pieces which were tested at 12 bar (Weld 1) and 35 bar (Weld 2).

The HAZ microstructure of Weld 1 consists of ferrite and austenite but with more ferrite than in the base metal. Weld 2 also had similar microstructure in the HAZ, but here there was found a 40-80 μm narrow layer at the weld interface with only ferrite. This observation is probably linked to the welding arc restriction with increasing chamber pressure (water depth), as the case when going from weld deposition of Weld 1 at 12 bar to Weld 2 at 35 bar. The smaller arc area may thus, in turn, cause more rapid cooling, which may be sufficient to prevent austenite nucleation within a narrow band close to the weld interface.

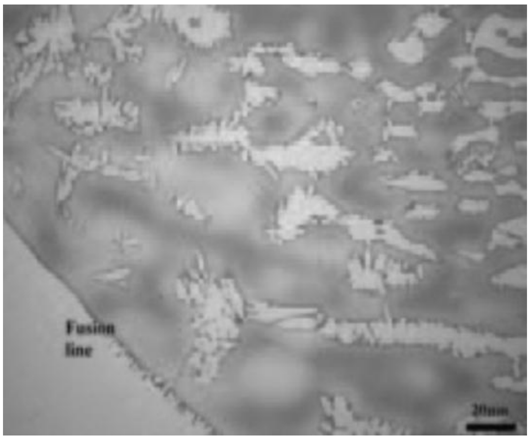

Fig. 4: Weld 1 - HAZ microstructure of cap bead.

A high-volume fraction of ferrite in the high-temperature region of HAZ in duplex stainless steels is not surprising, but rather usual. This is due to the grain coarsening of the ferrite taking place during the heating cycle followed by rapid cooling, which together with the grain coarsening may prevent austenite formation. Such high amount of ferrite is considered detrimental to notch toughness and also the corrosion resistance through possible precipitation of chromium nitrides (Cr_2N or CrN) in the ferrite which may take place due to limited solubility of nitrogen in ferrite.

We can see that weld metal yield strength is lower than that of the base metal. The tensile strength is similar to that of the base metal. There is a high ferrite volume fraction (~1.0) in a narrow (up to 40 μm) region at the weld interface. The weld metal microstructure study revealed dendrite solidification with primary and secondary dendrite Arms, and interdendritic regions with enrichment in solute elements, primarily Nb and Mo.

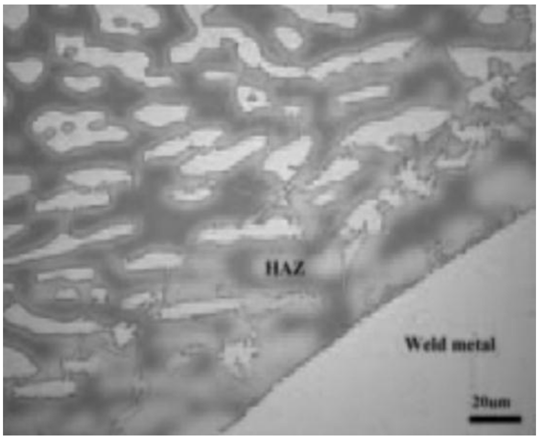

Fig 5: Weld 2-HAZ microstructure of cap bead.

(O. M. Akselsen, H. Fostervoll, and C. H. Ahlen, Hyperbaric GMA Welding of Duplex Stainless Steel at 12 and 35 Bar, Supplement to the Welding Journal, February 2009, pp.21s,26s and 28s.)

The decreasing solubility of these solutes during cooling resulted in formation of intermetallic phases. Base metal dilution resulted in large local variations in the weld metal chemical composition. [1]

D. Hydrogen accumulation in Duplex Stainless Steel

Where hydrogen content and ferrite level, in DSS weldments, are relatively high and sufficient stress is applied, hydrogen cracking may occur. The GTAW process, showed high hydrogen levels could be found in the weld metal despite the low, hydrogen content of the consumables. One of the potential sources for weld metal hydrogen is moisture in the shielding gas. The moisture content of a gas is usually expressed as dew point temperature. This dew point temperature is the temperature where water in the gas starts to condensate.

The moisture content of the shielding gas was found to affect the weld metal hydrogen level only slightly. Lower current levels were found to be associated with the increased hydrogen level. The hydrogen levels were found to be a function of heat input (through welding speed and current). Susceptibility to cracking was determined for a set of conditions believed to be most susceptible, which were high ferrite, high shielding gas moisture, low current (GMAW), high welding speed/low heat input (GTAW), high deposited hydrogen level and an increased restraint level.

Hydrogen-assisted cracking becomes more relevant with the increase in the ferrite content in duplex stainless steel. The austenite in duplex structure acts as a barrier to hydrogen escape. As austenite forms first at the grain boundaries of the original ferrite and envelopes the primary ferrite, the hydrogen present gets trapped within the ferrite and hydrogen diffusion is limited. When plastic deformation occurs in this situation, active hydrogen at the deformed austenite/ferrite interface may cause hydrogen cracking. Hydrogen in weld metal appeared to be more dependent on welding procedure rather than moisture content of the shielding gases investigated, or by hydrogen initially present in GTA or GMA consumables.[8, 19]

E. Shielding and Backing Gas

Pure argon (Ar) shielding and backing gases create weldments with sufficient corrosion resistance. However, Nitrogen loss is not uncommon resistance of the weld, it is beneficial to have additions of 1-2% Nitrogen in the AR shielding and 90% Nitrogen with 10% Hydrogen (H) in the backing gas. Nitrogen contents above 2% in the shielding gas can cause degradation of the tungsten electrode for GTAW processes. The addition of Hydrogen to the shielding may cause Hydrogen absorption in the weld, thus it is not recommended. Since DSS have relatively high chromium contents and relatively low thermal expansion, an oxide scale appearing as an oxide tint is produced during welding, which is typically thin and difficult to remove. The appearance and amount of heat-tint produced during welding can be minimized with low levels of oxygen (below 0.25%) in the shielding and backing gases. [9]

Process	Gas Types
GTAW	99.996%Ar; Ar+2%N_2
GMAW	Ar+1% O_2; Ar+30% He+1% O_2; Ar+2% CO_2; Ar+15% He+2% CO_2
FCAW	Ar+1%O_2; Ar+20%CO_2; Ar+2%CO_2
PAW	99.996%Ar

Table 2: Shielding gases suitable for the various gas shielded processes

(Influence of the gas composition on the geometry of laser-welded joints in duplex stainless steel, Branko Bauer, Angela Topi, Slobodan Kralj, Zoran Ko`uh)

F. Shielding gas developments for GTAW welding of duplex stainless steels

When GTAW welding is done with argon shielding gas, nitrogen is lost from the weld pool. This can result in a ferrite-rich weld metal, with inferior corrosion resistance to the parent metal. The loss of nitrogen from the weld pool appears to be due to the difference in partial pressure between the nitrogen dissolved in the weld pool and the gas directly above the weld pool. The partial pressure of nitrogen in the shielding gas, and hence the loss of nitrogen from the weld pool, can be modified by using a shielding gas containing a proportion of nitrogen. If the proportion of nitrogen in the shielding gas exceeds the suggested values, then the nitrogen content of the weld will increase along the weld length.

For duplex stainless steel, with a typical nitrogen content of 0.16%, to obtain a similar nitrogen content in the weld metal, the shielding gas should contain 1.0-1.2% N_2.To ensure that the welders exposure to ozone is below the occupational exposure standard, the shielding gas should contain a proportion of helium. These results have been used to formulate shielding gas mixtures for commercial use: For duplex stainless steel, there is Duplex shielding gas, containing (Ar-20% He-1.1% N_2).[17]

G. Filler Metal Selection

Welding consumables for DSS are similar in composition to that of the base material, with exception that the consumables do require nitrogen and higher levels of nickel to ensure an appropriate phase balance in the deposited weld metal. A nitrogen addition in filler metals, 0.14-0.20% N, helps to prevent the formation of σ phases. Increased addition of Ni promotes a change in crystal structure from ferrite to austenite and also delays the formations of intermetallic phases. It is important that the Cr-content of the deposited filler metal, provides a close match of the base metal. DSS and SDSS may be welded with a DSS/SDSS filler metal that is alloyed with higher amounts of Ni or, alternatively, they could be welded with a fully austenitic Ni- alloy filler metal. [10]

Table 3: Filler metals for the welding of DSS's.

Parent metal Sandvik	Welding process	Filler metal Sandvik	Chemical composition, typical									
			C max.	Si	Mn	P max.	S max.	Cr	Ni	Mo	N	Ferrite All weld metal, %
SAF 2304	TIG, MIG, SAW	23.7.L	0.020	0.4	1.5	0.020	0.015	23	7	-	0.14	30-40
	MMA	23.8.LR	0.030	<0.9	0.5	0.030	0.025	25	9	-	0.12	30-40
SAF 2304 and SAF 2205	TIG, MIG, SAW	22.8.3.L	0.020	0.5	1.6	0.020	0.015	22.5	8	3	0.14	30-40
	MMA	22.9.3.LR	0.030	<1.0	0.8	0.030	0.025	22.5	9	3	0.12	30-40
		22.9.3.LB	0.04	<0.5	0.8	0.030	0.025	22	9	3	0.15	30-40
	FCAW	22.9.3.LT	0.030	<1.0	1.5	0.030	0.025	22.5	9	3	0.15	30-40
SAF 2507	TIG, (MIG), SAW	25.10.4.L	0.020	0.3	0.4	0.020	0.020	25	10	4	0.25	30-40
	MMA	25.10.4.LR	0.030	0.5	0.7	0.020	0.025	25	10	4	0.25	30-40
		25.10.4.LB	0.040	0.4	0.9	0.030	0.025	25.5	9.5	4	0.25	30-40

(Welding practice for the Sandvik duplex stainless steels SAF 2304, SAF 2205 and SAF 2507 by Claes-Ove Pettersson and Sven-Åke Fager AB Sandvik Steel, S-811 81 Sandviken, Sweden)

V. THERMAL HISTORY

A. Preheat and Interpass Temperatures

DSS should be void of moisture prior to welding and to remove moisture, preheating to a maximum of 75°C may be applied. However, in some cases base metal should be allowed to cool to room temperature prior to welding. Generally, preheating is not recommended immediately prior to welding as it may negatively affect cooling rates required to achieve optimal phase balance.[3]

Heat input is a secondary factor relative to weld metal composition in controlling the Ferrite/ Austenite phase balance. Dilution and heat input from the dissimilar base metal had little or no effect on the mechanical properties. "Interpass temperature" refers to the temperature of the material in the weld area immediately before the second and each subsequent pass of a multiple pass weld. The maximum recommended interpass temperature should not exceed 150°C for DSS alloys and 100°C for SDSS alloys throughout welding operations. Excessive interpass temperatures can cause embrittlement and low impact values in the root region.[18]

B. Heat Affected Zone (HAZ)

The HAZ is the area of base metal which has had its microstructure and properties altered by welding or heat intensive cutting operations, i.e. by inducing intensive heat into the metal. The HAZ should have corrosion resistance and impact toughness comparable to the base material minimum requirements. Due to the low heat input welding processes and the higher thermal conductivity of the material, DSS and SDSS exhibit a narrow-HAZ, in comparison to austenitic-SS. If the heat input is too low, this will result in a weld that is predominantly ferritic and will not have the same characteristics as the base metal.[1, 13]

C. Post-Weld Heat Treatment (PWHT)

PWHT of DSS is generally not required but may be necessary when detrimental amounts of intermetallic phases have formed. To maintain the corrosive resistance, post weld cleaning is required.

The corrosion properties in post weld heat treated duplex stainless steel are related not only to the presence of the secondary austenite but also to its morphology, which in turn depends on the heat treatment parameters. A coarse secondary austenite induces better corrosion properties compared to the finer one. If Induction heat treatment is carried out, a significant thermal gradient may arise across the thickness of the weld so that different corrosion properties may be found across the thickness of the joint.[6]

Precipitation Mechanisms

DSS alloys solidify primarily as ferrite at approximately 1425°C and partially transform to austenite at lower temperature by a solid state reaction. Optimum phase balance of a DSS is shown in Fig. 5. The light globules in the dark body are unattached austenitic grains within the etched ferritic matrix respectively. Very little ferrite transforms to austenite, if the cooling rate is rapid, which results in an excessive ferrite phase at room temperature. Consequently, the cooling rate of duplex welds must be slow enough to allow the transformation of approximately 50% of the ferrite to austenite and, at the same time, fast enough to prevent the formation of intermetallic phases and deleterious microstructures. DSS is rendered susceptible to embrittlement and loss of mechanical properties, particularly toughness, through prolonged exposure at elevated temperatures, due to its high alloy content and the presence of a ferritic matrix. As cooling proceeds to lower temperatures in the range of 475-955°C for short periods of time the precipitation of carbides, nitrides and intermetallic phases, all of which can be detrimental, will occur. The most notable phases are alpha prime (α'), Sigma (σ), chi (ϰ), and Laves (η) phases. For this reason, DSS are generally not used at temperatures above 315°C. Cooling provided by the work piece itself is the most effective method of reducing the time that the HAZ is in the temperature range formation of these intermetallic phases.[3]

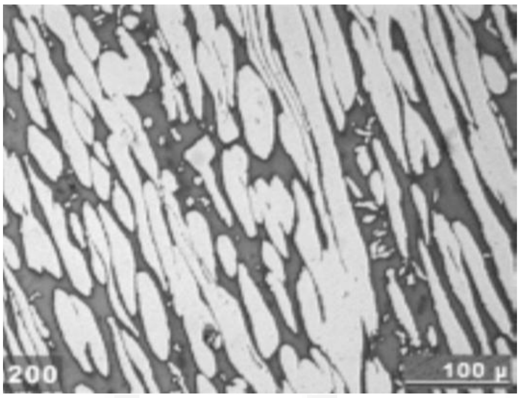

Fig. 5: DSS Micrograph at 200X

(Duplex stainless steel welding. Best practices (Part 1) Barry Messer, Andrew Wright, Vasile Opera. Fluor Canada Ltd., Canada.)

Duplex Stainless Steel	
	°C
Solidification range	1470 to 1380
Scaling temperature in air	1000
Sigma phase formation	700 to 950
Carbide Precipitation	450 to 800
475C/ 885F embrittlement	300 to 525

Table 4: Typical precipitation temperature for DSS

(Practical Guidelines for the Fabrication of Duplex Stainless Steel, Second Edition 2009, Published by the International Molybdenum Association (IMOA), London, U.K)

D. Ferrite measurement

At present, the absolute ferrite content in weld metal cannot be estimated as no such experimental methods are available, either destructive or non-destructive. This situation has led to the development and use, internationally, of the concept of a "ferrite number: (FN). So, the ferrite content of a weld metal is described by the FN which is determined using a standardized procedure. FN is approximately equivalent to the weight percentage ferrite content, particularly at low FN values. The most common methods to measure ferrite content of DSS are point count method (PCM) and an electromagnetic measuring device (EMD), both governed by ASTM E562. The PCM, a more time consuming but more accurate method, is best to verify the consistency of balanced α→γ during WPS and PQR development, but it is a destructive test. The EMD is a preferred method for verifying the austenite to ferrite ratio of production welds as it is a non-destructive test.[15, 1]

Rise in heat input and dilution, causes FN to decrease, in Duplex stainless steel. It decreases with a rise in welding current and welding speed and increases with a decrease in welding gun angle and rise in tip–to-workpiece distance. When the welding current is low, a decrease in welding gun angle increases the FN and when the welding current is high, a decrease in welding gun angle decreases the FN slightly. Similarly when the welding speed is high, a decrease in welding gun angle increases the FN and when the welding speed is low, a decrease in the welding gun angle decreases the FN slightly.[16]

VI. APPLICATIONS OF DUPLEX STAINLESS STEEL

DSS's good corrosion resistance and mechanical properties make it an ideal material for many applications. Duplex, Super Duplex and Hyper-duplex stainless steels are increasingly regarded as attractive alternatives to other kinds of stainless steels, in terms of both cost and durability. As a result, it is expected that the market will grow by 20% per year. Due to the very fine-grained structure, nitrogen alloying, and ferrite/austenite mixture, combination of high corrosion resistance, high mechanical strength (leading to weight reduction) and good weld ability, DSSs is preferred as fabrication material for many applications. DSSs may be used in many corrosive environments within the temperature range of approx. -50°C to less than 280°C. It was observed that heat exchangers are by far the most critical piece of equipment and that DSS in most cases are chosen as the first countermeasure to combat this form of corrosion. As regards pitting corrosion resistance, duplex alloys are as resistant as austenitic alloys. DSS have several applications in Oil & Gas, Chemical industry, Pulp & Paper industry, Water systems, desalination plants, Pollution control equipment, Chemical tankers, Architecture, Automotive Applications Biofuels.[14, 12]

VII. CONCLUSIONS

Castings and possibly thick sections may not cool fast when annealed causing sigma and other deleterious phases to form. A full solution annealing is advantageous, particularly if low service temperatures are foreseen. Strength of DSS is typically twice the yield of austenitic stainless steels. Minimum Specified UTS, typically 680 to 750N/mm^2 and Elongation, typically > 25%. Good corrosion resistance and mechanical properties of DSS are the result of well crafted WPS/PQR that define heat inputs and cooling rates to achieve weldments with optimum ferrite to austenite balance. The superior CSCC resistance and high strength is attributed to the presence of ferrite in DSS. On the other hand, austenite in DSS imparts the high aqueous corrosion resistance and low temperature impact toughness. The recommended phase balance of DSS and SDSS should contain 40-60% ferrite in the base metal and 35-60% ferrite in the weld metal.

Special consideration must be given to the narrow-HAZ. It is essential to have a discontinuous fine grain microstructure of ferrite and austenite in the narrow region. The high amounts of alloying elements give way to complex precipitation behavior in DSS. The formation of carbides, nitrides and intermetallic phases, which can be detrimental, will begin to form in short periods of time in the range of 475-955°C. For this reason DSS should not be used at temperature above 280°C, hence usable temperature range is -50 to 280°C. It has superior corrosion resistance than SS316 and good resistance to stress corrosion cracking in a chloride environment. Super Duplex Stainless steel is stronger and more corrosion resistant than DSS. Optimum DSS welds depend on multiple factors such as engineering design, material selection, pre/post-weld cleaning, joint preparation and most importantly, choice of a suitable welding process.[1]

REFERENCES

[1] Dr. Manish Samant, Mr. Kedar Godse and Dr. Manfred Rostek, Best Practices in Welding of Duplex Stainless Steel, Seminar on Emerging Trends in Welding Industry,pp.38-46, February 2012.

[2] Alvarez-Armas, A. F. Armas and S. Degallaix- Moreuil, Strain heterogeneities between phases in a duplex stainless steel. ScienceDirect, pp.2230, March 2010.

[3] Barry Messer, Andrew Wright, and Vasile Oprea, Duplex stainless steel welding , Best practices (Part 1). Stainless Steel World, November 2007, Fluor Canada Ltd., Canada

[4] Bonnefois B., Charles J., Dupoiron F., and Soulignac, P. 1991. How to predict welding properties of duplex stainless steels. Proc. *Duplex Stainless Steels* '91, Beaune, Bourgogne, France, Vol.1, pp.347-361.

[5] Dakhlaoui R., Baczmanski A., Braham C., Wronski S., Wierzbanowski K., and Oliver EC. Effect of residual stresses on individual phase, mechanical properties of austeno-ferritic duplex stainless steel. *Acta Mater* 2006; 54:5027-5039.

[6] P. Ferro, A. Tiziani, and F. Bonollo, Influence of Induction and Furnace Postweld Heat Treatment on Corrosion Properties of SAF 2205 (UNS 31803), Vol. 87, Welding Research, pp.306s, December 2008.

[7] O. M. Akselsen, H. Fostervoll, And C. H. Ahlen, Hyperbaric GMA Welding of Duplex Stainless Steel at 12 and 35 Bar, Supplement to the *Welding Journal*, pp.21s, 26s and 28s, February 2009.

[8] Gunn, R. N. 1997. Hydrogen cracking of duplex stainless steel multipass weldments. Technical note from Group Sponsored Project 5669 TWI.

[9] Branko Bauer, Angela Topi, Slobodan Kralj and Zoran Ko`uh. Influence of the gas composition on the geometry of laser-welded joints in duplex stainless steel.

[10] Claes-Ove Pettersson and Sven-Åke Fager. Welding practice for the Sandvik duplex stainless steels SAF 2304, SAF 2205 and SAF 2507. AB Sandvik Steel, S-811 81 Sandviken, Sweden.

[11] J.-O. Nilsson and G. Chai, The physical metallurgy of duplex stainless steels, Sandvik Materials Technology, R&D Centre, S-81181 Sandviken, Sweden.

[12] J. R. Davis, Corrosion of Weldments: ASM Internationals; Materials Park, OH 44073-002.

[13] Ramirez, A. J., Brandi, S. D., and Lippold, J. C. 2004. Secondary austenite and chromium nitride precipitation in simulated heat affected zones of duplex stainless

steels. *Science and Technology of Welding and Joining* 9(4).

[14] Bradshaw, R and Cottis, R A. Development and control of welding procedures for duplex stainless steels. *Welding &Metal Fabrication*, 61(3)9 129 – 136, April 1993,

[15] Kotecki, D. J. 1982. Extension of the WRC Ferrite Number system. *Welding Journal* 61(11): 352-s to 361-s.

[16] T. Kannan and N. Murugan, Prediction of Ferrite Number of Duplex Stainless Steel Clad Metals Using RSM, Supplement to the Welding Journal, May 2006, pp.100s.

[17] R Wiktorowicz and J Crouch, Shielding gas developments for TIG welding of duplex and super duplex stainless steels.

[18] E. J. Barnhouse and J. C. Lippold, Microstructure/Property Relationships in Dissimilar Welds between Duplex Stainless Steels and Carbon Steels, Welding Journal.

[19] V. V. D. Mee, H. Meelker and R. V. D. Schelde, How to Control Hydrogen Level in (Super) Duplex Stainless Steel Weldments Using the GTAW or GMAW Process, Welding Research Supplement, pp.7s to 10s and 14s.

[20] Practical Guidelines for the Fabrication of Duplex Stainless Steel, Second Edition 2009, Published by the International Molybdenum Association (IMOA), London, U.K.

