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Review

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PII: S2090-1232(17)30011-5

DOI: <http://dx.doi.org/10.1016/j.jare.2017.01.002>

Reference: JARE 507

To appear in: *Journal of Advanced Research*

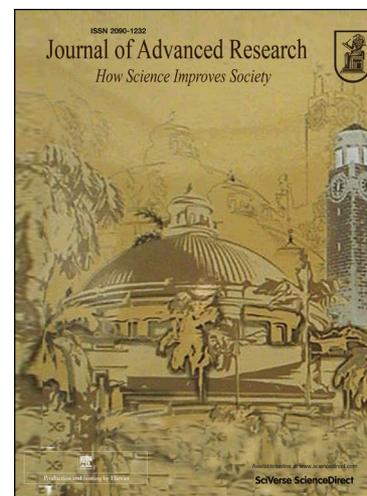
Received Date: 4 October 2016

Revised Date: 19 December 2016

Accepted Date: 6 January 2017

Please cite this article as: Vinoth Jebaraj, A., Ajaykumar, L., Deepak, C.R., Aditya, K.V.V., Weldability, machinability and surfacing of commercial duplex Stainless Steel AISI2205 for marine applications – A recent review, *Journal of Advanced Research* (2017), doi: <http://dx.doi.org/10.1016/j.jare.2017.01.002>

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**Weldability, machinability and surfacing of commercial duplex Stainless Steel AISI2205  
for marine applications – A recent review**

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**Short title:** Duplex stainless steel AISI 2205 for marine applications – A Review

**Abstract:** In the present review, attempts have been made to analyze the metallurgical, mechanical and corrosion properties of commercial marine alloy duplex stainless steel AISI 2205 with special reference to its weldability, machinability, and surfacing. In the first part, effects of various fusion and solid state welding processes on joining DSS 2205 with similar and dissimilar metals are addressed. Microstructural changes during the weld cooling cycle such as austenite reformation, partitioning of alloying elements, HAZ transformations, and the intermetallic precipitations are analyzed and compared with the different welding techniques. In the second part, machinability of DSS 2205 is compared with the commercial ASS grades in order to justify the quality of machining. In the third part, the importance of surface quality in a marine exposure is emphasized and the enhancement of surface properties through peening techniques is highlighted. The research gaps and inferences highlighted in this paper will be more useful for the fabrications involved in the marine applications.

**Keywords:** Duplex stainless steel; welding; machining; surfacing; shot peening

## Introduction

The anticorrosive stainless environment in both onshore and offshore applications is being a needful objective for many countries around the world. Among the group of stainless steel family, Duplex Stainless Steel (DSS) grades are contributing an important role in fabricating thousands of tonnage marine structures and machinery successfully over the past few decades [1]. DSS grades are mainly used in the fabrication of offshore oil and gas pipe lines, offshore concrete structures, offshore umbilical's, ocean mining machinery, chemical tankers in ships, fasteners used in marine machinery, construction of bridges in cold countries, paper, and pulp industries, pipe lines in desalination plants etc. The alloying process of modern DSS was started in 1980's only after understanding the importance of nitrogen in the chemical composition. Today, it has become a popular material and satisfying the combined needs of Ferritic Stainless Steel (FSS) and Austenitic Stainless Steel (ASS) grades. They are dual phase Fe-Cr-Ni-N system of alloys consist of an equal amount of ferrite ( $\alpha$ ) and austenite ( $\gamma$ ) phases in the microstructure [2 – 7]. During the alloying process of DSS, the parameters for solution annealing followed by water quenching are carefully monitored to control the duplex microstructure. Under equilibrium conditions, ferrite promoting elements (Cr, Mo, W, Nb, Si, Ti and V) are concentrated by diffusion into the ferritic structure. At the same time, austenite promoting elements (Ni, Mn, C, N, Co and Cu) are concentrated by diffusion into the austenitic structure. The combined lattice arrangement of Body Centered Cubic (BCC) and Face Centered Cubic (FCC) structure gives greater strength and offers excellent resistance against Stress Corrosion Cracking (SCC) [8]. Among the available DSS grades, AISI 2205 is more popular and contributing a predominant role in the marine fabrication industries for more than three decades. The yield strength and the ultimate tensile strength of DSS 2205 are 2 to 3 times greater than the commercial ASS grades such as 304L and 316L. To overcome the shortage of raw material resources, stainless steels for the future

generation should be optimized with respect to the mechanical and corrosion properties. DSS 2205 is a better alternative for the ASS grades and offers economic benefits by reducing the thickness of the members in the fabrication there by reducing the weight as well as the cost without sacrificing the strength.

Successful application of any material in service mainly depends on its ability to fabricate with minimum cost. Fusion welding plays a major role in the construction of various structures and machinery used in marine applications [9 – 11]. The Weldability of DSS 2205 is far superior to the FSS grades but lesser than the ASS grades. The welding metallurgy of DSS is quite complex due to the presence of more number of alloying elements in it. Also, DSS can be effectively used only in the temperature range between – 40°C and 300°C. The evolution of intermetallics such as sigma ( $\sigma$ ), chi ( $\chi$ ) and chromium nitride ( $\text{Cr}_2\text{N}$ ) phases take place above the temperature of 300°C which leads to a severe reduction in its properties related to mechanical and corrosion aspects. Due to the presence of ferrite phases in DSS, it undergoes ductile-brittle transition at low temperature below – 40°C. Further, joining of DSS by various fusion welding processes addressing some notable issues related to the microstructural changes in the weldment and HAZ, ferrite-austenite ratio, different forms of austenite phases and intermetallic precipitations etc. [12, 13]. It is found that the mechanical and corrosion properties of DSS weld differ from the parent metal and some of the failures were reported on DSS especially on its weldment and HAZ [2, 14 – 16]. Intensive use of DSS 2205 in the marine applications on a larger scale essentially needs the analysis of individual welding techniques with regard to their merits and pitfalls. Therefore, as the first part of this review, various types of DSS welds are reviewed from the literature with regard to their influences on the microstructure, mechanical and corrosion properties.

Moreover, machinability is an essential requirement for DSS 2205 in order to fabricate the components in a required size and shape. A conventional machining process like

milling, grinding, and turning is inducing grooved surface profiles due to the interaction between the tool and the workpiece during the process. Grooved surface profiles are more hazardous for the corrosive environment which causes a reduction in the fatigue life and corrosion attack due to the presence of more number of stress raisers on it. Surface roughness and tool wear are the two important aspects which are to be considered in deciding the machinability of a material. Machinability of DSS 2205 is generally lower than the ASS grades due to its high-temperature tensile strength and the lesser ductility. Therefore, as the second part of this review, the machinability of DSS 2205 is studied and compared with the commercial ASS grades.

The service provided by the DSS 2205 in the construction of marine machinery and structures is so grateful for the past few decades. However, the investigations related to the influence of surface quality on DSS to avoid the failures in a corrosive environment is not vast. Since most of the failures in the corrosive environment are arising from the surface of a material, the topography and the surface quality play a major role in extending the life of a material. It is essential to protect the surface from the high chloride and high sulphide sea water environment. There are few remedial techniques such as shot peening and Laser Shock Peening (LSP) which are available to improve the surface qualities from the as received and machined conditions. Surface modifications induced by peening stores compressive residual stresses on the surface and induces high-quality surface layer by hardening the metal skin, grain refinement and severe plastic deformation [17 – 21]. It will be extremely worthwhile if the existing literature on the commercial alloy DSS AISI 2205 is reviewed in order to understand the findings clearly and to make a better perspective for the future research. The present review is an effort in this direction to bring the cumulative database on the metallography, mechanical and corrosion properties of DSS 2205 with regard to its weldability, machinability, and surface engineering.

### Role of major alloying elements in DSS weld

The chemical composition of the DSS 2205 and its weld filler ER2209 are given in Table 1. Major alloying elements such as Cr, Mo, Ni and N play an important role in forming the weld and HAZ microstructure and promote the ferrite and austenite phases [22 – 25]. The Cr/Ni equivalent ratio for DSS usually lies above 2.4 and it is not susceptible to the formation of hot cracking during the fusion welding. The latest versions for calculating chromium and nickel equivalents are as follows:

$$Cr_{eq} = \%Cr + \%Mo + 0.5\% (Nb) + 1.5\% (Si)$$

$$Ni_{eq} = \%Ni + 30(\%C) + 0.5(\%Mn) + 30(\%N)$$

Chromium is used to increase the strength, corrosion resistance, hardenability and wear resistance of DSS [13]. It is a ferrite stabilizer which promotes the BCC structure of iron. During welding, progressive addition of chromium through the filler wire composition promotes the ferrite content in the weld. The hardness of the weldment is getting increased with an increase of chromium atoms. Also, increasing the amount of chromium causes significant improvement in the tensile strength of the DSS weld. But, reduction in the impact toughness particularly at the low temperature was observed due to the formation of excessive ferrite phases in the weldment [26].

Molybdenum supports chromium in pitting corrosion resistance. It also increases the hardenability and strength, particularly at the higher service temperature. However, the higher percentage of molybdenum usually forms intermetallic phases. Therefore, it is restricted to 4% in DSS. As like Cr, increasing the percentage of Mo also gives the significant reduction in the austenite phases and promoting the ferrite structure.

Nickel is necessary for getting a balanced microstructure in the DSS weld. It is an austenite stabilizer. It promotes the change of crystal structure from BCC to FCC structure. The addition of nickel suppresses the formation of intermetallic phases such as sigma and chi

phases etc. [27]. The addition of 9% nickel in the filler metal promotes higher austenite content in the fusion zone. Also, nickel plays a significant role in the enhancement of corrosion resistance of DSS [28]. The yield strength and the impact properties of weldment are greatly increased by increasing the nickel content. Excellent pitting potential was reported as the content of nickel increased in the weldment. The crack propagation rate of DSS in the sea water is also getting reduced when the percentage of nickel increases [29].

Nitrogen is an interstitial element which diffuses faster than the other substitutional alloying elements present in the DSS due to its smaller atomic size. The effect of nitrogen in the formation of austenite phases is higher than that of nickel. It is also an austenite stabilizer which increases the precipitation mechanism of austenite phases. It increases the pitting corrosion resistance, impact toughness and the tensile properties of DSS. Nitrogen also increases the micro hardness of both austenite and ferrite phases. It precipitates austenite phases at high temperature during the weld cooling cycle and also delays the formation of intermetallic phases. Ogawa et al reported that the chromium, molybdenum, and nickel are substitutional elements and have lesser ability to diffuse between ferrite and austenite during normal weld cooling conditions. But, nitrogen is an interstitial element that diffuses into the austenite very rapidly, nearly in the order of 100 times than the substitutional elements [30].

### **High Arc Energy Welding Processes**

The mechanical and corrosion properties of DSS weldment are purely structure sensitive and mainly depend on the type of joining process. DSS 2205 can be joined using all types of high arc energy fusion welding processes such as Gas Tungsten Arc Welding (GTAW) [31, 32], Gas Metal Arc Welding (GMAW) [28], Shielded Metal Arc Welding (SMAW) [11] Flux Cored Arc Welding (FCAW) [26, 33], Plasma Arc Welding (PAW) [34] and Submerged Arc Welding (SAW) [35 – 37]. However, these welding processes are having their own merits and limitations in forming the microstructure. Prolonged research on

welding of DSS 2205 recommends the heat input for welding in the range between 0.5 kJ/mm and 2.5 kJ/mm. Minimum heat input during welding leads to faster cooling rate thereby producing a higher amount of ferrite phases which causes the reduction in the tensile elongation as well as impact toughness. When cooling rate decreases, a large quantum of Widmanstätten austenite and intragranular austenite phases are getting formed within ferrite grains. Yinhui Yang et al stated that the slow cooling rate imposes more quantum of reformed austenite in the form of grain boundary austenite, Widmanstätten austenite and intragranular austenite phases in the weld [38]. In addition to heat input, type of cooling method also shows that the air cooled weld gives a large amount of reformed austenite than the water cooled one due to the slow cooling rate involved [39].

The microstructure produced by the GTAW process provides efficient and clean weldment when compared with other welding processes [40 – 46]. The inclusion content in the weldment is very low in GTAW due to the excellent protection by the shielding gas against the environment and due to slow deposition of the filler metal. Fusion zone of GTAW joint gives acceptable ferrite-austenite ratio. However, the weld microstructure is not similar to its parent metal microstructure. GTAW process is mainly used for root pass in the welding of DSS pipes to provide high-quality weld in the root region. However, the productivity is low in this process due to the slow deposition rate. In addition to GTAW, GMAW process also provides efficient and clean weldment which can also be used for root runs. The productivity is high in GMAW process when compared to GTAW due to the higher deposition rate. PAW on DSS2205 provides acceptable ferrite-austenite ratio in the presence of nitrogen addition with the argon shielding gas [34]. The weld microstructure obtained using FCAW process also provides acceptable ferrite austenite ratio with minimum cost. However, the formation of  $\text{Cr}_2\text{N}$  precipitation in the fusion zone of FCAW was observed if the amount of Cr increases beyond 22% which was reported earlier [26]. SAW process is mainly used for joining thick

sections in which the flux with low silica content is generally recommended to produce the acceptable ferrite content. Joining DSS using SAW process reported the precipitation of sigma phases near the fusion zone. It was reported that the formation of sigma phase leads to a notable effect in ductility, plasticity, and hardness of the weld. The higher heat input given during welding might be the reason for sigma precipitation. Careful control of heat input is necessary to avoid the deleterious precipitation of sigma phases during SAW process [36, 37]. DSS 2205 can also be joined using SMAW process with minimum cost. However, the corrosion resistance in the chloride environment and the mechanical properties are not superior for the joint made using SMAW process when compared to GTAW process [47].

Ferrite austenite ( $\alpha/\gamma$ ) ratio obtained by using various types of high arc energy welding processes is given in Table 2. It gives a clear picture in such a way that the autogenous welding process is not recommended for welding of DSS 2205 unless nitrogen is added with shielding medium. Almost all the welding processes which are using nickel enriched filler metal ER 2209 provide acceptable  $\alpha/\gamma$  ratio in the weldment. It is found that the chemical composition in the weld filler plays a predominant role in the austenite reformation than the cooling rate involved.

### **Power beam welding processes**

Power beam welding processes are also called as low arc energy welding techniques. As of now, the practical execution of DSS weld made using power beam welding processes in real time applications is very less in quantity due to the higher expense involved in the process as compared with the other commercial welding techniques. Power beam welding processes such as Laser Beam Welding (LBW) and Electron Beam Welding (EBW) offers benefits such as the absence of HAZ, less oxygen absorption in the weld and high productivity etc. The size of the fusion zone is getting reduced for LBW and EBW when compared to high arc energy welding processes. However, faster cooling rate achieved in

these processes leads to insufficient nucleation of austenite phases in the weldment [48 – 51]. LBW can be used for joining DSS if suitable provision is available for nitrogen addition during welding [52 – 55]. Otherwise, unacceptable weld microstructure i.e. insufficient austenite formation which leads to reduction in the properties of the weldment. The weldment produced without the addition of nitrogen in the shielding gas gives the absence of Widmanstätten structure in its microstructure. Only the grain boundary austenite and few intragranular austenite particles were found in the ferrite enriched matrix [56]. However, higher heat input through the continuous mode laser power nucleates acceptable amount of austenite phases in the weldment [57]. In addition to welding, a laser beam can also be used as a source to improve the characteristics of the weldment by means of surface treatment [58]. Since EBW is carried out in vacuum addition of nitrogen through the shielding medium is not possible. Though EBW process gives a lesser amount of austenite phases in DSS weld, its tensile properties are good enough because of its lower oxygen content in the weld. Using multi beam technique in EBW process is one way of producing acceptable weld microstructure in the DSS 2205 [59]. Remelting of nickel enriched welds using electron beam is an alternative method of promoting the austenite phases in the weldment [32]. Post Weld Heat Treatment (PWHT) is an alternative way to stabilize the austenite phases in the weldment [60]. Various ferrite-austenite ratios obtained by using power beam welding processes are given in Table 3. It is clear from the table that the use of LBW process without using nitrogen added shielding gas and autogenous EBW process causing significant variation between the quantity of ferrite and austenite phases in the weldment.

### **Microstructural changes in DSS weld**

#### ***Austenite reformation***

The parent metal microstructure of DSS AISI 2205 consists of dual phase ferrite-austenite structure approximately in equal proportions is shown in Fig 1. Austenite phases are

embedded in the ferrite matrix and the elongated austenite phases indicate the longitudinal direction i.e. rolling direction of a plate. Austenite reformation is an essential need in the welding of DSS 2205 in order to obtain the satisfactory mechanical and corrosion properties [1, 2, and 32]. The resultant ferrite-austenite ratio in the weldment and the HAZ decides the fruitfulness of welding DSS 2205. Cooling rate and the nickel enriched filler metal are playing a major role in the evolution of balanced weld microstructure. The weld microstructures of DSS expose significant difference from the parent metal microstructure and are compared in Fig 2 (a) and (b). Due to the presence of number of ferrite promoting elements, the weld microstructure follows ferrite-austenite solidification mode which nucleates delta ( $\delta$ ) ferrite in the matrix immediately after the solidification i.e. close to the temperature of 1450 to 1460 °C. Then, the austenite phases nucleate in three stages i.e. grain boundary austenite, Widmanstätten structure of austenite and intragranular austenite particles [33 – 35]. The elongated Widmanstätten structure of austenite phases and the intragranular austenite particles present in the weld and HAZ microstructures of DSS 2205 made using GTAW process are given in Fig 3 (a) and (b). Sudden cooling effect induced by the welding process, leads to significant variation in the grain size, orientation and shape in the weld microstructure when compared to base metal. Further, improper partitioning of alloying elements in the DSS weld leads to the notable reduction in the mechanical and corrosion properties [32]. Improper handling of welding parameters such as excessive heat input sometimes leads to sigma phase precipitation along the grain boundaries as shown in Fig 4. Even small quantity of sigma phase formation may cause enormous reduction in the ductility and corrosion resistance of the DSS weld.

### ***Secondary austenite formation***

The formation of austenite from the metastable ferrite at a lower temperature mainly during multi-pass welding is known as secondary austenite ( $\gamma_2$ ). Reheating of

weldment during subsequent passes leads to the formation of  $\gamma_2$  in weldment as well as HAZ. Also, the dissolving process of chromium nitride in the ferrite austenite interface leads to the formation of  $\gamma_2$ . The nucleation and growth of the  $\gamma_2$  phase usually occur by diffusive transformation ( $\alpha + \gamma \rightarrow \alpha + \gamma + \gamma_2$ ) on the ferrite-austenite phase grain boundaries and inside the ferrite grains. The presence of  $\gamma_2$  causes a loss of chemical balance between ferrite and the primary austenite thereby leads to pitting attack in the depleted regions. The chemical composition of  $\gamma_2$  phases on DSS welds are given in Table 4. Formation of  $\gamma_2$  phases can be avoided by the addition of nitrogen with the shielding gas which leads to the stabilization of fully saturated austenite phases. Further, it was reported that the hardness of  $\gamma_2$  phases depends on the chemical composition and the kinetics of its formation [Nowacki 33]. Widmanstätten type secondary austenite has more hardness than the intragranular austenite particles. The  $\gamma_2$  phases formed on the root side of the GTAW weld are given in Fig. 5 and 6. A recent attempt on DSS weld shows that the precipitation of  $\gamma_2$  phases leads to the pitting attack in the weldment due to the chemical imbalance between the phases [61]. However, the simple presence of  $\gamma_2$  is not causing the loss of corrosion resistance. The kinetics of formation and its location plays a major role in determining the corrosion resistance of the weld.

#### ***Chromium nitride precipitation***

Nitrogen has low solubility in the ferrite and its solubility decreases with a decrease in temperature [62]. The solubility of nitrogen in ferrite gets rapid reduction during cooling of the weld is also the reason for  $\text{Cr}_2\text{N}$  formation [25]. This leads to the formation of Chromium nitride ( $\text{Cr}_2\text{N}$ ) in the ferrite grain boundaries and also inside the ferrite grains. The nucleation of  $\text{Cr}_2\text{N}$  takes place during the cooling cycle of DSS in a temperature range less than  $900^\circ\text{C}$ . The formation of  $\text{Cr}_2\text{N}$  can be avoided by giving higher heat input in welding. High heat input gives sufficient time for redistribution of chromium in the depletion region by dissolving the chromium nitride precipitates [2, 24, 27, 45]. High heat input gives

sufficient time for alloying elements to segregate into the corresponding phases. The possibility for  $\text{Cr}_2\text{N}$  formation in the weld and the HAZ is greater on the power beam welding processes. Muthupandi et al reported the precipitation of  $\text{Cr}_2\text{N}$  in the ferrite phase of EBW weld due to the faster cooling rate [32]. Further, it was found that the formation of  $\text{Cr}_2\text{N}$  reduces the corrosion potential in the DSS weldment due to the depleted regions [40]. It is also found that during cooling cycle after welding, super saturation occurs in the zone nearer to fusion line and low solubility of nitrogen in ferrite causes the formation of  $\text{Cr}_2\text{N}$  in the HTHAZ [31].

### ***HAZ transformation***

Thermal cycle for HAZ transformation during welding of DSS 2205 is given in Fig 7. The zone close to the fusion line i.e. High Temperature Heat Affected Zone (HTHAZ) approaches the melting point and becomes fully ferrite on heating. Rapid thermal cycle experienced in this region leads to insufficient reformation of austenite phases. It gives approximately 80% of ferrite content as shown in Fig 8. Coarser ferrite grains in this region may lead to embrittlement at the low temperature [63]. Ferrite phases impose less ductility and formability than the austenite phases. Further, it leads to the reduction in the pitting corrosion resistance. Most of the fusion welding processes have reported the formation of coarser ferrite grains near the fusion line of DSS weld. Also, the width of the HTHAZ increases, with increasing arc energy during welding [64]. HTHAZ can be differentiated from the LTHAZ only through the metallography observation due to its narrow width.

The zone situated next to the HTHAZ i.e. LTHAZ attains the temperature range between 700 and 1000°C. This range of temperature is more prone to the formation of intermetallic phases. However, there is no literature mentioning formation of intermetallic phases in this zone. But, in an extremely slow cooling rate, sigma ( $\sigma$ ) can be precipitated in this region. Therefore, the welding parameters should be controlled to ensure, that the overall

cooling conditions are fast enough to avoid deleterious precipitations in this zone [63]. Even very less percentage of sigma phase precipitation would cause a detrimental effect in the mechanical and corrosion properties of DSS [2]. The LTHAZ of DSS 2205 made using GTAW process is shown in Fig 9.

### **Influence of shielding gases on DSS weld**

The reliability and the load carrying capacity of the weld made by GTAW and GMAW processes are usually higher than the other type of welding processes due to the shielding of weldment against the atmospheric reaction of molten weld pool during the fusion process. In general, Argon (Ar) and Helium (He) gases are used as shielding medium to protect the weld [65]. When compared with argon, helium provides high bead width and penetration. The side wall penetration is better in using helium than in the argon. But, helium provides erratic arc and spatters during welding. Therefore, pure helium is not recommended as a shielding medium. However, argon imposes optimum  $Cr_{eq}/Ni_{eq}$  ratio and provides stable arc as well as narrow penetration when compared with helium. During welding, the loss of nitrogen predicted was around 0.07% which is half of the amount of nitrogen present in the chemical composition of its parent metal [34]. This causes a severe reduction of Pitting Resistance Equivalent Number (PREN) value in the weldment of DSS which leads to reduction in the corrosion resistance. It can be compensated by mixing of nitrogen with argon during welding to promote austenite structure. Therefore, a special mixture of shielding gas in combination of helium, argon and nitrogen is recommended for welding DSS.

Adding nitrogen to argon shielding gas has greater influence in the weld microstructure to bring down the ferrite content within the appreciable amount by promoting austenite phases in the weld [66]. Also, nitrogen enriched weldment gives advantageous effect on the mechanical properties [67, 68]. In addition, nitrogen in the shielding gas along with argon increases the pitting corrosion resistance [69]. Nitrogen increases the stabilization of austenite

phases also with even distribution of chromium, nickel, and molybdenum in austenite and ferrite phases. It is observed that the addition of nitrogen results in improving the percentage of elongation and the ultimate tensile strength. Further, it avoids the formation of intermetallic phases such as CrN, Cr<sub>2</sub>N, sigma and other phases in the fusion zone and HAZ [70 – 72]. Because, nitrogen has a capability of slowing down the precipitation of intermetallic phases in the weldment.

### **Mechanical properties of DSS weld**

#### ***Micro Hardness***

The hardness of the DSS parent metal depends on the individual austenite and ferrite phases present in its microstructure. Ferrite phase exhibits more hardness than the austenite phase due to the presence of higher Cr and Mo atoms in it. When compared with parent metal region, DSS weldment gives higher hardness due to the strain induced hardening during weld solidification, rapid thermal cycle, and the formation of residual stress in the weld. Further, there is no significant variation between the hardness of ferrite and austenite phases in the weldment [32]. This is mainly due to more or less similar chemical composition of ferrite and austenite phases in most of the locations in the weld. Insufficient time for partitioning of alloying elements during the weld cooling further leads to similar hardness in both ferrite and austenite phases.

The heat input in welding causes significant variation in the hardness of DSS weld. It was found that the hardness of the DSS weldment is getting reduced when the heat input is increased [64]. However, the reduction in the hardness of the weld is not lesser than the hardness of its parent metal. Higher hardness values were observed due to excessive ferrite content in the weldment and Cr<sub>2</sub>N formation due to the lower arc energy. Further, hardness measured on the root side of DSS weld is higher than the top face due to multipass welding [33]. Nucleation and the growth of Widmanstätten type secondary austenite due to

reheating the previously deposited weldment constitute the major influence for increasing the hardness in the weld root. Further, cooling condition after welding shows that the DSS weld subjected to water cooling gives higher hardness than the air cooled one. This is due to high quenching effect and the larger amount of ferrite phases present in the weldment [39]. With regard to shielding gas, the addition of nitrogen with the shielding gas promotes maximum hardness in the weldment [34].

### ***Impact Toughness of DSS Weld***

The parent metal of DSS offers outstanding impact toughness within the service temperature range of - 40°C to 300°C. However, the toughness of DSS weld shows significant reduction when compared to its parent metal. This is mainly due to the formation of welding induced residual stresses, uneven partitioning of alloying elements, coarser ferrite grains near the fusion line and the sudden quenching effect during the weld cooling etc. Nickel enhanced weld filler and the optimum heat input causes an improvement in the absorbed energy by means of improved ductility caused by the austenite enrichment in the DSS weld [64, 73, and 74]. Cooling condition after welding shows that weld subjected to air cooling absorbs higher impact energy than the water cooled ones [39]. At the room temperature, both ferrite and austenite phases behave in a ductile manner. But, at a low temperature, ferrite phase changes into brittle nature thereby reduction in the toughness was observed. The impact load at this temperature deforms and elongates only the austenite phases and in the ferrite phase, brittle fracture was observed. DSS weld made by GTAW absorbed a higher amount of energy than GMAW. The presence of secondary austenite is high in the weldment of GMAW leads to the reduction in the impact strength [75]. Some of the studies were highlighted that the impact toughness of the DSS weld was lesser than the parent metal due to the improper partitioning of alloying elements during weld solidification.

Also, among the available fusion welding processes, GTAW offers higher impact toughness for the DSS weld [6].

### ***Tensile Properties of DSS Weld***

Almost all the types of welding processes are achieving the acceptable tensile properties from the DSS weld. Filler metal selection plays a predominant role in defining the tensile strength of the weld. Use of nickel enriched filler ER 2209 impose the weld to achieve the strength of the DSS parent metal and drives the weld to maintain its ductility. Also, the fractured location outside the weld reveals the tensile strength of the DSS weld [75]. Formability of DSS weld shows no cracks in the bent specimens which confirms the ductility of the weldment as shown in Fig. 10 [63]. DSS has significant anisotropy behavior which has different tensile properties with respect to the various directions. It has the higher capability of elongation in the longitudinal direction and higher tensile strength in the transverse direction. Therefore, the welding direction should be in the transverse direction of a rolled plate to obtain the better mechanical properties during service. Additionally, nitrogen in the shielding gas plays important role in enhancing the tensile behavior of the DSS weld. The tensile properties obtained using different welding processes are listed in Table 5. As far DSS 2205 is concerned, the investigations related to the super plastic forming and the hot tensile behavior of DSS 2205 are limited in the existing research literature.

### **Corrosion resistance of DSS weld**

Tremendous corrosion resistance can be achieved when using DSS in the most aggressive acidic chloride and sulfide environments. DSS grades are better alternative for ASS grades to achieve high strength and excellent corrosion resistance than the commercial ASS grades. The presence of austenite phases in the high strength ferrite matrix with the proper partitioning of alloying elements gives better resistance against SCC and pitting attack in the most aggressive environments. Heon-Young Ha observed that the microstructure with

57% of ferrite offers maximum pitting potential beyond which the corrosion resistance was getting decreased [76]. Though corrosion resistance for parent metal is higher, the probability of corrosion attack in the DSS weldment [77, 78] is significantly higher because of the microstructural changes caused by the welding i.e. loss of nitrogen content in the weldment, nucleation of secondary austenite phases, formation of coarser ferrite grains,  $\text{Cr}_2\text{N}$  precipitations inside the ferrite grains, uneven partitioning of alloying elements and the intermetallic precipitations such as sigma, chi etc. [79 – 82]. Corrosion resistance of DSS weld mainly depends on the resultant microstructure.

Among the dual phases present in DSS, ferrite has more susceptibility to the pitting attack than the austenite phases. The low solubility of nitrogen in the ferrite phase leads to pitting attack in the ferrite than the austenite phase. Further, cooling rate in welding also plays a significant role in the pitting corrosion resistance of DSS welds. The amount of chromium nitride ( $\text{Cr}_2\text{N}$ ) formation gets reduced due to increase in dissolving time. Therefore, better pitting corrosion resistance can be achieved by means of larger reformed austenite in the form of Widmanstätten structure and intragranular austenite particles. Chehuan et al suggested the weldment with the heat input of 1.26 kJ/mm offers better corrosion resistance than the weld made using 0.8 kJ/mm [83]. Yinhui Yang et al proved that the pitting potential moved to nobler values when the cooling rate decreases [38]. The authors stated that the heat input in welding plays a major role in improving the corrosion resistance of DSS by minimizing the formation of  $\text{Cr}_2\text{N}$  due to the slow cooling rate of DSS weld.

In addition, PWHT in the range between 1050°C and 1100°C causes improvement in the corrosion resistance by means of solid state transformation of alloying elements in the DSS weld [32, 51, 93]. PWHT promotes austenite reformation in the weld and the HAZ, as well as changes the grain size and shape. In addition, it restores ductility in the weldment by relieving the residual stresses induced by the welding process. The weld microstructures

obtained before and after PWHT in GTAW process are given in Fig 11 (a) and (b). However, from the industrial point of view, doing PWHT for large sized components is practically very difficult. Hence, to achieve the benefits of corrosion resistance in the DSS weld, the welding parameters such as heat input, interpass temperature, shielding gas with appropriate nitrogen content, types of welding processes have to be utilized properly within the permissible limits. Recent study reveals that the use of electromagnetic interaction with low intensity during welding is an alternative way to improve the corrosion resistance of DSS weldments by avoiding the formation of deleterious phases such as sigma, carbides, and nitrides [84].

DSS 2205 exhibits a high resistance to SCC failure by the presence of high strength ferrite matrix in its microstructure [85, 86]. However, severe sulfide containing caustic solutions may encourage an SCC attack in DSS, particularly in the weld. In such a situation, austenite phase is more susceptible to SCC attack than the ferrite phase. Ananya Bhattacharya & Preet Singh reported the presence of tensile residual stress in the austenite phase of DSS weld due to which the SCC attack was first started and grown into the austenite phases [87]. However, the resistance primarily depends on the chemical composition of the phases. Higher chromium content in the weld may not cause a significant attack in both the phases.

Microbiological Induced Corrosion (MIC) is one of the special types of corrosion attack in the marine environment [16, 88, 89]. Antony et al (2008) have investigated the effect of MIC on DSS weld in the presence of Sulfate Reducing Bacteria (SRB). It was found that the austenite phases are more susceptible to MIC attack than the ferrite phases. Ferrite phases in the HAZ which are depleted in chromium are also attacked by SRB. William Liu 16 also pointed out the MIC attack on DSS 2205 pipe, especially on the austenite grains. Nitrogen content near the fusion zone played a substantial role in the MIC attack. However,

the influence of nitrogen content of DSS on MIC attack needs to be addressed further in order to get the clear understanding of the corrosion mechanism.

### **Solid state welding processes**

The development of solid-state welding processes such as Friction Stir Welding (FSW) and friction welding pays more attention in the welding research recently. Joining of DSS grades using solid state welding processes is an open field in the current research scenario [90]. Santos et al reported the formation of fine grains of austenite and ferrite phases in the stirred zone during FSW of DSS 2205. The authors further stated that the ferrite phase in DSS undergoes complete recrystallization and grain growth, while the austenite phases showed only the partial recrystallization in the stir zone. Also, it was reported that the advancing side of the stir zone has stronger grain refinement than the retreating side. Further, deformed austenite grains are formed in the thermo-mechanically affected zone which is near to the retreating side [91]. As of now, the research in FSW of DSS 2205 is still under open in many areas such as optimization of FSW parameters to achieve the better mechanical properties, studies on the fatigue behaviour of FSW joint and the comparison of various types of corrosion attack in the stir zone of DSS 2205 with its parent metal etc. Also, DSS weld made using FSW process was not yet referenced so far in any of the structures particularly in the marine environment. Another solid state welding process which is used to join cylindrical parts is friction welding. Asif et al found the reduction of impact toughness in the friction-welded joint by means of minimum austenite reformation. However, when compared to the other fusion welding methods, the impact toughness obtained from the friction weld is higher especially at the low temperature. Further, the corrosion resistance of the friction weld is better than the parent metal and it was increased with an increase of heat input during welding [92]. In addition, PWHT of friction welded DSS joint at 1080°C provides balanced

microstructure [93]. Solid state welding processes are also used for joining dissimilar metals [100, 101].

### **Dissimilar welding on DSS 2205**

Dissimilar welds are more popular in oil and gas industries, desalination pipe lines and power plants. In many situations, ASS grades are replaced by DSS grades where high resistance to SCC and better strength are required. Replacement of material mainly takes place in the ASS weldment because of high susceptibility to SCC attack. Among the available ASS grades, 316L is a suitable material for the marine environment where SCC failure is a major concern. However, by the presence of fully austenitic microstructure, the susceptibility to SCC attack on ASS 316L weld in high chloride environment is greater than the DSS grades. Therefore in such a situation, the dissimilar weld between DSS 2205 and ASS 316L is a better alternative to avoid the failure. Selection of suitable filler metal and choosing appropriate welding technique are important tasks to attain the required mechanical and corrosion resistance properties in the dissimilar weld. Due to the reduction in the strength of the weld, austenitic fillers (ER 316L, 304L, 308LMo, ER 347, ER 309L) are not suitable for welding between DSS 2205 and ASS grades. The filler metal ER 2209 is more suitable for getting high strength and SCC resistance. The yield strength and the ultimate tensile strength of the dissimilar weld are generally close to the strength of the weakest among the two metals joined together. As far as dissimilar weld of DSS 2205 with other alloys experienced so far, GTAW is more suitable than any other welding technique to obtain weldment properties [47]. Some of the dissimilar welds in DSS 2205 with other alloys successfully joined using various joining techniques and their remarks are given in Table 6.

### **Machinability of DSS 2205**

Use of DSS in several marine applications requires good machining properties. Surface finish and its topography play a major role in determining the lifespan of DSS in a

marine exposure. In general, machinability of DSS 2205 is poor when compared to conventional austenitic grades such as 316L and 304L. The higher thrust force is required to machine the surface of DSS due to its high-temperature tensile strength. Nomani et al stated severe adhesion wear on the tool flank surface due to the formation of built-up edge [103]. The report states that the drilling of DSS causes tool wear mainly abrasion and adhesion on the flank and rake surfaces of the tool. Further, wear rate of the drill tool was increased when drilling more number of holes in DSS. Flute damage was observed during drilling which may lead to catastrophic failure of the tool. However, when compared with super DSS 2507, the machinability of commercial DSS 2205 alloy is moderately superior. Amplified surface roughness is an important pitfall in the machining of DSS which leads to poor surface quality when compared to ASS grades. Jiang et al found that the grindability of DSS 2205 is lesser than the ASS 316L which was observed by the higher surface roughness, number micro cracks and voids on the ground surface and less grinding ratio [104]. The addition of Sulphur in the chemical composition of DSS 2205 leads to enhanced machinability. However, it will result in weld hot cracking and reduction in the corrosion resistance. The study related to the optimization of machining parameters for DSS by conventional machining processes using various cutting tools and operating conditions are still under open for research. Also, the investigations on modern day non-traditional machining processes such as wire cut EDM, laser cutting, plasma cutting, water jet machining and abrasive jet machining on DSS are limited in the current research scenario. Extension Usage of DSS in medical and electronic components in near future may lead to onward research in the field of machining.

### **Surfacing of DSS 2205**

In general, machined surface profiles are not recommended for the corrosive environment due to the grooved surface texture [105]. Polished surface is better than the machined surface. However, from the practical point of view usage of mirror polished surface

is a million dollar process for large size marine components. Failures in the marine environment are mostly arising from the metal surface. Since the morphology of the surface plays a major role in enhancing the lifespan of DSS, surface protection using suitable remedial techniques is very essential. Peening techniques are more useful in enhancing the surface quality as well as to increase the life of a material especially in the corrosive environment [106]. Peening induces trough profile on the metal surface which offers more advantageous effects. For an understanding point of view, the surface morphology of peened surface is compared with machined and polished surfaces which are shown in Fig 12 (a) to (d). Recent research in DSS 2205 with regard to shot peening offers fruitful outcomes in the real-time applications. Shot peening induces grain refinement on the surface of DSS by impacting spherical shots on it [107]. Lateral stretching and severe plastic deformation on the surface grains of DSS induced by shot peening are given Fig 13 (a) and (b). Qiang Feng et al have pointed out the effect of shot peening on the surface of DSS 2205 strongly affects the austenite phase more than the ferrite phase with the same peening condition adopted on both the phases. It was found that the ferrite phases of DSS were in a state of compressive nature of residual stress whereas the austenite phases were in a state of tensile nature of residual stress before the peening process. After shot peening, the maximum amount of compressive residual stress was reported in the austenite phases than the ferrite phase. It should be noted that the tensile effect of austenite phases before peening process induces greater residual stresses in it after peening. Also, austenite has more strain hardening capability than the ferrite. Qiang Feng et al additionally found that the stress peening on DSS 2205 improves the surface properties by inducing high magnitude of compressive residual stresses when compared to conventional shot peening without prestressing [108 – 110].

Sanjurjo et al have reported the improvement of surface properties in DSS which plays a major role in the enhancement of fatigue life [19]. The authors have concluded that

the effect of shot peening on the corroded surface plays the significant role in fatigue life improvement than shot peening on the polished surface. Al-Obaid stated the influence of shot peening on SCC resistance of DSS which shows no evidence of failure in the peened specimens even though the applied stress on the specimen were nearly 50% of the yield strength whereas the unpeened specimens were failed within a short duration in a boiling magnesium chloride solution [111]. Lim et al examined Laser Shock Peening (LSP) which was played a predominant role in enhancing the life of DSS 2205 in desalination pump parts by increasing the corrosion resistance and reducing the wear rate in abrasion environment [112]. Rubio-González et al stated the effectiveness of LSP by proving the increased fatigue life and reduction in the fatigue crack growth of DSS. Also, it was found that LSP does not induce any grain refinement on the surface [113]. The ferrite and austenite phases of DSS 2205 persist unaltered even after the LSP applied on the surface whereas residual compressive stress induced by LSP increases the fatigue life of DSS. Friction Stir Processing (FSP) is another promising technique which has been evolved few years back. FSP on DSS 2205 shows a remarkable increase in the resistance against cavitation erosion by inducing severe grain refinement by rupturing the ferrite-austenite grains on DSS 2205 [114].

### **Conclusions**

In the present review, thorough investigations are made from the recent literature with regard to the weldability, machinability and surfacing of DSS 2205 and the conclusions are arrived as follows:

High arc energy welding processes such as GTAW, GMAW, SMAW, SAW, PAW, and FCAW are suitable for welding DSS 2205 within in the allowable welding parameters. LBW process can be considered for welding if appropriate ways are available for adding nitrogen through the shielding gas. Austenite enrichment is possible in EBW process by means of remelting the nickel enriched weldment by electron beam.

Nickel enriched filler metal ER 2209 and nitrogen added shielding medium play a crucial role in forming the microstructure which contains larger amount of austenite phases in the DSS weld. Also, the addition of nitrogen through the shielding medium slows down the formation of intermetallic phases. The addition of Chromium beyond 22% in the weld filler leads to the formation of excessive ferrite phases in the DSS weld.

DSS solidifies initially as delta ferrite and austenite nucleates in three different stages after welding. Grain boundary allotriomorphs, Widmanstätten structure, and intragranular austenite particles are the three forms of austenite phases present in the fusion zone. The zone next to the fusion line i.e. HTHAZ approaches close to the melting point which gives nearly 75 to 80% of ferrite phases due to the rapid cooling involved in this region.

DSS exhibits higher hardness in the HTHAZ and its weldment when compared to its parent metal region. Coarser ferrite grains in the HTHAZ leads to higher hardness. Also, the formation of  $\text{Cr}_2\text{N}$  leads to a rapid increase in the hardness of DSS weld. Formation of secondary austenite phases in the weld due to multipass welding also gives higher hardness in particularly at the root region of the weld.

DSS exhibits higher impact toughness in the temperature range between  $300^\circ\text{C}$  and  $-40^\circ\text{C}$ . However, the toughness of DSS weld has been decreased significantly due to the formation of secondary austenite phases, residual stresses in the fusion zone, uneven partitioning of alloying elements due to lack of time in solidification during welding etc. Formation of coarser ferrite grains near the fusion line is also the reason for the reduction in the impact toughness of DSS weld.

Almost all types of welding processes are meeting the required tensile properties in the DSS weld. Increasing the percentage of ferrite stabilizers such as chromium and molybdenum in the weldment leads to increase in the tensile strength and reduction in the

percentage of elongation. Further, increasing the amount of nitrogen in the weldment causes an increment in the hardness of austenite phases which leads to higher yield strength.

Parent metal of DSS 2205 offers excellent SCC resistance and pitting corrosion resistance. However, welding of DSS causes the significant reduction in the pitting corrosion resistance due to the formation of intermetallics such as  $\text{Cr}_2\text{N}$  and  $\gamma_2$ . Further, the presence of tensile residual stress in the austenite phases causes the reduction in the SCC resistance of DSS weld.

DSS 2205 exhibits poor machinability than the ASS grades such as ASS 304L and 316L in terms of tool wear, surface roughness and cutting force. Poorly machined surfaces are generally not recommended for the marine exposure due to their grooved surface profiles which will endanger the material's life drastically. Shot peening, LSP and FSP are significantly enhancing the surface properties of DSS 2205 which are strongly recommended in the corrosive environment.

### **Future perspectives of research**

Based on the existing literature, the following areas of research are identified as thirsty areas on DSS 2205 which are to be focused in the future research.

The investigations regarding the erosion-corrosion behavior of DSS and its weldment in the high-pressure sea environment is an essential need for the development of deep-sea technology so that DSS can be effectively used in the remotely operated underwater vehicles.

Mechanical and corrosion properties of DSS weldments made using GTAW, GMAW, FCAW, SAW, PAW, SMAW, LBW, EBW, and friction weld are accessible in the existing literature. However, the studies on the mechanical as well as corrosion properties of DSS weldments made using FSW process are not yet referenced in the present literature.

The studies on the influence of microstructural changes in fatigue life of DSS weld through different welding techniques and comparison of fatigue life between DSS weld and

its parent metal are lacking in the current research scenario. Further, the investigations related to the corrosion fatigue of DSS and their welds in the marine exposure are limited in the present literature.

Existing literature shows that the machinability of DSS 2205 is generally poor than the ASS grades such as 304L and 316L. More usage of DSS in real-world applications needs intensive research in the field of optimization of machining parameters to develop the machining characteristics.

Peening techniques are extremely useful for the enhancement of surface quality which increases the fatigue life and the SCC resistance. In addition, comparison of different peening methods such as shot peening, dual shot peening, LSP and their influences on enhancing the surface properties would enforce better usage of DSS in the marine fabrication.

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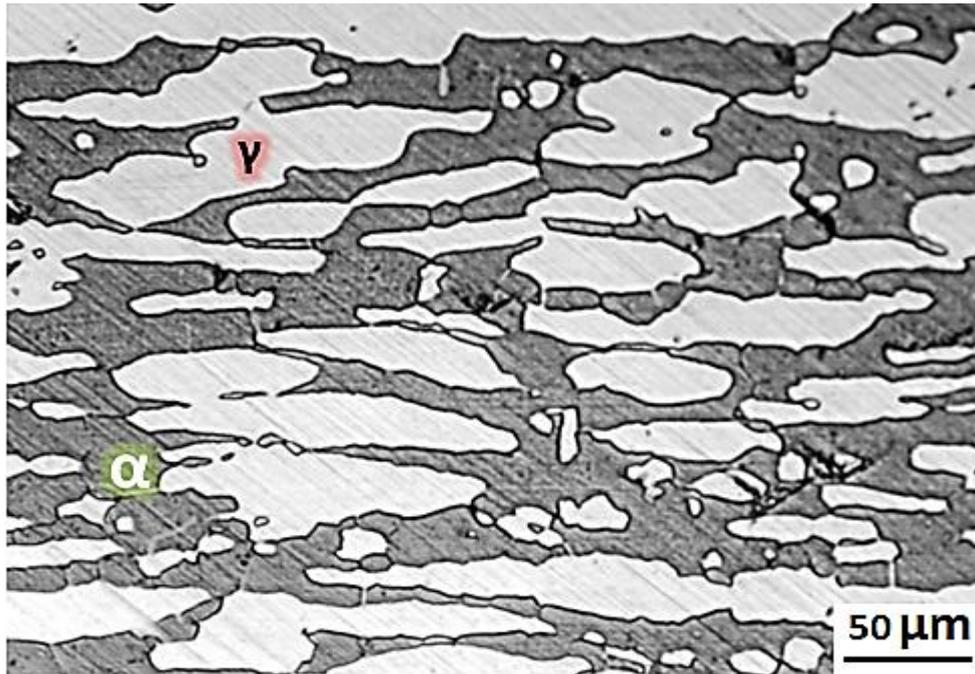
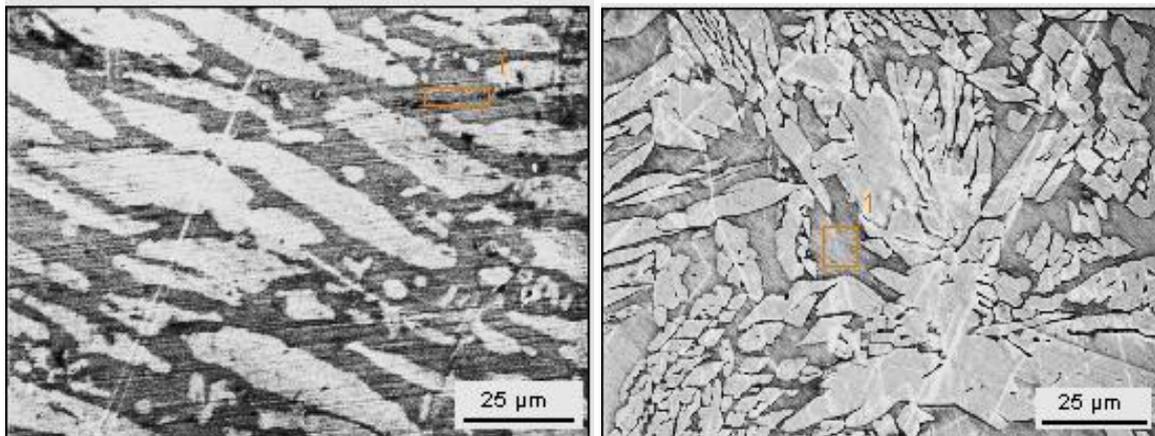


Fig 1. Parent metal microstructure of DSS AISI 2205



(a) Base metal microstructure

(b) Weld microstructure

Fig 2. Microstructure of base metal and weld

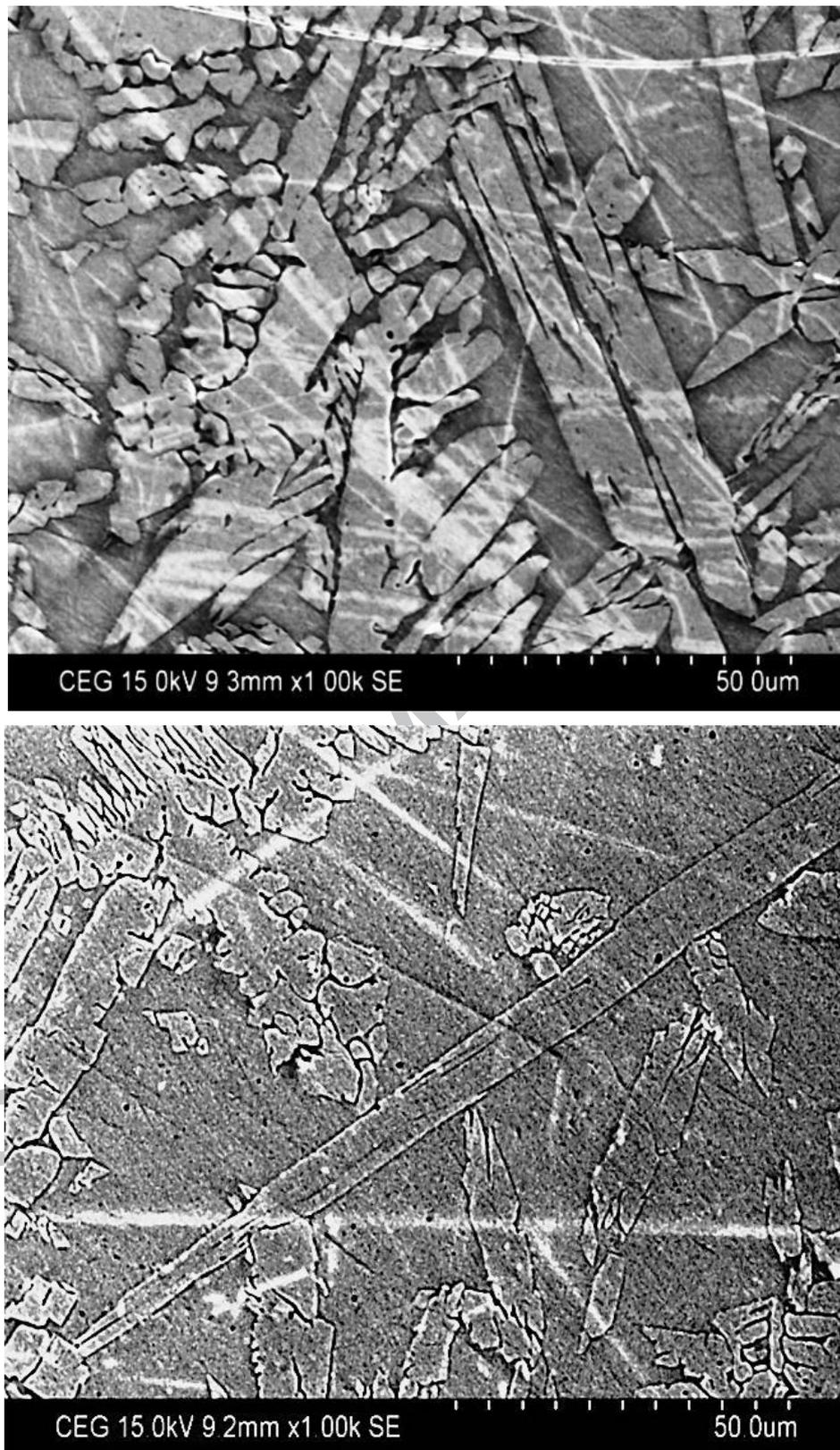


Fig 3. Widmanstätten austenite structure in (a) weld (b) HAZ

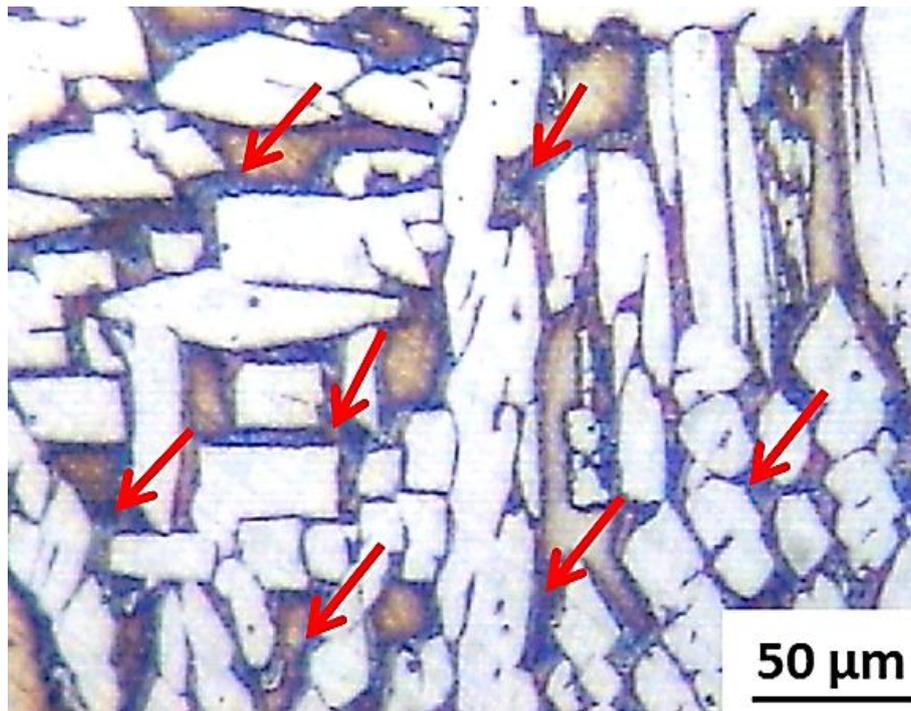


Fig 4. Sigma phase in DSS weld

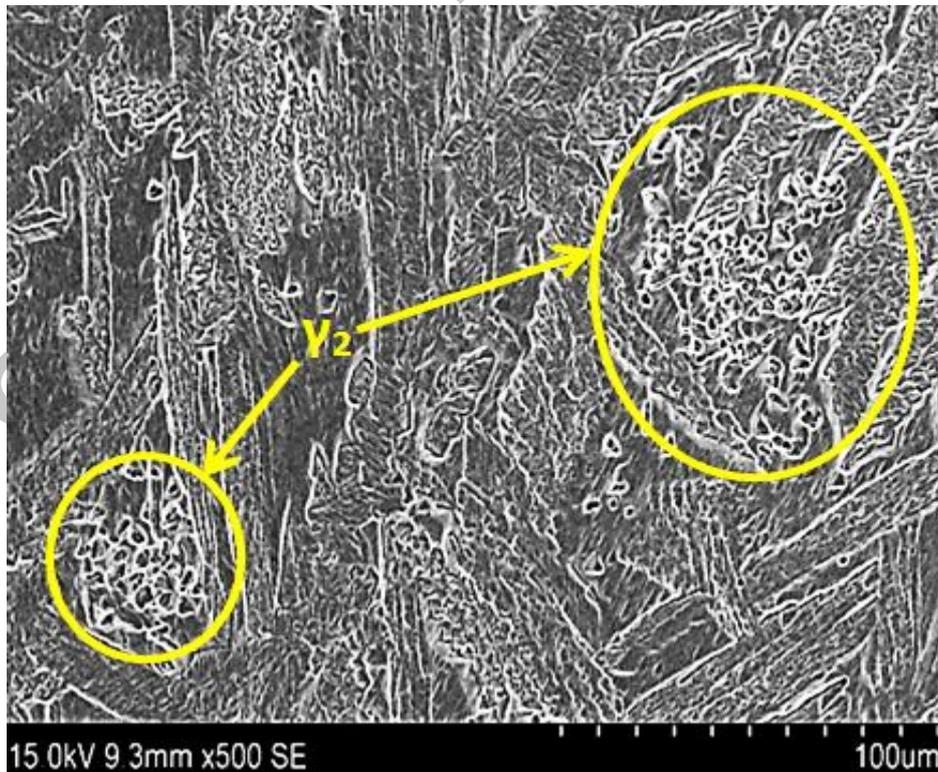


Fig 5. Intragranular type Secondary Austenite in weld

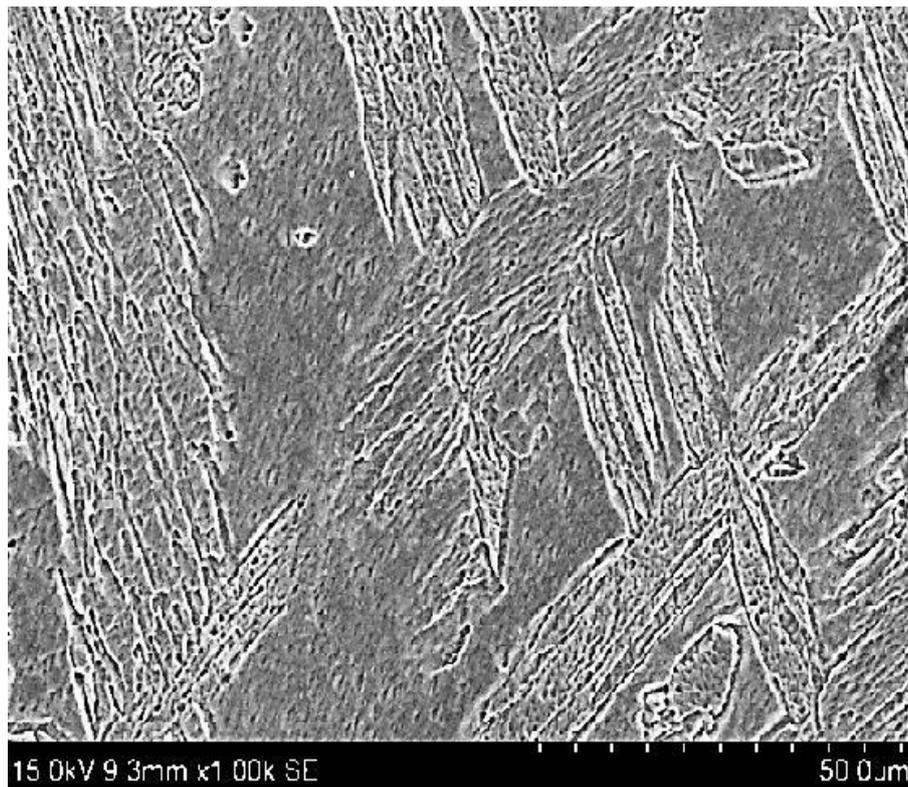


Fig 6. Widmanstätten type Secondary Austenite in weld

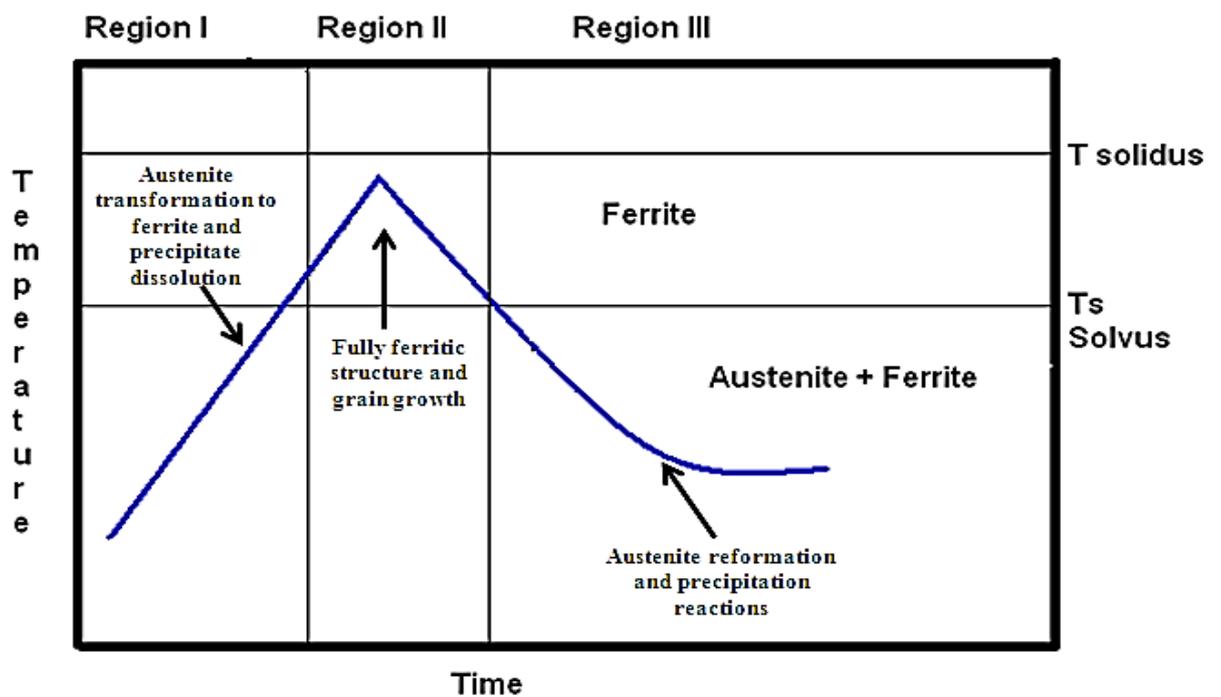


Fig 7. HAZ transformation cycle

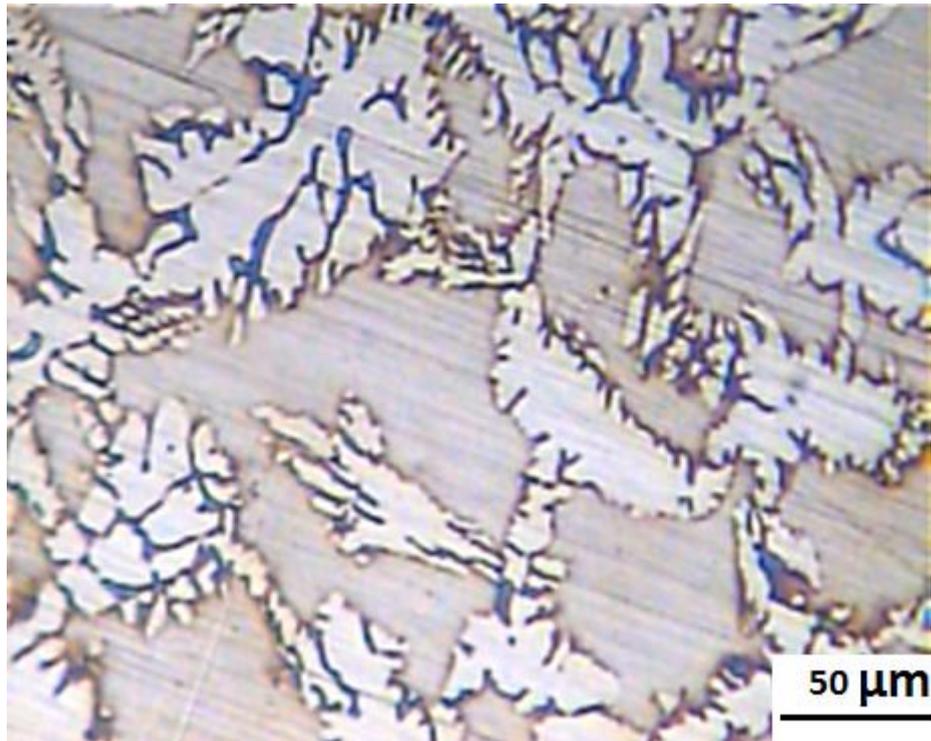


Fig 8. HTHAZ in GTAW weld

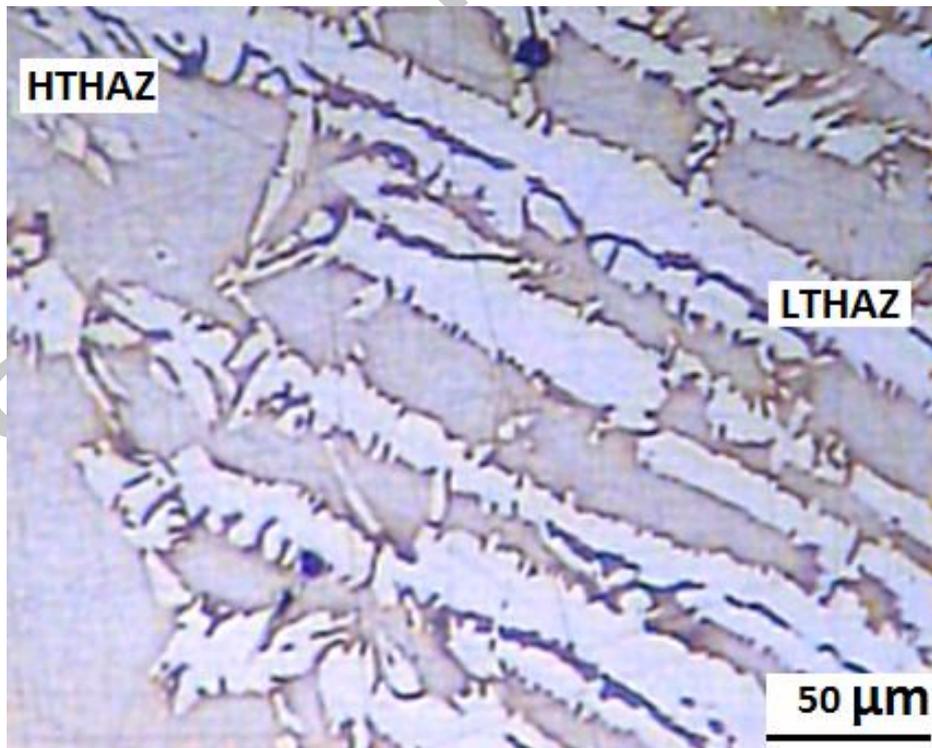
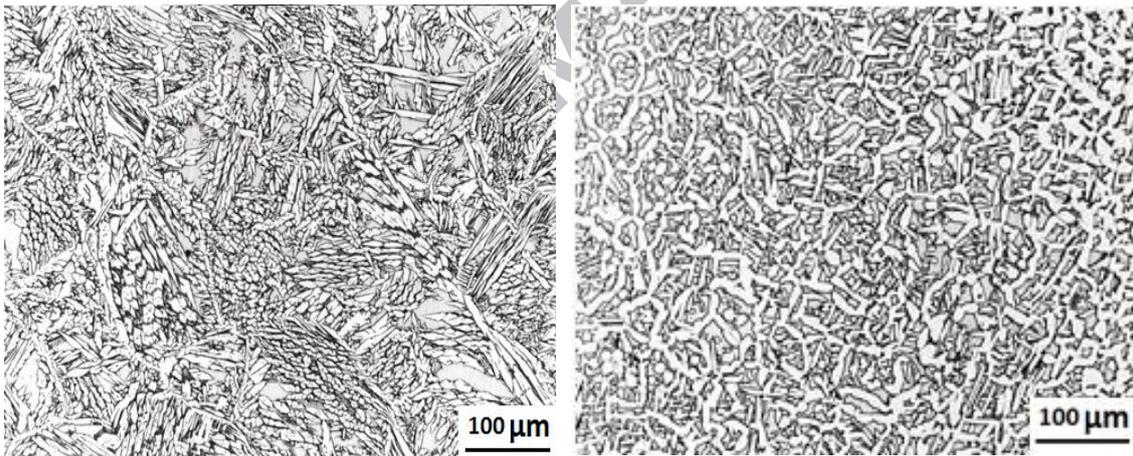


Fig 9. LTHAZ in GTAW weld



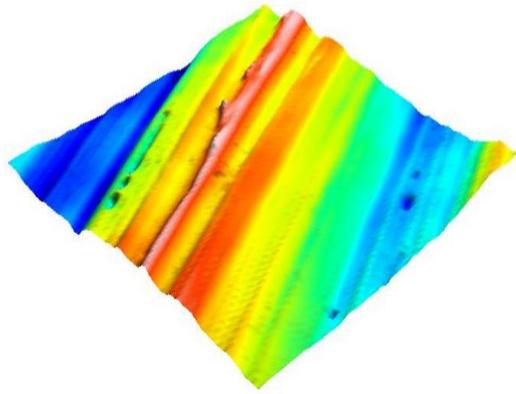
Fig 10. Formability of DSS weld 180° bend



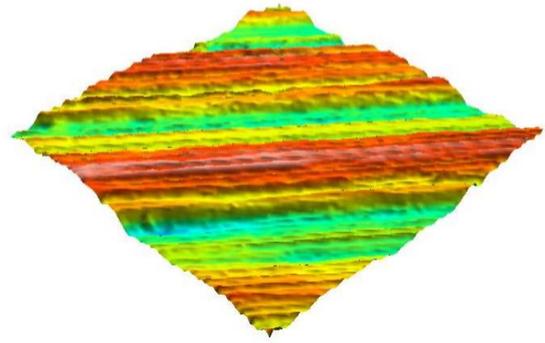
(a) Before PWHT

(b) After PWHT

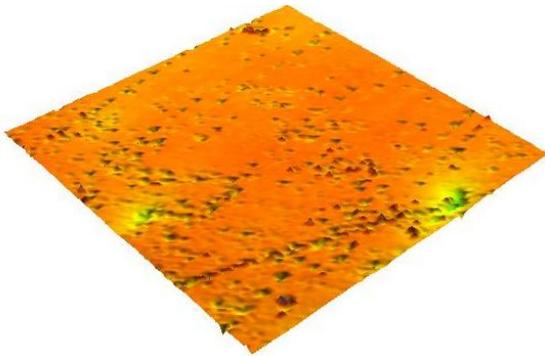
Fig 11. GTAW Microstructure of DSS



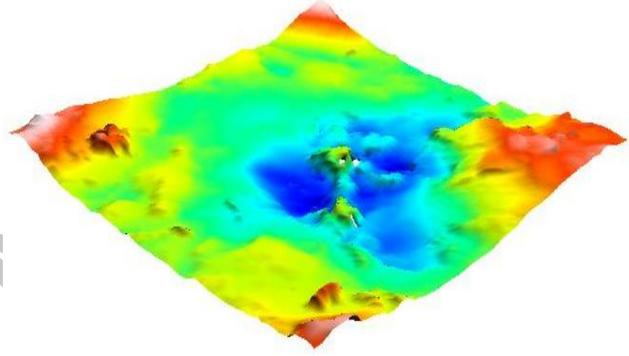
(a) Milled surface



(b) Ground surface



(c) Polished surface



(d) Peened surface

Fig 12. Surface topography of DSS

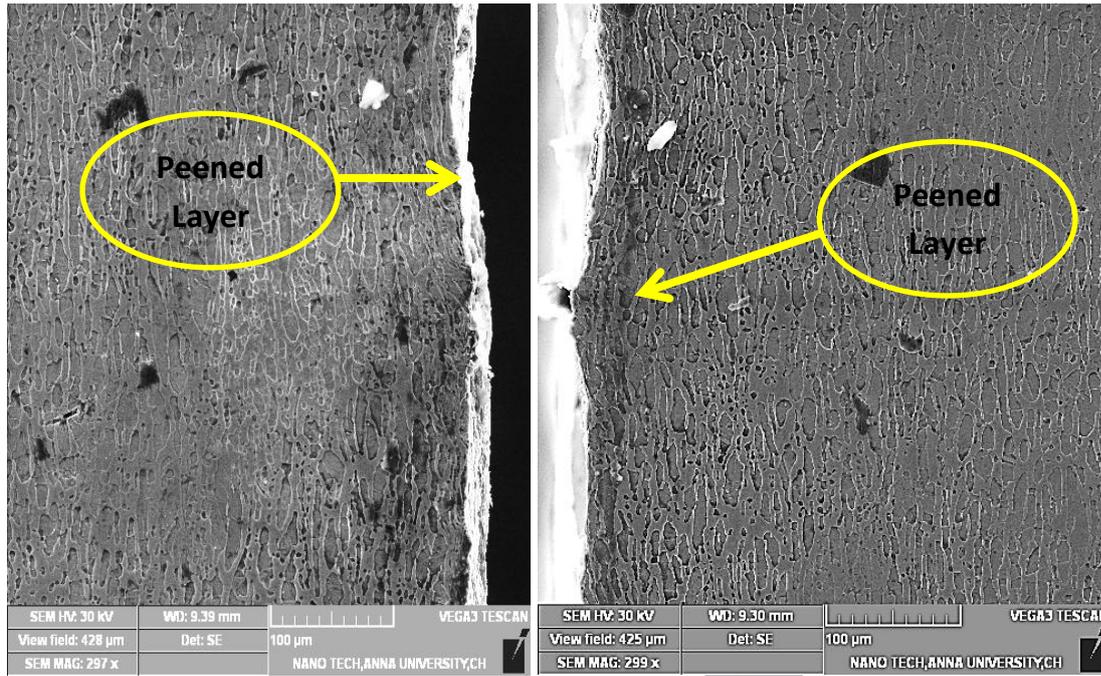


Fig 13. Shot peened layers of DSS 2205 (a) Location 1 (b) Location 2

Table.1. The chemical composition of DSS AISI 2205 and ER 2209 [6, 63]

UNS Number	C	Mn	S	P	Si	Cr	Ni	Mo	N	Fe	PREN Range*
S31803 OR S32205	0.03	2.00	0.02	0.03	1.00	21.0 – 23.0	4.5 – 6.5	2.5 – 3.5	0.08 – 0.20	Balance	30.5– 37.8
ER 2209	0.009	1.50	0.0005	0.018	0.38	22.89	8.66	3.03	0.15	Balance	--

\*PREN (Pitting Resistance Equivalent Number) = %Cr + 3.3 (%Mo) + 16 (%N)

Table 2.  $\alpha/\gamma$  ratio in high arc energy welding processes

Authors and Year	Type of Welding Process	Heat Input (kJ/mm)	Ferrite / Austenite ( $\alpha/\gamma$ )
Mourad et al [57]	GTAW (Argon) + ER 2205 filler	0.528	53/47
Muthupandi et al [32]	GTA weld with nickel enhanced filler	1.44	58/42
	Autogenous GTAW (Argon)	1.44	78/22
Kordatos et al [39]	GTAW (Air cooled welds) (Argon)	110A	46.7/53.3
	GTAW (Water cooled) (Argon)	(DCEN)	56.9/43.1
Ananya Bhattacharya & Preet Singh [87]	SAW	--	45/55
	FCAW	--	45/55
Múnez et al [28]	GMAW (Ar+2% CO <sub>2</sub> )	0.31	45.37/54.63
Bhatt et al [69]	GTAW (Ar) + nickel enhanced filler	0.36	43/57
	GTAW (95% Ar + 5% N <sub>2</sub> )+ nickel enhanced filler	0.36	35/65
	GTAW (90% Ar + 10% N <sub>2</sub> )+ nickel enhanced filler	0.36	29/71
	Autogenous GTA weld (Ar)	0.24	64/36
	Micro plasma (Ar)	0.50	73/27
José María et al [70]	MIG (Ar+2% CO <sub>2</sub> )	0.935	45/55 (App.)
	MIG (Ar+2% CO <sub>2</sub> +2.96% N <sub>2</sub> )	0.924	42/58 (App.)
	MIG (Ar+2% CO <sub>2</sub> + 4.83% N <sub>2</sub> )	0.943	35/65 (App.)
	MIG (Ar+2% CO <sub>2</sub> + 6.4% N <sub>2</sub> )	0.890	33/67 (App.)

Table 3.  $\alpha/\gamma$  ratio in power beam welding processes

Authors and Year	Type of Welding Process	Heat Input (kJ/mm)	Ferrite / Austenite ( $\alpha/\gamma$ ) Ratio
Mourad et al [57]	LBW (Argon)	0.96	61/39
Muthupandi et al [32]	EB-remelted nickel enhanced weld	0.283	61/39
	Autogenous EBW	0.283	86/14
Roguin et al [34]	EBW	--	83/17
	LBW (Argon+ 20% N <sub>2</sub> )	--	70/30
Young et al [51]	LBW	0.37	75/25
Bhatt et al [69]	EBW	0.43	77/23
Yanze Yang [60]	LBW	0.045	93/7

Table 4. Chemical composition of  $\gamma_2$  phase on DSS weld

Authors	Type of welding	Phase	Cr	Mo	Ni	N
Paulraj et al [61]	GTAW low PREN	$\delta$	22.30	3.32	7.87	0.05
		$\gamma$	21.93	2.81	7.96	0.22
		$\gamma_2$	11.52	0.90	8.10	0.20
	GTAW high PREN	$\delta$	24.12	3.24	7.35	0.05
		$\gamma$	21.70	2.74	7.81	0.27
		$\gamma_2$	12.86	0.96	8.12	0.23
García-Rentería et al [84]	DSS GMAW ER 2209/ Ar + 3% N <sub>2</sub>	$\delta$	20.92	2.77	6.87	-
		$\gamma$	20.12	2.81	7.57	-
		$\gamma_2$	14.21	2.11	10.89	-

Table. 5. Tensile properties of DSS welds

<b>Authors</b>	<b>Type of welding</b>	<b>Yield strength MPa</b>	<b>Ultimate tensile strength MPa</b>	<b>% of elongation</b>
ASM Hand book [6]	DSS 2205 parent metal	450 (min)	620 (min)	25(min)
Mourad et al [57]	GTAW	450	621	25
José María et al [70]	MIG	--	730	18.06
Kang & Lee [26]	FCAW	757	890	25
Jian Luo et al [36]	SAW	--	795	--
Mourad et al [57]	LBW	453	623	26
Ku et al [48]	EBW	509	735	44
Asif et al [92]	Friction weld	664	852	38

Table 6. Various dissimilar combinations in DSS 2205 and their remarks

Authors	Dissimilar weld combination	Filler metal	Remarks
Shaogang Wang et al [47]	DSS 2205/ 16MnR	GTAW/ ER 2209	GTAW is suitable for dissimilar welding than SMAW
Neissi et al [97]	DSS 2205/ ASS 316L	Pulsed Current GTAW & Constant Current GTAW ER 2209	Pulsed current GTAW gives higher pitting resistance than the constant current GTAW process
Aboufazi Moteshakker, Iman Danaee [99]	DSS 2205/ ASS 316L	GTAW/ ER 347, ER 316L and ER 309L	Among the austenitic filler metals used ER 309L is suitable with respect to corrosion test
Srinivasan et al [102]	DSS 2205/ Carbon steel IS 2062	SMAW/ ER 2209, ER 309	ER 2209 is better than ER 309 with regard to corrosion resistance
Serdar Mercan et al [94]	DSS 2205/ AISI 1020	Autogenous friction welding	Optimized welding parameters increases the fatigue strength of the joint
Bettahar et al [95]	DSS 2205/ super martensitic SS 13Cr	GTAW/ ER 2507	ER 2507 is a overmatching weld filler and the fatigue strength of the weld is less than the parent metals
Jing Wang et al [98]	DSS 2205/ Low alloy steel	TIG & MIG/ ER 2009	Corrosion attack was found between low alloy steel and the weld



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