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Investigations on anisotropy behavior of duplex stainless steel AISI 2205 for optimum weld properties

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Abstract

The present investigation aims to analyze the anisotropy behavior of 8 mm thick rolled plate of duplex stainless steel AISI 2205. The study aims to connect the importance of anisotropy properties with fusion welding to achieve the optimal mechanical properties of the weldment by justifying suitable direction for welding. An outcome of the investigation implies that duplex stainless steel exhibits maximum impact toughness in the longitudinal direction i.e. rolling direction when compared to transverse and diagonal directions. Further, the existence of significant directionality was confirmed by analyzing the tensile behavior which gives greater tensile strength in the transverse direction and higher amount of elongation and better formability in the longitudinal direction. The present work was extended by fabricating the weldment using gas tungsten arc welding by keeping the welding direction perpendicular to the rolling direction of a plate. Microstructure and the mechanical properties of the weld were assessed and compared with the behavior of its parent metal.

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Keywords: duplex stainless steel; anisotropy; ferrite; austenite; welding; mechanical properties

1. Introduction

In general, the materials in the family of stainless steel such as austenitic and ferritic grades are isotropic materials. The existence of anisotropy behaviour in the stainless steel plates by a small amount is

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unavoidable due to the manufacturing process of a plate such as rolling. However, the properties of Duplex Stainless Steel (DSS) vary significantly with respect to the different directions due to the presence of both ferrite and austenite phases in its matrix [1, 2]. Since DSS comes under the anisotropic material, the orientation of the grains on the rolled plate plays a major role in the variation of mechanical properties. There are two types of anisotropy possibilities in any material i.e. crystallographic anisotropy produced by severe plastic deformation during the rolling and the mechanical fibering due to the second phases present in the direction of working. In recent days, DSS plays a major role in achieving weight reduction by replacing ASS grades such as 304L and 316L with thinner structures due to their high strength nature and excellent corrosion resistance. DSS grades are widely used in petrochemical industries, offshore structure, oil and gas pipe lines under the ocean, ocean mining machinery, paper and pulp industries etc. [3 – 5]. However, the weldability of DSS leads to complex scenario due to the presence of more number of alloying elements in it. The mechanical properties of DSS weld show remarkable variance in their magnitudes when compared to its parent metal [6 – 10]. Even though enough research works were carried out in the welding of DSS using various fusion welding processes, the importance of finding suitable direction for welding DSS to obtain optimum mechanical properties of the weld was not yet discussed in detail. It is essential to justify the direction for welding of DSS plate to obtain better ductility in the weld. Fusion welding of DSS plays a major role in the fabrication of marine structures. Joining two metals without sacrificing their properties is quite impossible. Cooling rate and the chemical composition of the filler metal used in the welding are playing a major role in the properties of DSS weld [7, 12, 15, 18]. Thus, it is mandatory to select the suitable welding process and to control the welding parameters such as current, voltage, welding speed, shielding gas and filler metal selection etc. [11 – 19]. Among the available fusion welding processes, Gas Tungsten Arc Welding (GTAW) process is the most efficient one with respect to the mechanical and corrosion properties of DSS weld [6]. The present work was carried out in two phases such that the initial study aims to find the anisotropy properties of DSS such as impact toughness, yield strength, ultimate tensile strength, and the percentage of elongation in the three different directions. And, the second phase of the work is focused to achieve the optimum weld strength and ductility by justifying suitable direction for welding of DSS plate.

2. Experimental

Table.1. Chemical composition of DSS 2205 and ER 2209

	C	Mn	Si	S	P	Cr	Ni	Mo	Cu	N	Ti	V	Co	Nu	W	Fe
DSS2205	0.027	1.463	0.42	0.01	0.02	22.8	5.5	3.3	0.1	0.18	0.004	0.06	0.010	0.02	0.04	Balance
ER2209	0.009	1.50	0.38	0.0005	0.018	22.89	8.66	3.03	-	0.15	-	-	-	-	-	Balance

Table.2. Welding parameters

Weld pass	Current (A)	Voltage (V)	Time taken (Sec)	Argon gas flow rate (L/min)
Pass 1	125	14	114	10
Pass 2	125	14	130	10
Pass 3	125	14	117	10
Reverse Pass	125	14	90	10
Polarity			DCEN	
Purging gas flow rate (L/min)			10	
Heat Input			1.32 kJ/mm	
Welding speed			1.33 mm/sec	

The chemical composition of DSS AISI 2205 and the filler metal ER2209 used in this study are given in Table 1. It was found using the optical emission spectrometer test. Since austenite reformation is an important phenomenon in DSS, nickel enriched filler metal ER 2209 is used to achieve the acceptable weld microstructure. To study the anisotropy behaviour of DSS, Charpy impact test was carried out at room temperature as well as subzero temperature. The test samples were extracted from the DSS plate in three different directions such as longitudinal (0°), transverse (90°) and diagonal (45°) directions of the rolled plate and the notches were prepared. Three samples were tested for each condition i.e. room temperature as well as subzero temperature. Samples were brought to subzero temperature using the dry ice. To investigate the tensile behaviour of DSS, the samples were extracted again from the three directions of the rolled plate. In addition, the formability of DSS was investigated by conducting three point bend test in the longitudinal and transverse directions and the load taken to achieve the 180° bend was measured. With the justified direction for welding from the anisotropy study, the weld properties of DSS were found using Gas Tungsten Arc Welding (GTAW) in the prepared samples of dimensions 150 mm×150 mm×8 mm with the standard groove geometry as shown in Fig 1. During welding, 99.9% of pure argon gas was used as a shielding medium. The welding parameters used in this study are given in Table 2.

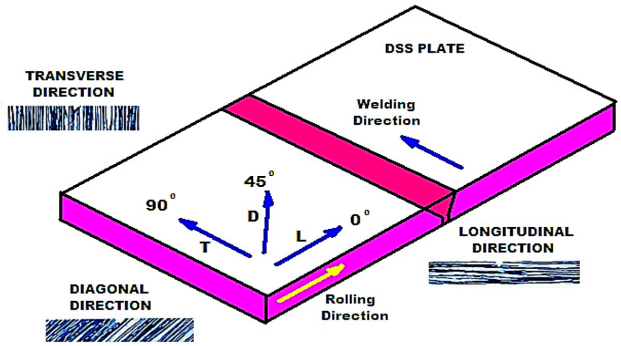


Fig.1. Welding Direction

3. Results and Discussions

3.1. Microstructure of DSS

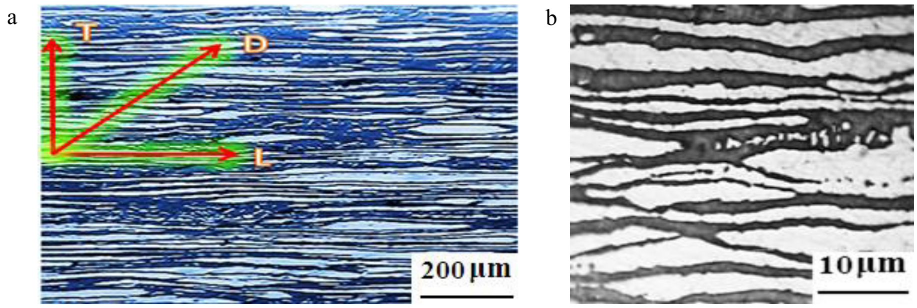


Fig.2 (a) DSS parent metal microstructure (b) Elongation of grains in the rolling direction

The parent metal microstructure of DSS 2205 gives approximately equal amount of phase percentage i.e. ferrite austenite ratio which is shown in Fig 2(a). The microstructure shows that the austenite phases are embedded in the ferrite matrix and elongated in the rolling direction with a lamellar morphology as given in Fig 2(b). The elongation of grains in the microstructure reveals the rolling direction. Mode of solidification plays an important role in the formation of DSS microstructure. Due to the presence of more number of ferrite promoting elements, it gives ferrite austenite solidification mode i.e. fully ferritic structure initially after solidification and further the nucleation of austenite phases take place in the matrix of ferrite by a peritectic eutectic reaction. This is known as type 'FA' solidification mode [3]. The amount of austenite phases present in the microstructure mainly depends on Cr_{eq}/Ni_{eq}

ratio. As a result of dual phase microstructure, the presence of ferrite promoting elements such as chromium, and molybdenum are mainly diffused into the ferrite phases and the austenite promoting elements such as nickel, nitrogen and carbon are mainly diffused in the austenite phases. Longitudinal direction (L), transverse direction (T) and diagonal direction (D) are indicated in the DSS microstructure.

3.2. Anisotropy behaviour of DSS

3.2.1. Impact toughness of DSS

DSS parent metal exhibits significant anisotropy behaviour during the impact toughness test with respect to the different directions. It gives higher impact energy in the rolling and the diagonal directions. The presence of elongated austenite phases in the direction of impact causes severe plastic deformation in the samples. More amount of plastic deformation was observed in the fractured samples extracted from the longitudinal direction. The individual values of impact energy obtained from the samples at room temperature and subzero temperature are shown in Figure 3(a) and (b). Notable variations in the impact toughness between room temperature and subzero temperature were observed in the transverse specimens. It was found that the reduction in impact toughness was maximum in the subzero temperature than in the room temperature. This is mainly due to the presence of ferrite phases in the microstructure of DSS which undergoes ductile brittle transition at low temperature [5]. The average values of impact toughness obtained from the tested samples are shown in Fig 3 (c). The impact toughness values obtained in the longitudinal direction are closer to the diagonal direction.

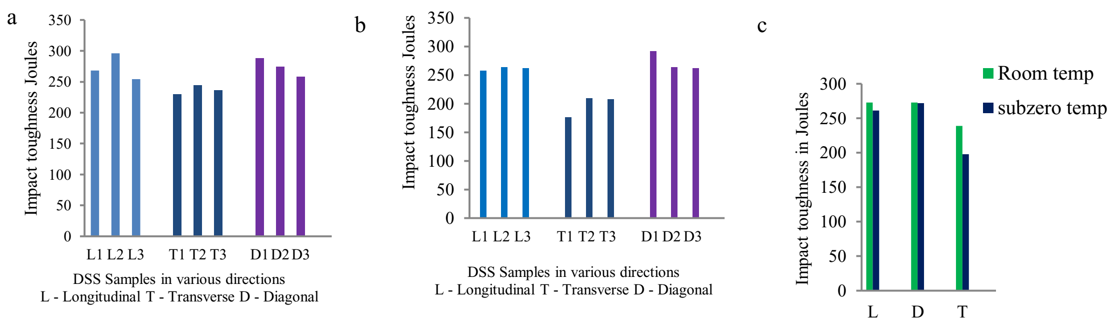


Fig.3. Impact toughness (a) At room temperature (b) At subzero temperature (c) Comparison of average impact toughness

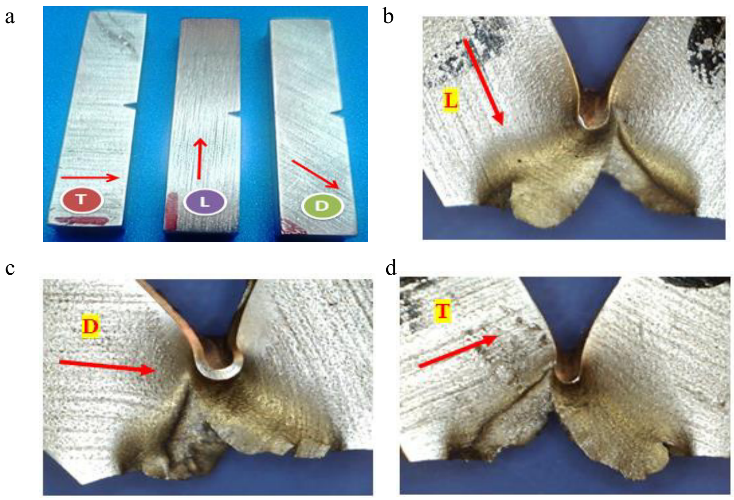


Fig.4. Plastic deformation (a) Notches in different directions (b) Longitudinal sample (c) Diagonal samples (d) Transverse sample

The presence of crack absorber i.e. austenite phases in the rolling direction of DSS has a greater influence in the impact toughness test [2]. Continuous tearing of the banded structure in the transverse specimen is the main reason for lowering the impact toughness in the transverse direction. The comparisons of plastic deformation absorbed by the samples with respect to the different directions are given in Fig 4 (a) to (d). Also, none of the tested samples were broken into two pieces which show the work hardening capability of DSS.

3.2.2. Tensile behaviour of DSS

Tensile properties of DSS parent metal such as yield strength, ultimate tensile strength and the percentage of elongation obtained are given in Figure 5(a) to (c). DSS exhibits a higher amount of yield strength and ultimate tensile strength in the transverse direction. Plastic deformation induced during rolling in the longitudinal direction leads to difficulty in deforming the metal in the transverse direction [1]. Significant loss in ductility was observed in the transverse direction which was observed by less percentage of elongation. Also, reduction in the cross section area of the fractured sample is less in the transverse specimen when compared to the longitudinal specimen. A higher percentage of elongation was observed in the longitudinal direction due to the presence of elongated austenite grains in the rolling direction which is more capable for deformation. This has been confirmed by the observation of least reduction in the cross section area of the fractured surface. The fractured cross-sectional areas of longitudinal and transverse specimens are compared in Fig 6(a) and (b). It is better to use transverse direction as a welding direction to gain higher amount of ductility in the DSS weld, because in real time applications structural members are usually oriented in the longitudinal direction so that the loading direction coincides with the rolling direction.

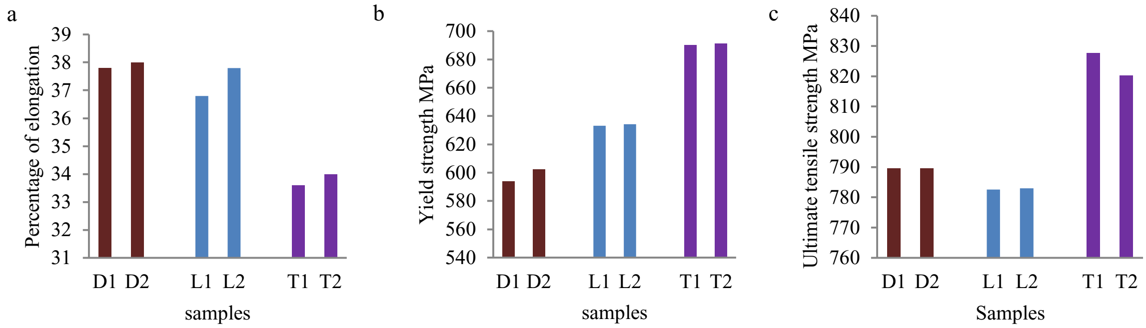


Fig.5. Tensile properties of DSS (a) Percentage of elongation (b) Yield strength (c) Ultimate tensile strength

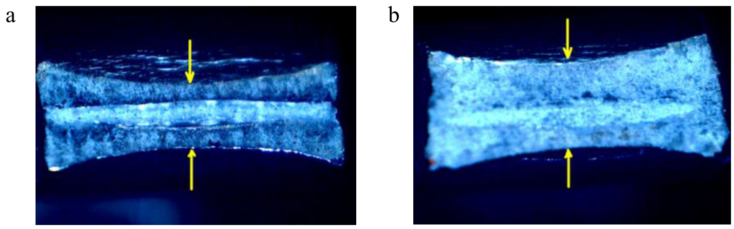


Fig.6. Fractured surface (a) Longitudinal direction (b) Transverse direction

3.2.3. Formability of DSS

DSS has better formability in the longitudinal direction when compared to the transverse direction which was confirmed by three point bending test. Two similar samples were subjected to bending in each direction. The load taken by the longitudinal direction samples to achieve 180° bend are 30.35 kN and 30.05 kN and the load taken by the transverse direction samples are 32.44 kN and 32.04 kN. The variation observed between the longitudinal and transverse direction samples were around 2 kN. The tested samples before and after bending are given in Fig 7 (a) and (b). Also, during bending material was flowed towards longitudinal direction for the samples T1 and T2 which implies that DSS microstructure tends to flow more in the longitudinal direction.

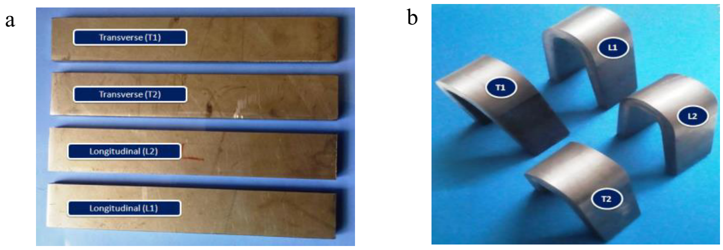


Fig.7. Bend test samples (a) Before bending (b) After bending

3.3. Microstructural analysis of DSS weld

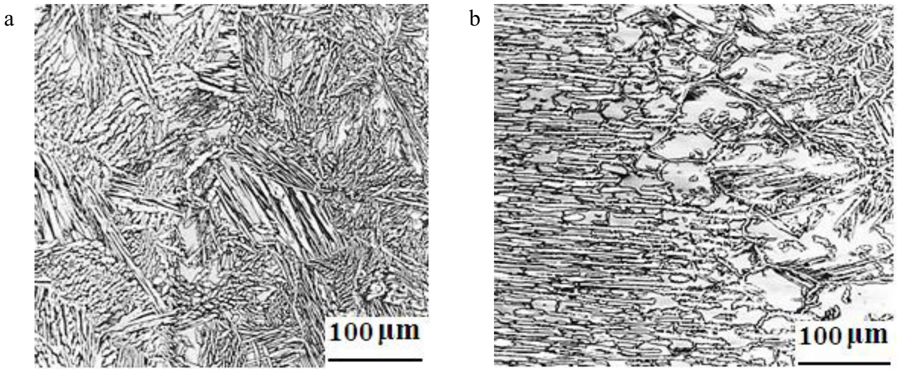


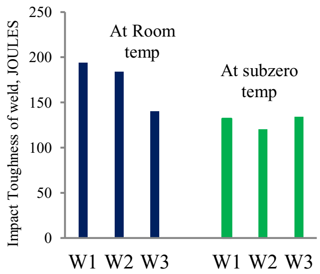
Fig.8. DSS Weld microstructure (a) Weld (b) HTHAZ

Weld microstructure shows that the precipitation of both ferrite and austenite phases in it. Initially, the weld region solidifies as delta ferrite matrix and then the nucleation of grain boundary austenite, Widmanstätten structure of austenite and intragranular austenite phases have taken place. The root region of the weld shows nearly 80% of austenite phases due to the repeated heating of weldment by multipass welding. This implies that multipass welding promoting the formation of austenite phases in the weld root region which is shown in Fig 8 (a). Enrichment of nickel content in the filler metal and moderate cooling rate does not promoting any intermetallic phases such as chromium nitride, sigma, chi etc. in the weldment. High-Temperature Heat Affected Zone (HTHAZ) shows nearly 80% of coarser ferrite grains which are formed due to the temperature attained by this region during the welding process. During welding, this region attains nearly the melting point temperature i.e. 1450°C, in which DSS is fully ferritic nature. The HAZ transformation cycle has three regions such as austenite transformation to ferrite, fully ferritic structure and the austenite reformation. Rapid cooling followed by the welding process in this region causes insufficient formation of austenite phases as shown in Fig 8(b). Also, the probability of forming Cr_2N in this region is more. Nitrogen has low solubility in the ferrite and its solubility in ferrite decreases with decrease in temperature. This leads to the formation of Chromium nitride (Cr_2N) in the ferrite grain boundaries and also inside the ferrite grains [7, 20, 21]. However, there is no observation of Cr_2N precipitation in this study. HTHAZ can be differentiated from the LTHAZ only through the metallography microstructural observation. The zone next to HTHAZ is known as Low Temperature Heat Affected Zone (LTHAZ). This will attain the temperature range between 700 and 1000°C during welding which is more prone to the formation of intermetallic phases. However, it was found that there is no formation of intermetallic phases in this zone. But at an extremely slow cooling rate, sigma (σ) can be precipitated in LTHAZ during the temperature range of 800 to 900ºC [5]. Therefore, the welding parameters should be controlled to ensure, that the overall cooling conditions are fast enough to avoid deleterious precipitations in the LTHAZ. Even very less percentage of sigma precipitation can cause detrimental effect in the mechanical and corrosion properties of DSS.

3.4. Mechanical properties of the Weld

DSS weld exhibits almost similar behaviour as like its parent metal during the tensile test. Use of transverse direction as a welding direction as well as enriched Nickel filler are the reason behind the values of percentage of elongation, yield strength and the ultimate tensile strength. The tensile properties achieved from the weld are given in Table 3. Also, none of the samples were fractured in the weld region. All the tested samples were fractured in the parent metal region. However, the impact toughness of the DSS weld was reduced significantly than the DSS parent metal even the weld zone contains higher amount of austenite phases. The absorbed impact energies of the welded samples at both room temperature and sub-zero temperature are given in Fig 9 (a). It reveals that the reduction in the impact toughness caused by the effect of welding by forming irregular grain orientations of ferrite and austenite phases, secondary austenite phases in the weld, coarser ferrite grains near the fusion line and improper diffusion of alloying elements. The formation of welding induced residual stresses also plays a major role in the reduction of impact properties in the weld. However, the present study was not intended to study the formation of residual stresses in the weld. Further, the amount of plastic deformation under impact loading is very low for the weld when compared with the parent metal samples. Welded samples gave almost brittle fracture during the impact loading as given in Fig 9 (b).

a



b

Fig.9. (a) Impact toughness of DSS weld (b) Cleavage fractured of DSS weld sample

Table.3. Tensile properties of DSS weld

Sample No.	Yield strength MPa	Ultimate Tensile strength MPa	Elongation %
Weld 1	620.15	799.6	34.3%
Weld 2	647.23	783.4	30.2%

4. Conclusions

In the present work, anisotropic properties of DSS AISI 2205 were investigated to justify the suitable direction for welding and the weld properties of DSS in the justified direction were analyzed. The following conclusions were arrived as follows:

DSS gives higher impact energy and maximum percentage of elongation in the longitudinal direction i.e. rolling direction. It gives greater yield strength and ultimate tensile strength in the transverse direction i.e. perpendicular to the rolling direction. DSS has better formability in the longitudinal direction which was confirmed by three point bending method.

In order to obtain better ductility in the DSS weld, the welding direction must be in the transverse direction so that the loading direction in real time applications will be in the longitudinal direction i.e. rolling direction.

The microstructure of DSS weld gives three different forms of austenite phases i.e. grain boundary austenite, widmanstätten structure of austenite and intragranular austenite phases. Further, it has coarser ferrite grains near the fusion line.

The tensile properties of the DSS weld are almost equal when compared to the parent metal of DSS. However, under impact loading DSS weld shows significant reduction of impact toughness even the welding was carried out in a transverse direction in which the highest ductility is possible during loading. Therefore, it is recommended that welding should not be carried out in any other direction to avoid further reduction in the ductility under loading. The findings of this work will be useful for the fabrications involved in the marine applications.

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