Brief Survey of the Microstructural, Mechanical and Corrosion Properties of Duplex Stainless Steels SMAW Weldments.

Ibrahim Momoh-Bello Omiogbemi 1,2*, Rajneesh Kumar Gupta3, Danjuma Saleh Yawas2, Matthew Olatunde Afolayan2, Emmanuel Toi Dauda4,

1 Department of Mechanical Engineering, Air Force Institute of Technology, Kaduna-800282, Nigeria
2 Department of Mechanical Engineering, Ahmadu Bello University, Zaria-10211, Nigeria
3 Engineering Division, CSIR-National Metallurgical Laboratory, Jamshedpur- 831007, India
4 Department of Metallurgical and Materials Engineering, Ahmadu Bello University, Zaria-10211, Nigeria

*Corresponding Authors e-mail: omiogbemi1@gmail.com, rkgupta@nmlindia.org

Abstract. Duplex stainless steels (DSSs) structures, especially the American Iron and Steel Institute (AISI)type 2205 and 2507 have greatly attracted the attention of many researchers, engineers, manufacturers as well as the end-users of the products because of its superior engineering properties like strength, good toughness, particular resistance to corrosive environments and to stress corrosion cracking (SCC). Due to its worldwide progressive growth, demand and utilization, this novel steel (DSS) is rising very fast, especially in marine, power plants, chemical process, mining, petrochemical, oil and gas, pharmaceutical and many other related engineering applications. Generally, the joining of DSSs alloys is a big problem due to its susceptibility to sensitization caused by the precipitation of additional phases when heated above 600°C. Conversely, improper selection of welding parameters, imbalance ratio of austenite/ferrite phases can lead to corrosion susceptibility, solidification cracking and susceptibility to plastic deformation. Shielded metal arc welding (SMAW) technique with recommended consumables (E2209 and E2594 or E2595) is used in the fabrication of the multiphase steels with the aim of obtaining the optimum weldment with the desired input welding criteria, optimum mechanical properties with minimum defects from the microstructural perspective and excellent corrosion behaviours. This review is therefore geared towards accentuating the influence of arc welding processes, and SMAW in particular on the microstructure, mechanical and corrosion properties of DSSs weldment.

Keywords SMAW; AISI 2205; AISI 2507; Microstructural properties; Mechanical properties; Corrosion resistance

1 Introduction

Welding can be seen as a fabrication technique of creating a permanent joint resulting from the melting of the metal surfaces of the work-piece to be joined together, with or without the employment of pressure and a filler rod, having a similar composition with the base metal [1].
Generally, the duplex stainless steels (DSSs) structure has been recognized as a well-established type of stainless-steel family for more than 90 years. The earliest mention of DSSs officially was from 1927 [2]. It became obvious during the 20th century that the ferrite phase in DSSs provides excellent protection for the steel against chloride-induced SCC that is a major menace of the counterpart austenitic stainless steels (ASSs). However, the consumption of DSSs in many engineering and other industries increase annually by up to 20% and more [3].

Considering the appropriate compositions, physicochemical and thermo-mechanical processing, the novel DSSs, which display a dual-phase structure of austenite–ferrite, can be realized. The increased yield strength and excellent opposition to SCC are some of the advantages presented by DSSs upon single-phase grades of stainless steel [4-7].

DSSs structure has recorded several outstanding successes in contrast to its counterpart ASSs due to the volatile nature of the price of nickel (Ni) alloy in the general market year over year [8]. One of the major problems of ASSs structures is their susceptibility to several aggressive media [9]. Hence, many industries and engineering sectors are trying to adopt alternative stainless steel with a low percentage of nickel (Ni), having better or comparable performance as that of usual ASSs [10].

Many technical and scientific reports on DSSs delivered in conferences held around the world have aggrandized the great demand for the novel steel structure globally. Some of these conferences are St. Louis in the United State of America, 1982, Den Hauge-Netherland, Beaune-France, Yokohama-Japan, York-United Kingdom, Maastricht-Netherland, Venice-Italy and Grado-Italy in 1986, 1991, 1993, 1994, 1997, 2000, 2007 respectively till the present time. During these conferences, scientific and valuable technical presentations relating to the aspect of metallurgy such as phase precipitations and corrosion behaviour together with the mechanical characterization of dual-phase DSSs based on the experiences in the industry concerning the valuable areas of utilization of lean DSS grade 2304, standard DSS grade 2205 and Super DSS grade 2507. These types of DSS mentioned above were ratified to be essential grades with better performance in service applications experience for more than two decades which resulted in the conclusion made by the aforementioned conferences that there is a high demand for DSSs structure as an alternative of austenitic 300-series counterpart [11-14]. This has further led to the implementation of novel steel (DSSs) in combination with other alloying elements for different operation by several countries like Saudi Arabia, Spain, West Indies, Malta, Sharjah and Cyprus in various sectors such as brackish water reverse osmosis (BWRO), large multi-effect desalination (MED) plants, bleaching plants, multi-stage flash (MSF) plants, and large seawater reverse osmosis (SWRO) plants [15-18].

Amidst the various classifications of stainless-steel grades, the manufacturing of DSSS constitutes less than 200,000 tonnes which are approximately one percentage (1%) of the whole production of stainless steels worldwide, in the year 2007. The conference held in Feinox, 2008 forecasted that by 2020, the manufacturing/production of DSSs will be increased by about 4% as illustrated in Fig. 1. Conversely, the ASSs was 63.1% in demand during the year 2004. It decreased by 1.1% in 2007, as a result of the fluctuation of the price of nickel (Ni) alloy. Therefore, based on this factor, a 53% share of ASSs was forecasted up to 2020 as shown in Fig.1 [19-20].

![Figure 1](image_url)

Figure 1 The trend and forecast of stainless steel; associated with Baldo [20].
Furthermore, the volatility of the price of Ni-alloy is unstable which has adversely affected the general stainless steel producers and end-users. Since nickel is the major alloy in most largely used austenitic stainless steels 300-series, its supplies (SSs) to the global market demand has not been met. This resulted in the search for better alternatives with low nickel alloy such as ASS 200-series (Cr-Mn) and the 400-series (ferrite grades) normally applicable in mild aggressive environments and for structural purposes as depicted in Figure 1. Presented in the figure, it is obvious that 10% of austenitic stainless steel 200-series was produced in the year 2007 and about 6% was forecasted up to the year 2020. Looking at the years; 2013 and 2014, 19.8% and 18.9% were produced respectively for the same steel (200-series) which signifies a drop of about 0.9% in the production rate between 2013 and 2014 as illustrated in Figure 2 and Figure 3. While the ferritic grades (400-series) demand and manufacturing are geometrically going up as a result of the low price, better thermal productivity, and easy recyclability. About 27% of 400-series was produced in 2007 and 37% prediction was made up to 2020. However, 25.5% and 25.2% were produced in 2013 and 2014 respectively which indicate a 0.3% decrease in the production between the two years (2013 and 2014). Also, stainless steel products global demand was about 37.7 million tonnes in 2015, there was a little increase from 37.1 million tonnes in 2014 (2% increase). From literature, the annual average growth of stainless steel generally from 2011 to 2014 was 8% while the overall global production of steel in 2015 was about 1.6 billion tonnes and stainless steel was about 2.6% of the total [21-23].

Figure 2 Some grades of stainless-steel production in 2013; Associated with [22].

Figure 3 Some grades of stainless-steel production in 2014; Associated with [22].
1.1. Weldability of stainless steels

As posited by some researchers [24] welding happens to be the most essential technique used in the joining of similar and dissimilar metals. To obtain high productivity in welding fabrication, large heat input is needed. The validity of several welding recommendations in comparison with those made available during the period of DSSs conferences of more than two decades ago is still useful. This is because the use of welding fabrication and development is an essential factor in the practical utilization of steel on a large volume since productivity stands as the main factor of any manufacturing industry [25-26]. A paper publication by Nowacki and Rybicki [27] dwells more on the effect of heat input on stainless steel materials but so far, there has not been a proposal on the systematic approach on the influence of high heat input with respect to corrosion properties of DSSs.

Many researchers have immensely contributed to the investigations of welding, mechanical and corrosion characteristics of low nickel alloy stainless steel (SSs) structure in a less corrosive environment [28-30], but for a better choice for highly corrosive media, low nickel alloy of DSSs (AISI 2205 and AISI 2507) is required and this formed the motivation for further investigations of this novel alloy in this review paper.

In the present investigation, an attempt was made to systematically analyse the outcomes of many researcher’s findings that are geared towards the influence of welding procedure, especially SMAW on the microstructural, mechanical and corrosion resistance of DSSs grades (AISI 2205 and AISI 2507) neglecting the other classes of DSSs because of the few research done in them. The phase transformation when DSSs [standard duplex stainless steel (DSS) and super duplex stainless steel (SDSS)] are undergoing solidification during welding together with some selected electrodes for its sound welding was simplified. Finally, the present issues and future focus/perspective of the review were explored.

2 Transformation of austenite- ferrite phases in DSS and SDSS structures

Presented in Table 1 are the chemical compositions of standard DSS and SDSS with their respective welding consumables [31, 32]. The respective ferrite content proportion of the parent metals of DSS and SDSS are 46% and between 40-65% measured by a method called image analysis technique [31, 119]. Verma et al. [33] and Dandekar et al. [32] concluded that standard DSS grade 2205 and SDSS grade 2507 can be successfully welded by E2209 and E2594 electrodes respectively having the same composition with its parent metals of 2205 and 2507 grades.

| Table 1 Chemical analysis (wt. %) of base metals of DSS 2205 and SDSS 2507 |
|-----------------|---|---|---|---|---|---|---|---|---|
| Element | C | S | Mn | Si | Cr | N | Mo | P | Ni |
| DSS (2205) Wt. | 0.053 | 0.020 | 0.420 | 0.450 | 100 | 0.800 | 0.700 | 0.030 | 0.165 |
| Wt. % | 0.019 | 0.025 | 0.040 | 0.078 | 0.880 | 0.550 | 0.110 | 0.035 | 0.090 |
| DSS (2507) Wt. | 0.030 | 0.020 | 0.790 | 0.610 | 860 | 0.420 | 0.630 | 0.030 | 0.260 |
| Wt. % | 0.030 | 0.020 | 0.790 | 0.600 | 0.800 | 0.300 | 0.250 |


Hindering the formation of secondary phases seems not to be the major problem when subjecting DSSs to solution heat treatment or welding fabrication. An optimum balance of the dual-phase (ferrite-austenite) of the DSSs structure are key factors to obtaining better corrosion resistance and mechanical properties [34-36]. These dual-phases (ferrite-austenite) are the constituents that made up the microstructure of DSSs parent metal as shown in Fig. 4 (a)- (c) having micrographs of the optical micrograph, SEM-micrograph and TEM-micrograph respectively at different magnifications.

![Figure 4: Parent metal of DSS micrographs (a) optical view (b) SEM view and (c) TEM view; Associated with [35].](image)

The transformation of the microstructure of DSSs during cooling can be conveniently expounded. The basic influence of the important alloying elements can be summarized using the current parameters of two equivalents (nickel-Nieq and chromium-Creq) calculation in equations 1 and 2 respectively [38, 39].

\[
\text{Nieq} = \% \text{Ni} + 30\% \text{(C)} + 0.5 \% \text{(Mn)} + 30\% \text{(N)}
\]

\[
\text{Creq} = \% \text{Cr} + \% \text{Mo} + 0.5 \% \text{(Nb)} + 1.5 \% \text{(Si)}
\]

Generally, duplex stainless steels’ solidification is completely in the ferrite (\(\delta\)) mode while the austenite (\(\gamma\)) phase nucleates basically below a specific temperature called the ferritic solvus in the order of \(L + \delta \rightarrow \delta + \gamma\), where \(L\) is the liquid. To expound more on the mode of solidification in DSSs which is based on the ratio of \(\text{Creq/Nieq}\), the Fe–Cr–Ni pseudo-binary diagram, that can be used as a vital instrument for predicting solidification mode [40-44]. Essentially, the constituents of DSSs are within the alpha (\(\alpha\)) and gamma (\(\gamma\)) phases. It is noted that in several stainless-steel structures chemistry, there is an enlargement of phase to conveniently separate both the high and low-temperature ferrite phases. From the pseudo-binary Fe-Cr-Ni diagram, it is observed that there is the existence of ferrite (\(\delta\)) uninterruptedly from the solidification region to the ambient temperature (room temperature precisely) for the DSSs structure which resulted in the recognition of all ferrite to be classified as ferrite (\(\delta\)) because of the continuous revolution with the same composition [45]. The low impurity has practically rendered DSSs to be highly resistant to solidification cracking. From the works of Lippold...
[46] and Sieurin [47], it is evident that the solidification mode is completely ferritic if $\text{Cr}_{eq}/\text{Ni}_{eq} > 1.95$. Hence, for the parent metal of DSSs, the range is between 2.25-3.5, where $\text{Cr}_{eq}/\text{Ni}_{eq}$ for SDSSs equals 2.25 and that of DSS equals 2.62, and this was confirmed by Fourie and Robinson [45] in their attempt to evidentially show the chromium and molybdenum diffusion at the ferrite ($\delta$) region.

Figure 5 Optical micrograph of DSS welded section; Associated with [48].

Subsequently, as presented in Fig. 5, it is evident that during solidification at the weldment (fusion zone FZ), the various morphology of austenite ($\gamma$) phase appears; the first phase that directly nucleates from the matrix of ferrite called the grain boundary austenite (GBA) formed the part of austenite network in the system. At a solidification temperature range of 1350 to 800°C, there exists GBA nucleation. The formation of Widmanstatten austenite (WA) grain from GBA can subsequently be evident but has sufficient nickel (Ni) in comparison with the ferrite region and also, as compared to GBA, it possesses a limited amount of chromium, nitrogen, and molybdenum [48, 49, 50-52]. The cooling rate effect causes the formation of intergranular austenite (IGA) driven by a high propelling force but later precipitates at a moderate temperature which made the DSSs susceptible to pitting corrosion problem as a result of the presence of Cr, Mo, and N that possesses limited alloying element in the system [53].

It was confirmed by Shinohara et al. [54] that the precipitation of $\sigma$ phase in stainless steel structures possesses a diffusion-regulated phase revolution capability in some certain compositions of chromium and nickel alloys (about 25% Cr to 20% Ni). This is evident in the Cr alloy having an essential role in the rate of precipitation increase of the $\sigma$ phase of the steel. However, the rate of $\sigma$ phase precipitation happens to be about 100 times higher in $\delta$-ferrite than in the counterpart $\gamma$-austenite phase [55]. This simply implies that the speed of diffusion of the $\sigma$ phase in $\delta$ – ferrite was higher in contrast to the $\gamma$-austenite region. The percentage composition of chromium and molybdenum alloys in the $\delta$ – ferrite depreciated and there was a resultant simultaneous appreciation of nickel alloy at the of $\sigma$ phase precipitation in the steel. The whole stated mechanism resulted in the secondary austenite phases ($\gamma_2$) formation through the $\delta$ – ferrite [56].

3. Microstructure, mechanical and corrosion properties of DSS AISI 2205 and SDSS AISI 2507 weldment

Generally, the welding of standard DSS and super DSS to a design specification as recommended is always a difficult task. Though, their weldability by most of the conventional welding techniques such as SMAW is a possibility. The mechanism in the SMAW process is such that it can be efficiently used for positional welding and to perfect fabrication on joints that have restricted accessibility requiring mostly direct current electrode positive (DCEP) that gives excellent welding output. The recommendation of a short arc for the SMAW technique helps to promote stability and decrease the risk of nitrogen pick up capacity during welding since N is an essential factor in the balanced proportion of the dual-phases of the steel structure ($\delta$ -ferrite and $\gamma$-austenite phases) in the weldment.
[57]. Table 2 presents the welding parameters together with the recommended standard electrodes for SMAW of DSSs grade AISI 2205 and AISI 2507 [58, 59-60]

**Table 2 Recommended welding parameters and standard electrode for SMAW of DSS and SDSS**

| Welding technique | Grade of DSS | Electrode diameter (mm) | Voltage (V) | Speed (cm/min) | Current (A) | Electrode type |
|-------------------|--------------|-------------------------|-------------|---------------|-------------|---------------|
| SMAW AISI 2205    | 2.50         | 20-22                   | 4-6         | 50-60         | E2209       |
|                   | 3.25         | 23-25                   | 7-9         | 80-100        | E2209       |
| SMAW AISI 2507    | 4.00         | 24-26                   | 15-25       | 125-135       | E2594       |

3.1 The Behaviour of welding on the mechanical properties of DSS AISI 2205 and SDSS AISI 2507 structures

3.1.1 Effect of heat treatment temperature on the mechanical properties of AISI 2205 and AISI 2507

Essentially, intermetallic phases and compounds have an adverse effect on the toughness of duplex stainless steel. Considering the heat treatment temperature on the Charpy impact energy of duplex stainless steel (AISI 2205) as posited by Badjia et al., [61], it was evident from their findings that the temperature from which the highest amount of sigma phase was noticed was at specimen annealed at 850 °C and this temperature, the lowest toughness of the steel was observed. They also studied the corresponding variations in the tensile strength and elongation at different annealed temperatures (from 800-1050°C). The complicated phase transfiguration observed during the heat treatment (using the annealing method) of duplex stainless steel (AISI 2205) resulted in the variation of its mechanical characteristics. It was also evident from their results that the monumental increase in the tensile properties of the steel (AISI 2205) and the corresponding decrease in its elongation was caused by the application of heat treatment from 800 to 1050 °C. The optimum combination of these parameters (tensile strength and elongation) can be seen at a heat treatment temperature of 1050 °C (σ =775 MPa, A =36.45%), and the gradual reduction in the tensile strength after annealing at a temperature above 1050 °C was as a result of the increment in the volume fraction of ferrite in the steel in accordance to the works of Zucato et al. [62] and Sato [63] on the relationships between microstructural phase transformation of DSSs to its mechanical properties. From their fractographical study on the HAZ after annealing at two different temperatures (850 and 1050°C), it can be concluded that the variations in the failure mode mechanisms from an intermediate kind of failure to a dimpled rupture failure were a product of the annealed temperatures observed from 850 to 1050 °C.

Wang et al. [64] subjected some samples for heat treatment mechanism own to the interest of investigating its influence on the microstructure of SDSS AISI 2507. As presented in Figure 6 is the heat treatment temperature of SDSS AISI 2507 weldment with their corresponding σ—phase content and hardness values respectively. There is a consistent trend of increasing and reducing the capacity of the two parameters (σ—phase content and hardness) as the heat treatment temperature increases. It was evident that the maximum σ—phase content (up to 35%) and hardness value (up to 374 HV) were observed at a heat treatment temperature of 850°C. Further increase in the heat treatment resulted in a sharp decrease in these properties (σ—phase content and hardness). Figure 6 (b) shows an appreciable increase of the hardness value of SDSS AISI 2507 structure after heat treatment as seen with the control sample whose hardness value was 264 HV and significantly improve above this range after heat-treated from 800 to 950 °C. Calliari et al. [65], classify σ—phase as brittle with the hard
intermetallic compound having a mean hardness value of 800HV approximately. This infers that $\sigma$—phase performs a vital role in the hardness properties of the steel (SDSS AISI 2507) structure as it tends to enhance its value and usefulness in-service environment.

Figure 6 Heat treatment temperature of SDSS AISI 2507 weldment with their corresponding (a) $\sigma$—phase content and (b) hardness values; Associated with [64].

3.1.2 Effect of welding on the hardness and tensile properties of AISI 2205 and AISI 2507

Presented in Figure 7 [66], are the micrographs of the various zones (base metal-BM, heat affected zone-HAZ and fusion zone-FZ) of DSS AISI 2205 with their corresponding hardness values. Figure 8 presents the comprehensive average hardness results of both DSS AISI 2205 and SDSS AISI 2507 at their respective zones (BM, FZ and HAZ). Figure 8a indicates the welding process used (SMAW) in obtaining the different hardness values while Figure 8b illustrates the DSS electrode type used with their corresponding hardness values in the regions (BM, FZ and HAZ). The results show a strong correlation between the hardness values obtained at the FZ and the HAZ regions of DSS structures. The changes in the hardness values at the microstructure at the different regions of the steel is an indication of fast heating and cooling welding cycle that could have caused a remarkable change in the ferrite-austenite phase transformation [67].

Figure 7 Micrographs and hardness values of duplex stainless steel: (a) BM, (b) FZ and (c) HAZ. Adapted from welding product program; Associated with [66].
Figure 8 Mean Hardness values (Hv) of DSS AISI 2205 and SDSS AISI 2507 at various zones of welded joints and base metals indicating (a) the welding process used and (b) the electrode type used; Associated with [36, 66].

Dandekar et al. [32], Lima et al. [68] and Belkessa et al. [69] have examined the mechanical properties of DSS AISI 2205 and SDSS AISI 2507 weldments quantitatively with the aid of tensile technique to analyse the tensile strength and yield strength of the structures with their corresponding elongation using the SMAW, GTAW and LBW methods with the recommended electrodes. It was observed that during the tensile analysis, some weldments fractured at the BM with a significant fracture mode of ductility. The ultimate tensile strength of the SDSS AISI 2507 welded with SMAW and LBW were relatively the same for all the weldments (approximately 867.6 MPa and 862.0 MPa) except for GTAW whose ultimate tensile strength is relatively less (approx. 834.0 MPa) as shown in Table 3 and Figure 9.

Table 3 Tensile properties of DSS AISI 2205 and SDSS AISI 2507 welded joints

| Welding technique | Grade of DSS | Ultimate strength (MPa) | Elongation (%) | Region of fracture | Electrode type |
|-------------------|--------------|-------------------------|----------------|--------------------|----------------|
| SMA W 2205        | AISI 2205    | 768.15                  | 35.81          | -                  | E2209          |
| SMA W 2507        | AISI 2507    | 869.3                   | 14.3           | BM                 | E2594          |
| SMA W 2507        | AISI 2507    | 867.6                   | 14.5           | BM                 | E2595          |
| GTAW 2507         | AISI 2507    | 834.0                   | 61.3           | BM                 | -              |
| LBW 2507          | AISI 2507    | 862.0                   | 86.9           | BM                 | -              |
The features of the microstructure in welding play an essential role in the fabrication of steel generally and in the effectiveness and integrity of the welded joint of DSSs in particular. Welding fabrication, however, has to be carried out to achieve an optimal ferrite to austenite balance in the weld, at the same time free from dangerous intermetallic phases as well as the nitrides phases (CrN, Cr$_2$N) [25, 70]. It has been well reported [71,72] that the type of fusion welding techniques that enhances the sufficient formation of austenite phase in AISI 2205 and AISI 2507 weldment is the higher arc energy welding techniques such as SMAW, gas metal gas welding (GMAW), gas tungsten gas welding (GTAW) and SAW as a result of the gradual cooling mechanism involved. This is not so with lower energy welding techniques like electron beam welding (EBW) and laser beam welding (LBW) method which supports rapid cooling rate and result in low precipitation of austenite at the weldment.

However, below 25% austenite composition contained in DSSs joint is generally unsatisfactory in many sectors of utilization [73], notwithstanding there is an acceptable recommendation by the Norsok standard 74] that the percentage of the content of austenite should be 30% in the weldment for the inspection of piping structures. Asif et al. [75] pointed that when DSSs undergo a post-weld treatment immediately after welding fabrication for about 15mins at a temperature of 1050°C accompanied fast water quenching mechanism to annul the formation of sigma ($\sigma$) as well as other phases like nitrides and intermetallic at the point of cooling which invariably promotes the composition of the austenite ($\gamma$) phase. Some mechanical properties of the weldment such as impact toughness are essentially improved. Also, it is evident that post-weld heat treatment promotes the Cr and Mo diffusion in the ferrite ($\delta$) region whereas the austenite stabilizers such Ni and N enhances the austenite phase to achieve an efficiently balanced ratio of ferrite to austenite in the weldment.

Heat input plays a crucial part in the geometry of weld bead, microstructural characterisation, mechanical and corrosion opposition properties of DSSs weldment [76]. However, to achieve satisfactory austenite to ferrite phase balance in DSS AISI 2205, the required heat input is at the range of 0.5-2.5kJ/mm while for SDSS AISI 2507 weldment, the recommended heat input is between 0.3-1.5kJ/mm. This will help to prevent the formation of detrimental phases in the weld [77].

Based on several works of other researchers on DSSs, it is noted that the realisation of precipitation of Cr$_2$N and CrN in DSS AISI 2205 grade and SDSS AISI 2507 grade is mainly a result of the application of low heat input and rapid cooling mechanism. It is however evident that at high heat input above the recommended heat input above and a faster cooling cycle of the weldment, there is the possibility of Cr$_2$N phase formation because of the nucleation of N in the ferrite region at a temperature relatively below 900°C while below the temperature of 1100°C, CrN formation is inevitable on thecondition that Cr$_2$N and austenite phases are subdued. This is following the claim of Hertzman [78], that there is the presence of CrN in DSSs weldment along with some alloying metals like Cr, Fe and Mo.
3.1.3 The effect of welding on the corrosion properties of DSS AISI 2205 structure and SDSS AISI 2507 structures

As evident from the several types of research previously carried out by some researchers, DSSs such as AISI 2205 and AISI 2507, generally demonstrate strong resistance to SCC in chloride-containing environments [79]. Although their susceptibility to SCC is a consequence of different parameters such as microstructures, applied load/stress, alloying elements or the kind of medium of application [79, 80-87]. The selective dissolution of the various components of the steel (DSSs) phases or pitting corrosion may be the cause of the initial initiation of cracks in the steel structures [82, 83].

Tsai [88] used the potentiodynamic polarization method to assess the susceptibility of SCC of AISI 2205 in nitrogen (N₂) deaerated sodium chloride (NaCl) medium of about 1-26 wt.% of a 6.0 pH at a specified temperature range of 25 to 90°C. Using a specially designed saturated calomel (SCE) as the reference electrode (kept at room temperature) whiles the platinum mesh was used as the counter electrode. The slow strain rate testing (SSRT) technique [82] was utilized to determine the SCC susceptibility of AISI 2205 weldment in N₂ deaerated NaCl medium (1-26 wt%) of 6.0 pH value at a range of temperature between 25 to 90°C using austenitic stainless steel of type AISI 316 as a comparison. From the study, a vast rate range of passive part was observed with a current surge seen at -160mV which corresponds to the potential of pitting corrosion. Validation of these pits was done via SEM analysis on the surface of the experimental sample.

Bhattacharya [89] investigated the corrosion susceptibility of AISI 2205 in a sulfide-containing caustic environment where the steel (AISI 2205 was exposed to the media of 150g/L of NaOH in combination with 50g/L of Na₂S for the corrosion analysis. Presented in Figure 10 is the overview of the findings of the experimentation. Conversely, the findings are quite distinct from those obtained from the chloride-containing solution where the general and localized corrosion susceptibility of DSSs is significantly caused by the influence of microstructure [90]. This characteristic of DSS is contrary to that in the acidic chloride containing media, where the condensation of intermetallic phases like σ-phase and chi phases happen to cause the initiation of the corrosion via selective dissolution of Cr and Mo reduced parts within the parameters of precipitations [91].

![Figure 10](image)

**Figure 10** Corrosion rates of DSS AISI 2205 in sulfide-containing caustic solution; Associated with [89].

Paranthaman- et al. [92] investigated the electrochemical properties of gas tungsten arc welding (GTAW) of AISI 2507 SDSS weldment and compared it with its base metal (BM) through a technique of potentiodynamic polarization test. The analysis was carried out in various concentrations of sodium chloride compositions of 3.5M of NaCl, 4.5M of NaCl and 5.5M of NaCl to establish a basement for the findings. It was evident from their results that the samples analysed in 3.5M of NaCl medium for corrosion susceptibility of the AISI 2507 SDSS weldment showed minimal deterioration current
density and migrate to the positive direction of corrosion potentials in comparison with the specimens analysed in the various concentrations of the chloride media (4.5M NaCl and 5.5M NaCl). From the potentiodynamic polarization analysis, it was noticed that the γ-austenite phase present in the weldment in a relative amount resulted in excellent electrochemical properties of the AISI 2507 SDSS specimens welded with GTAW. This shows a higher percentage of γ-austenite phases in the FZ than at the BM with a less stable δ-ferrite [93].

These findings are in agreement with that of Alsarraf [34] who carried out a potentiodynamic polarization on SDSS AISI 2507 weldment to comprehend the significant function of the configuration as well as the microstructure on the corrosion and passivation properties of SDSS AISI 2507 immersed in aqueous NaCl (3.5%) salt at ambient temperature.

3.1.4 Effect of process parameters on the properties of DSS AISI 2205 and SDSS AISI 2507 weldment

Different welding techniques have been deployed over the years for the fabrication of AISI 2205 and AISI 2507 structures. Reviewed here are some of these techniques:

Yurtisik et al. [94] researched on the characterization of DSS weld metals using a hybridized welding process of plasma-metal inert gas welding method. The focus was to achieve duo purposes of deep penetration properties in keyholes area and metal deposition capability of plasma and metal inert gas welding processes respectively. The hybridization of these two welding techniques helped to achieve the following: a less heat input as compared to the conventional individual welding processes as illustrated in Table 8 and suppression of the precipitation capability of the secondary phases that serve as great barriers to the deterioration and toughness properties of the novel steel at the weldment and heat-affected zones [95]. This resulted in the achievement of efficient cooling time balance austenite to ferrite phases.

Hu and Xue [96] researched on the influence of process parameters on the weld quality during double-pulsed GMAW of AISI 2205 duplex stainless steel and considered the influence of the number of both strong and weak pulses along the welding speed as illustrated in Figure 11. The mechanical and microstructural characterisations were conducted on the welded samples of DSS AISI 2205 also. The findings showed that amongst the three factors considered (welding speed, number of strong pulses and number of weak pulses), welding speed had the greatest influence on the quality of weldment of the steel (DSS AISI 2205) and then the number of weak pulses and lastly the number of strong pulses as seen in their average ranges R as 6.25, 5.50 and 5.25 respectively and it is in agreement with the method adopted by Xie et al. [97] in analysing the weld quality of aluminium alloy double pulsed GMAW. The systematic order mathematically is $S > N_2 > N_1$.

![Figure 11](image.png)

**Figure 11.** The orthogonal analysis of the welding parameters used; Associated with [96].

Taban and Kaluc [98] have studied the welding behaviour of DSSs and SDSSs using laser and plasma arc welding methods. Mechanical and microstructural examinations were carried out on the
weldment together with the ferrite content measurement. It was found that at controlled heat input, the ferrite-austenite ratio at the weldment was balanced which resulted in an excellent toughness of DSS and SDSS welded with plasma arc welding technique as compared to the counterpart laser welding method. Subsequently, there was variation in the content of ferrite in the weldment in an acceptable range which shows its importance in realizing sound mechanical and microstructural properties [99-101]. Subsequently, Urena et al. [35] researched on the best welding conditions (such as welding intensity and travel speed) determination for welded butt joints of DSS structure of grade 2205 with the aid of plasma-arc welding. The conduction mode and the keyhole mode as types of welding modes were utilized for the evaluations of the metallurgical weldability and the possible net energy input for adequate application. Investigations on the parametric effect of welding for individual modes on the dimensional geometry of the weldment as well as their ferrite content analysis were carried out successfully [102]. It was noticed that the best heat input was at the ranges 2.5kJ/cm and 3.2 kJ/cm adopting the keyhole mode. Also, a substantial increase in the content of the ferrite up to about 20% was evident in the microstructural weldzone [103].

Paulraj and Garg [104] investigated the effect of welding parameters on the deterioration characteristics of GTAW of DSS and SDSS weldments. The influence of heat input on the mechanical properties (Table 7), and cooling rate, inter-pass, shielding gas on the corrosion resistance of the weldments were observed after welding DSS AISI 2205 and SDSS AISI 2507 pipes with the GTAW technique. Figure 12 present the summary of the influence of heat input on the mechanical properties of welded DSS AISI 2205 and SDSS AISI 2507 pipes employing the GTAW technique. Samples No.1 to 4 are samples of DSS AISI 2205 welded under low PREN condition and samples No. 5 to 8 are samples of DSS AISI 2205 welded under high PREN condition with their corresponding heat inputs. The same tread was applied for samples No. 9 to 12 and samples No.13 to 16 for SDSS AISI 2507 welded under low and high PREN conditions respectively with their unity standard deviation error.

![Figure 12](image)

Figure 12. Summary of the influence of heat input on the mechanical properties of welded DSS AISI 2205 and SDSS AISI 2507 under low PREN and high PREN conditions; Associated with [10].

Microstructural characteristics, as well as the determination of the ferrite content of the materials, were carried out using an appropriate standard. The microstructures of the weld metal were contrasted with the corrosion findings. The various phases of the weldment with respect to pitting resistance were investigated along with the influence of austenite secondary phase on the degradation of the steels (AISI 2205 AND AISI 2507) which can result in the loss of resistance of the passivation of the steel [105].

Luo et al. [31] researched on the effect of post-weld heat treatment (PWHT) on the welded joint of DSS grade 2205 using the submerged arc welding (SAW) method with the specified welding parameters. The sigma (σ) and delta (δ) phases of the DSS weldment are increased as the amount of gamma (γ) phase decreases after PWHT. Since the microstructure of the HAZ can be enhanced by PWHT,
the micro-hardness at this zone (HAZ) was observed to be reduced by PWHT. The fine dendrite structure of the microstructure of base metals changes gradationally to coarse columnar grains from the boundary of fusion to the centre weld zone. The successive segregation of the compositions of sigma (σ) and delta (δ) phases was as a result of the formation of the columnar grain at the weld zone of DSS weldment. Yuan et al. [106] studied that if by any means the Ni composition in the welding rod of DSS is high, the resultant effect will be higher austenite formation when the SAW process is employed in the weldment. Hence, the mechanical properties and corrosion resistance of weldment are excellently enhanced. Using the same SAW method, Sieurin and Sandstrom [48] have studied that the quota of austenite transformation in the HAZ of DSS grade 2205 hinders the formation of the sigma phase. It was found that in SAW of DSS grade 2205, the mean ferrite content in the weldment increases at the heat-affected zone of 150°C during interpass temperature [27, 107]. As a result of the heat treatment (HT), there were many formations of the sigma phase elements at the fusion zone which invariably led to the reduction in the toughness of the welded joint (FZ) and thereby increases the microhardness [108-110].

Due to its flexibility, portability, simplicity, and applicability, the shielded metal arc welding (SMAW) technique seems to be one of the most extensively utilized welding methods in several engineering fields of applications [46, 111]. SMAW method serves as a better alternative for preventing nitrogen loss for nitrogen alloy steel structure through the provision of self-protecting slag as a cover [112] Srinivasan et al. [113] studied the microstructure and corrosion properties of DSS grade 2205 and low alloy steel weldment using SMAW method. It was evident that the DSS electrode grade E2209 and ASS electrode grade E309 can be used to join DSS 2205 to a low alloy steel structure with the aid of the SMAW method. They both possess good general corrosion resistance but their pitting corrosion resistance was observed to be inferior when compared with the base metal of DSS grade 2205. There was also an observance of the carbon depletion region near the fusion boundary at the side of the low alloy steel structure.

Verma et al. [33] investigated the microstructure, mechanical and intergranular corrosion behaviour of dissimilar steels of grade 220 (DSS and grade 316L ASS welded by SMAW method using electrodes with a similar configuration to the base metal of the DSS (E2209 electrode). 0.45 to 0.60kJ/mm heat inputs were considered by the authors. The optical emission microscope (OES) and scanning electron microscopy (SEM) were utilized in the characterization of the microstructures while energy dispersive spectroscopy (EDS) attached to the SEM was used in obtaining the localized chemical information. The intergranular corrosion analysis was carried out based on the level of sensitization using the double loop electrochemical potentiokinetic reactivation technique. Paying close attention to the evaluation of the effect of weld dilution on mechanical properties and the measurement of ferrite content of the weldment using ferritscope. It was noticed that the weld joint accomplished the needed ferrite content for the different heat inputs mentioned above. The high cooling rate resulted in higher ferrite content which invariably increased the hardness and tensile properties of the steel at the lower heat input in comparison with higher heat input. It was also evident that the impact energy observed using the E2209 electrode for the welding was high without any reasonable defect.

Wang et al. [114] have investigated that the Tungsten inert gas welding (TIG) technique using filler materials of grade ER2209 seems to have better suitability for the joining of dissimilar metals of DSS grade 2205 and 16MnR steel as compared to using the SMAW method. There was no observance of precipitation of intermetallic phases in the two welding techniques. Susceptibility to pitting corrosion in chloride environment (3.5% sodium chloride) of the weldment produced by the shielded metal arc welding method was higher than the joint produced by the TIG welding technique due to the finer grains in the TIG welding method.

Gupta et al. [118] investigated the effect of heat input on microstructure and corrosion behaviour of SDSS 2507 welded by SMAW technique with E2595 electrode adopting duo heat inputs mechanism low (0.54kJ/mm) and high (1.10kJ/mm). The calibration of the ferritscope used in determining the ferrite content of the weldment at the BM, FZ and HAZ was done following AWS A4.2 standards in collaboration with the World Institute, United Kingdom and the preparation of tensile samples for experiment on the SDSS AISI 2507 weldment for the two levels of heat input (low and high), using ASTM E8M-04 standard [115-117]. The results of the mechanical properties of the weldment deduce the similarity among the parameters of interest; tensile strength, hardness and impact toughness using the two heat inputs. It is also evident from the corrosion studies using 3.5% concentration of common
salt (NaCl) solution that the steel (SDSS 2507) indicated about less a percentage (1%) level of sensitization which indistinguishably possesses pitting possibility for the used heat inputs (low and high), resulting in the recommendation of low heat input in the fabrication of SDSS 2507 structures [118].

From the above brief literature survey, the results of other authors (though relatively scarce) with respect to their researches on the influence of welding, particularly the SMAW process on the microstructural, mechanical and corrosion properties of DSSs weldment (AISI 2205 and AISI 2507 grades) were concisely analysed.

3 Conclusions

Having gone through some scientific research works from other researchers on general DSS (AISI 2205 and AISI 2507) in particular using various welding techniques but specific attention on SMAW, the following conclusions can be drawn: SMAW technique can be successfully used to fabricate DSS AISI 2205 and SDSS AISI 2507 when all relevant welding conditions are maintained during welding. Improper control of welding parameters to achieve a balanced ferrite-austenite phase during welding of DSS AISI 2205 and SDSS AISI 2507 structures can adversely affect its service application. Painstaking control of the ferrite content in the weldment of the steel structures can effectively promote better mechanical properties and excellent corrosion resistance of both DSSs (AISI 2205 and AISI 2507). The consequential effect on the precipitation quantum of $\sigma$ phase, and its subsequent influence on the hardenability of the two distinct plates of steel weldment could be engineered by heat treatment temperature. Adequate attention must be given to the weld cycle solidification to avoid the precipitation of the sigma phase in DSSs which is usually between 600°C-1000°C. ASTM standard electrodes for effective fabrication of AISI 2205 and AISI 2507 structures are E2209 and E2594 electrodes respectively due to their relatively similar compositions with the base metal chemistry. It was evident that microstructures have a great influence on the weldment of AISI 2205 and AISI 2507 in respects to their corrosion-resistant performance in chloride-containing environments. Low heat input is relatively recommendable for the fabrication of AISI 2507 owe to its insignificant influence on the weld integrity.

Funding and Acknowledgments

The great support received from the CSIR-TWAS funding in CSIR-National Metallurgical Laboratory, Jamshedpur is highly acknowledged (Award No.: 22/FF/CSIR-TWAS/2018). The authors also would like to thank Dr S. C. Ghosh, Dr A. Das and Mr Roshan from CSIR- National Metallurgical Laboratory, Jamshedpur for creating a smooth environment for the final draft of this review.

Compliance with ethical standards

The authors declare that there is no conflict of interest in the course of the review

References

1. Ghusoon R.M., et al., Effects of Heat Input on Microstructure, Corrosion and Mechanical Characteristics of Welded Austenitic and Duplex Stainless Steels: A Review. Metals 2017. 7(39); DOI: 10.3390/met7020039
2. Bain E.C. and W. E. Griffith, An introduction to the iron-chromium-nickel alloy. Trans. AIME. 75: p. 166-213.
3. Smuk O. (2004) Microstructure and Properties of Modern Powder Metallurgy of Super Duplex Stainless Steels. PhD thesis presented to the Department of Materials Science and Engineering, Division of Ceramics, Royal Institute of Technology, Stockholm, Sweden.
4. Lo K. H., et al., Recent developments in stainless steels. Materials Science Engineering. R. Rep. 2009. 65: p.39-104.
5. Bonollo F., et al., Welding processes, microstructural evolution and final properties of duplex and super duplex stainless steels. In Duplex Stainless Steels; John Wiley & Sons, Inc.: Hoboken, NJ, USA; 2013. p. 141–159.
6. Kisasoz A., et al., Effect of annealing time and cooling rate on precipitation processes in duplex corrosion-resistant steel. Metal Sci. Heat Treat, 2016.57. p.544–547.
7. Srikanth S., et al., Development of Lean Duplex Stainless Steels (LDSS) with Superior Mechanical and Corrosion Properties on Laboratory Scale. Adv. Mater. Res. 2013.794: p. 714–730.
8. Oshima T., et al., Efforts to save nickel in austenitic stainless steels. ISIJ Int. 2007.47: p. 359–64.
9. Malik A.U., et al., Relevance of corrosion research in the material selection for desalination plants. In: Proceeding of 2nd scientific symposium on maintenance planning and operations.1993. P. 885–900.
10. Boillot P. and J.Peultier, Use of stainless steels in the industry: recent and future developments. Procedia Engineering, 2014. 83: p. 309–321.
11. Charles J. and S.Bernhardson, Materials to meet your needs. In: Proceeding conference on duplex stainless steel 1991. p. 3–48.
12. Charles J., Why and where duplex stainless steels. In: Proceeding of 5th international conference on duplex stainless steel 97, stainless steel world. KCI Publishing, 1997. p. 29.
13. Charles J., A review after DSS '07”. In: Proceeding conference, stainless steel world, 2007
14. Olsson J, Snis M (2007) Duplex—a new generation of stainless steels for desalination plants. Desalination, 205: 104–13.
15. Olsson J. and H.Groth, A new approach to reduced costs. In: Proceeding IDA and WRPC world conference on desalination and water treatment, evaporators made of duplex stainless steel, 1993.
16. Olsson J. and K. Cosic, Stainless steels for SWRO plants high-pressure piping. In: Proceeding IDA world conference on desalination and water re-use, 2003.
17. Olsson J., et al., MSF chambers of solid duplex stainless steel. In: Proceeding IDA World conference on desalination and water re-use, 2003.
18. Peultier J., et al., New trends in selection of metallic material for desalination industry. In: Proceeding IDA world congress, 2009.
19. Charles J., Past, present and future of the duplex stainless steels. In: Proceeding of international conference and expo on duplex stainless steels, 2007.
20. Baldo S., Innovative steels for structural and corrosion resistance applications. PhD Thesis presented to the Department of Engineering’s Chemical Processes (DPCI), University of Padua, Italy, 2010.
21. Outokumpu Annual report 2015, (Accessed on 6th April 2020 from www.outokumpu.com//Outokumpu Annual report, 2015) pp. 1–116
22. What prospects for stainless steel in 2016? Stainless Steel World January/February magazine, (Accessed on 6th April 2020 from www.stainless-steelworld.net/pdf/What prospects for stainless steel in 2016.pdf) p. 1–5
23. The ferritic solution. International stainless steel forum published in April 2007.(Accessed on 6th April 2020 from www.worldstainless.org)
24. Yang Y., et al.,The effect of large heat input on the microstructure and corrosion behaviour of simulated heat-affected zone in 2205 duplex stainless steel. Corrosion Science, 2011.53:p.3756–3763.
25. Van-Nassau L., et al.,Welding duplex and super duplex stainless steel, Doc. IIW-1165, Welding in the World, 1999.31 (5): p. 323-343.
26. Jacques C. and B.Sven, Duplex Stainless Steels. Proceedings Conference Duplex Stainless Steels ’91, Beaune, France, 1991. www.tib.eu/en/search/id/TIBKAT%3A124397204/Duplex-stainless-steels-91-28-3Octoberre-1991-Beaune/
27. Nowacki J. and P. Rybicki, The influence of welding heat input on submerged arc welded duplex steel joints imperfection. Journal of Materials Processing Technology, 2005.164-165: p. 1082–1088.
28. Vashishtha H., et al., Welding behaviour of low nickel chrome-manganese stainless steel. ISInternational, 2014, 54: p. 1361–1367.
29. Taiwade R. V., et al., Studies on welding and sensitization of chrome manganese austenitic stainless steel. Trans Indian Inst Met. 2011, 64: p. 513–8.
30. Taiwade R. V., et al., Effect of welding passes on heat-affected zone and tensile properties of AISI 304 stainless steel and chrome-manganese austenitic stainless steel. ISIJ International, 2013, 53: p. 102–109.
31. Luo J., et al., Microstructure of 2205 duplex stainless steel joint in submerged arc welding post-welded heat treatment. Journal of Manufacturing Processes, 2014, 16(1): p. 144-148.
32. Davis R., et al., Shielded metal arc welding of UNS S32750 steel: Microstructure, Mechanical Properties and corrosion behaviour”. Materials Research Express, 2018, 5(10); IOP Publishing Ltd, DOI: 10.1088/2053-1591/aad99a
33. Verma J., et al., Microstructure, Mechanical and Intergranular Corrosion Behavior of Dissimilar DSS 2205 and ASS 316L. Shielded Metal Arc Welds. The Indian Institute of Metals, (IIM), 2016. DOI 10.1007/s12666-016-0878-8
34. Alsarraf J., Hydrogen Embrittlement Susceptibility of Super Duplex Stainless steel. PhD Thesis submitted to School of Applied Sciences, Cranfield University UK, 2010.
35. Urena A., et al., Weldability of a 2205 duplex stainless steel using plasma arc welding. Journal of Materials Processing Technology, 2007, 184: p. 624–631.
36. Zou N. D., et al., Deformation characteristic and prediction of flow stress for as-cast 21Cr economical duplex stainless steel under hot compression. Mater. Des., 2013, 51: p. 975–982.
37. Betchar K., et al., Microstructure and mechanical behaviour in dissimilar 13Cr2205 stainless steel welded pipes. Mater. Des., 2015, 85: p. 221–229.
38. Alvarez-Armas I. and S. Degallaix-Moreuil, Duplex Stainless Steels”. Published by ISTE Ltd. and John Wiley & Sons, 2009. P. 141-155.
39. Vinoth J. A., et al., Weldability, machinability and surfacing of commercial duplex Stainless Steel AISI 2205 for marine applications – A recent review. Journal of Advanced Research, 2017; DOI:10.1016/j.jare.2017.01.002
40. Sun Z., et al., Effect of dual torch technique on duplex stainless steel welds. Materials Science and Engineering, A, 2006, 356: p. 274–282.
41. Leone G. L. and H. W. Kerr, The ferrite to austenite transformation in stainless steels. Welding Journal, 1982, 61: p. 13s–22s.
42. Glownia J., et al., Delta ferrite predictions for cast duplex steels with high nitrogen content. Mater Charact, 2001, 47: p. 149–155.
43. Jayachitra R., et al., Characterization of duplex stainless steel heat-treated at 1300 °C.Int J Sci Res Publ., 2012, 2: p. 1–6.
44. Di X., et al., Microstructural evolution of transition zone of clad X70 with duplex. Mater Des., 2016, 95: p. 231–236.
45. Fourie J. W. and F.P.A. Robinson, Literature review on the influence of weld-heat inputs on the mechanical and corrosion properties of duplex stainless steels”. J S Afr Inst Min Metall, 1990, 90: p. 59–65.
46. Lipplold J. C. and D.J. Kotecki, Welding Metallurgy and Weldability of Stainless Steels. WileyHoboken. Interscience, New Jersey, 2005.
47. Sieurin H., Fracture toughness properties of duplex stainless steels. Dissertation. Royal Institute of Technology, 2006.
48. Sieurin H. and R. Sandstrom, Austenite Reformation in the Heat-Affected Zone of Duplex Stainless Steel 2205. Materials Science and Engineering, A, 2006, 418: p. 250–256.
49. Kacar R., Effect of solidification mode and morphology of microstructure on the hydrogen content of duplex stainless steel weld metal. Mater Des., 2004, 25: p. 1–9.
50. Wang S. H., et al., Gamma phase transformation in pulsed GTA weld metal of duplex stainless steel. Mater Sci Eng A, 2006, 420: p. 26–33.
51. Liu H. and X.Jin, Secondary austenite morphologies in fusion zone of welded joint after post-weld heat treatment with a continuous wave laser. J Mater Sci Technol., 2012, 28(3): p. 249–254.
52. Geng S., et al., Evolution of microstructure and corrosion behaviour on 2205 duplex stainless steel GTA-welding joint. J Manuf Process, 2015, 19: p. 32–37.
53. Nilsson J. O., et al., Secondary austenite formation and its relation to pitting corrosion in duplex stainless steel weld metal. Mater Sci Technol., 1995.11: p. 276–283.
54. Shinohara K., et al., Recrystallization and sigma phase formation as concurrent and interacting phenomena in 25%Cr-20%Ni steel. Materials Transactions, 1979.20(12): p. 713-723.
55. Baerlecken E. and H. Fabritius, Umwandlungskinetik der sigmaphase in einer Eisen-Chrom-Legierungsmischung 48% Chrom,’ Arch Eisenhüttenwes, 1995.26: p. 679-686.
56. Garz C. M. and A. J. Ramirez, Growth kinetics of secondary austenite in the welding microstructure of a UNS S32304 duplex stainless steel”. Acta Materialia, 2006.54(12): p. 3321-3331.
57. Goswami P. and R. Bapat, Duplex stainless steel: Metallurgy, engineering codes &welding practices Part 2. Stainless Steel World, 2014. p.1-5. www.stainless-steel-world.net.
58. Karlsson L., Welding duplex stainless steels—a review of current recommendations. Weld World, 2012.56: p. 65–76.
59. Verma J. and R. V.Taiwade, Effect of welding processes and conditions on the microstructure, mechanical properties and corrosion resistance of duplex stainless steel weldments—A review. Journal of Manufacturing Processes, 2017.25: p. 134–152 DOI: http://dx.doi.org/10.1016/j.jmapro.2016.11.003.
60. Messer B., et al., Duplex stainless steel welding: best practices. Fluor Canada, Stainless Steel World, 2007.
61. Badjia R., et al., Phase transformation and mechanical behaviour in annealed 2205 duplex stainless steel weld. Materials Characterization, 2008.59: p. 447-453.
62. Zucato I., et al., Microstructural characterization and the effect of phase transformations on toughness of the UNS 31803 duplex stainless steel aged treated at 850 °C. Mater Res., 2002.5(3): p. 385 –389.
63. Sato Y. S. and H. Kokawa, Preferential precipitation of sigma phase in duplex stainless steel welds metal. Scr Mater., 1999.24: p. 659 –663.
64. Mengjiao W., et al., Effect of Heat Treatment Temperature and Lubricating Conditions on the Fretting Wear Behavior of SAF 2507 Super Duplex Stainless Steel. Journal of Tribolog, Transactions of the ASME, 2019.141: p. 101601-101608.
65. Caliari I., et al., Influence of Isothermal Aging on Secondary Phases Precipitation and Toughness of a Duplex Stainless Steel SAF 2205. J. Mater. Sci., 2006.41(22): p. 7643 –7649.
66. Welding Product Programme: Duplex and Super Duplex stainless steel, Selectarc Welding. Accessed on 15th April, 2020 from www.fsh-welding.com.
67. Zhang W., et al., Modelling of ferrite formation in a duplex stainless steel weld considering non-uniform starting microstructure. Acta Mater., 2005.53: p. 4441 –453.
68. Lima M.S.F.et al.,Mechanical and Corrosion Properties of a Duplex Steel Welded using Micro-arc or Laser” Materials Research, 2015. 18(4): p. 723-731. DOI: http://dx.doi.org/10.1590/1516-1439.007115.
69. Belkessa B., et al., Microstructure and Mechanical Behavior in Dissimilar SAF 2205/API X52 Welded Pipes. Acta Metall. Sin. (Engl. Lett., 2016.29(7): p. 674–682. DOI 10.1007/s40195-016-0428-8.
70. EN 1011-3, Welding – Recommendations for welding of metallic materials, Part 3: Arc welding of stainless steels.
71. Kannan T. and N.Murugan, Effect of flux-cored arc welding process parameters on duplex stainless steel clad quality J Mater Process Technol., 2006.176: p. 230–239.
72. Nowacki J., Ferritic-austenitic steel and its weldability in large size constructions. J Achiev Mater Manuf Eng., 2009.32(2): p. 115–141.
73. Hsieh R. I., et al., Effects of cooling time and alloying elements on the microstructure of the gleeble-simulated heat-affected zone of 22% Cr duplex stainless Steel. J Mater Eng Perform, 2001.10(5): p. 526–536.
74. Norsok Standard M601, Welding and inspection of piping. Lysaker, Norway: Standards Norway-2004.
75. Asif M. M.,et al., Effects of post-weld heat treatment on friction welded duplex stainless steel joints. J Manufac Process, 2016.21: p. 196–200.
76. Giridharan P. K. and N. Murugan, Optimization of pulsed GTA welding process parameters for the welding of AISI 304L stainless steel sheets. Int J Adv Manuf Technol., 2009.40: p. 478–489.

77. Sadeghian M., et al., Effect of heat input on microstructure and mechanical properties of dissimilar joints between super duplex stainless steel and high strength low alloy steel”. Mater Des., 2014.60: p. 678–684.

78. Hertzman S., The influence of nitrogen on microstructure and properties of highly alloyed stainless steel welds. ISIJ Int., 2001.4 (6): p. 580–589.

79. Nilsson J. O., Overview: Super duplex stainless steels. Materials Science and Technology, 1992.8: p. 685-700

80. Kim K.Y., et al., Electrochemical and Stress Corrosion Properties of Duplex Stainless Steels Modified with Tungsten Addition. Corrosion., 1998.54(11): p. 910-921. DOI: 10.5006/1.3284810

81. Kudo T., et al., Stress Corrosion Cracking Resistance of 22%Cr Duplex Stainless Steel in Simulated Sour Environments. Corrosion., 1989.45(10): p. 831-838. DOI: 10.5006/1.3584990

82. Laitinen A. and H. Hänninen, Chloride-Induced Stress Corrosion Cracking of Powder Metallurgy Duplex Stainless Steels. Corrosion, 1996.52(4): p. 295-306. DOI: 10.5006/1.3293641

83. Miyasaka A., et al., Critical Stress for Stress Corrosion Cracking of Duplex Stainless Steel in Sour Environments. Corrosion., 1996.52(8): p. 592-599. DOI: 10.5006/1.3292149

84. Mark-Wilhelm S. and R. D. Kane, Effect of Heat Treatment and Microstructure on the Corrosion and SCC of Duplex Stainless Steels in H2S/Cl– Environments”. Corrosion, 1984.40(8): p. 431-439. DOI: 10.5006/1.3593951

85. Magnin T. and J. M. Lardon, Cyclic deformation mechanisms of a two-phase stainless steel in various environmental conditions. Materials Science and Engineering A, 1988.104: p. 21-28, DOI: 10.1016/0025-5416(88)90402-8

86. Van-Gelder K., et al., The stress corrosion cracking of duplex stainless steel in H2S/CO2/Cl– environments. Corrosion Science, 2000.42:p. 545-559. PII: S0010-938X (99) 00105-5

87. Bhattacharya A., Stress Corrosion Cracking of Duplex Stainless Steels in Caustic Solutions. A PhD Dissertation Submitted to the Academic Faculty, Georgia Institute of Technology Atlanta, U.S.A., 2008.

88. Bhattacharya A. and P. M. Singh, Role of microstructure on the corrosion susceptibility of UNSS32101 Duplex Stainless Steel. Corrosion, 2008.64(6): p. 532 540; DOI: 10.5006/1.3278489

89. Magnabosco R. and N.Alonso-Falleiros, Pit morphology and its relation to microstructure of 850 °C aged duplex stainless steel. Corrosion, 2005.61 (2): p. 130-136 DOI: 10.5006/1.3278167

90. Paranthaman V., et al., Analysis of structure property relationship of super duplex stainless steel AISI 2507 weldments for severe corrosive environments. Materials Research Express, 2018.5(9); DOI:https://doi.org/10.1088/2053-1591/aad585

91. Rousset N. B. S., et al., Role of surface finishing on pittingcorrosion of a duplex stainless steel in sea water. Journal of Materials Engineering and Performance, 1996.5(2): p. 225-231.

92. Yurtisik K., et al., Characterization of duplex stainless steel weld metals obtained by hybrid plasma-gas metal arc welding. Soldag. insp., 2013. 18(3) São Paulo July/Sept. 2013, Technical PapersArtigosTécnicosDOI: 10.1590/S0104-92242013000300003

93. Nilsson, J. O. and A. Wilson Influence of isothermal phase transformations on toughness and pitting corrosion of super duplex stainless steel SAF 2507. Materials Science and Technology, 1993.9: p. 545–554. DOI: 10.1179/mst.1993.9.7.545
96. Hu Y. and J. Xue, Effects of Process Parameters on the Weld Quality During Double-Pulsed Gas Metal Arc Welding of 2205 Duplex Stainless Steel. Transactions on Intelligent Welding Manufacturing, 2018. © Springer Nature Singapore Pte Ltd, https://doi.org/10.1007/s978-981-10-8350-3_7

97. Xie H., et al., Analysis of strong and weak pulse ratio on weld quality of AA6061 aluminium alloy double pulsed gas metal arc welding. Trans China Weld Inst., 2015.36 (12): p. 77–80

98. Taban E. and E. Kaluc, Welding Behaviour of Duplex and Super-Duplex Stainless Steels using Laser and Plasma Arc Welding Processes. Welding in the World Peer-reviewed Section, 2011.155(8): p. 48-57.

99. Forgas J. A., et al., Ferrite quantification methodologies for duplex stainless steel. Journal of Aerospace Technology and Management, 2016.8(3): p. 357–362. DOI: 10.5028/jatm.v8i3.653

100. Bermejo V. A. M., Predictive and measurement methods for delta ferrite determination in stainless steels. Weld J, 2012.91(4): p. 113-s to 121-s

101. Farrar M. C. J., The measurement of ferrite number (FN) in real weldments-Final Report. Weld in the World, 2005.49(5–6): p. 13–2. DOI: 10.1007/BF03263405.

102. Klug H. P. and L. E. Alexander, X-ray Diffraction Procedures for Polycrystalline and Amorphous Materials, 2nd edition, John Wiley & Sons Inc., New York, 1974.

103. Zhang M. and S. B. Zhang, Observation of the keyhole during plasma arc welding. Welding Research Supplement, 1999. p. 53-s-58-s.

104. Paulraj P. and R. Garg, Effect of welding parameters on pitting behaviour of GTAW of DSS and super DSS weldments. Engineering Science and Technology, an International Journal. Karabuk University. Publishing services by Elsevier B.V., 2016. DOI: 10.1016/j.estch.2016.01.013

105. Yuko D. K. and S. Wolynec, Evaluation of the corrosion-resistant phase formed during the sigma phase precipitation in duplex stainless steels, Materials Research, 1999.2: p. 239–247. DOI: 10.1590/S1516-14391999004000002

106. Yuan X., et al., Microstructure and XRD Analysis of Brazing Joint for Duplex Stainless Steel Using a Ni-Si-B Filler Metal. Material Characterization, 2009.60(9):923-931

107. McPherson NA, Li Y, Baker TN (2000) Microstructure and Properties of as Welded Duplex Stainless Steel. Science and Technology of Welding and Joining, 5(4): p. 235-244.

108. Luo J., et.al., Double-Sided Single-Pass Submerged Arc Welding for 2205 Duplex Stainless Steel. JMEPEG, 2013.22: p. 2477–2486. DOI: 10.1007/s11665-013-0529-8

109. Fonseca G. S., et al., Sigma Phase in Super duplex Stainless Steel: Formation, Kinetics and Microstructural Path. Materials Research, 2017.20 (1):249-255. DOI: 10.1590/1980-5373-MR-2016-0436

110. Sidhu G. S. and S. S. Chatha, Role of shielded metal arc welding consumables on pipe weld joint”. International Journal of Emerging Technology Advanced Engineering, 2012.2(12): p. 746-750.

111. Gunn R. N., Duplex Stainless Steels, Microstructure Properties and Applications, Abington Publishing, Cambridge, England, 1997.

112. Srinivasan P. B., et al., Microstructure and corrosion behaviour of shielded metal arc-welded dissimilar joints comprising duplex stainless steel and low alloy steel. Journal of Materials Engineering and Performance, 2006.15: p. 758-764. DOI: 10.1361/105994906X150902

113. Wang S., et al., Characterization of microstructure, mechanical properties and corrosion resistance of dissimilar welded joint between 2205 duplex stainless steel and 16MnR. Materials and Design, 2011.32: p. 831-837. DOI: 10.1016/j.matdes.2010.07.012

114. Practical guidelines for the fabrication of duplex stainless steel. 3rd Edition, IMOA 1999-2014, published by International Molybdenum Association (IMOA), London, UK. www.imoa.info

115. Standard Test Method for Tensile Testing of Metallic Materials. E8-04, ASTM, PA, USA, 2004. DOI:10.1520/E0008-04, www.astm.org

116. Standard Procedures for Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic and Duplex Ferritic-Austenitic Stainless Steel Weld Metal, AWS A4.2M (ISO 8249:2000 MOD), 2006.
118. Gupta A., et al., Effect of Heat Input on Microstructure and Corrosion Behavior of Duplex Stainless Steel Shielded Metal Arc Welds. The Indian Institute of Metals, 2018. https://doi.org/10.1007/s12666-018-1294-z

119. Hosseini V. A., et al., Ferrite content measurement in super duplex stainless steel welds”. Welding in the World, 2019.