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Research Article

Duplex Stainless Steel-2205; A short review of alloy addition and welding behavior

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Abstract

The present review paper consists of mainly two sections. Section one, mainly aims to review the effect of alloy addition on duplex stainless steel-2205 grade. While section second, reviewed the effect of different welding parameters of various welding processes on microstructure, mechanical properties and corrosion resistance of duplex stainless steel-2205 grade. Duplex steel mainly consists of ferrite and austenite. Duplex steel find wide uses in off shore application, due to its admirable mechanical properties and great corrosion resistance. The above properties of duplex steel can be improved by adding various alloying elements i.e. chromium, nitrogen, molybdenum, manganese, nitrogen, copper etc. Generally, the welding of duplex steel is not an easy task. Different welding process uses the thermal, chemical, mechanical and electrical phenomena for melting the duplex steel's faying surface. The effect of various welding inputs of different welding processes (submerged arc welding, Plasma arc welding, Electron beam welding, Laser beam welding, Tungsten inert gas welding and Friction stir welding) being used for welding of duplex steel are reviewed. Finally, a compressive study is made on effect of welding conditions on microstructure, mechanical properties and corrosion resistance of duplex stainless steel-2205 grade.

Keywords: *Duplex stainless steel (DSS), alloying element, wielding methods (SAW, PAW, EBW, LBW, TIG, FSW), welding parameters, mechanical properties, microstructure.*

Introduction-Generally, duplex stainless steel (DSS) contains more than of 30% of austenite and ferrite, and contains chromium (Cr) more than 19%. In modern DSS, austenite and ferrite are present in equal % in their microstructure. DSS shows higher tensile strength and greater resistance to corrosion as compared to other steels [1-3]. Nature of DSS is isotropic, due to presence of balance structure of ferrite and austenite. DSS shows maximum impact strength in longitudinal direction as compared to diagonal and transverse direction [4]. Microstructural variation in weld metal (WM) fusion zone and heat affected zone (HAZ) can be reported from fusion weld of DSS. It is reported that HAZ's microstructure is ferritic completely. A conversion of austenite generally occurs at the time of temp. decrement, during welding of DSS [5]. Mechanical properties of WM found to be decreased due to increase in corrosion exposure area. Which is the result of damage of ferritic and austenitic phase (due to welding thermal cycle) [6-7]. The increasing demand of DSS as compared to austenitic stainless steel (ASS) is due to change in price of Ni year on year [1,8].

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Due to the lower sustainability of ASS, DSS is now a days is preferred in many industries [9]. Due to half % of ferrite and austenite, DSS gives better performance in many corrosive environments [2-3]. Many industries like offshore, chemical industries, pulp and paper industries, disclination plants and petrochemical industries are now a days promoting the DSS [10-11]. DSS is having three times more ultimate tensile strength and yield strength as compared to austenitic grade like 316L, 304L. DSS, also offers economic profit without affecting the strength of weldments [12-13]. DSS, contains dual-phase microstructure i.e. ferrite and austenite [14-16]. The appropriate phase balance is the critical factor for improving the corrosion resistance and mechanical strength of DSS [17]. Maintain of ferrite to austenite balance during welding of DSS is suggested, which is disrupted at high temp [18]. The required phase balance in DSS after welding is retained by solution annealing. Generally, preheating of DSS is not advised, because it eases back the cooling of HAZ [19-20].

Historical Development of DSS-Stainless steel were developed in first decades of 20th century in Germany and United Kingdom. Martensitic and ferritic Fe-Cr steels were the earliest steel grade. But with respect to time, the austenitic Fe-Cr-Ni steels becomes the largest group of steel. Due to ease of welding, ease in production & fabrication, the growth of austenitic alloys becomes appreciable. The steels were sensitive to grain boundary carbide precipitation during welding and heat treatment process, due to value (near to 0.08%) of minimum carbon. Steels, also becomes more sensitive to intergranular corrosion attack [21]. Duplex alloy is one having two-phase structure and contains both phases in significant quantities. First reference to duplex alloy come in existence in 1927, from the publication of Bain and Griffith. Grade 435 E (25%Cr-5%Ni-1%Mo) came in existence in 1932-33. In 1933, a new grade of duplex steel (18%Cr-9%Ni-2.5%Mo) came in existence, which shows high volume fraction of ferrite in austenitic matrix. Also, the new grade was not sensitive to intergranular corrosion (IGC) in different media of corrosion [22]. In France, USA and Sweden in 1940, a new group of stainless steel, with addition of copper was marketed and patented. A research was further proceed for duplex alloy having low Ni content, which was encouraged by shortage of Ni during Korean war in 1950-51. It becomes clear that balance of ferrite and austenite has better resistance to stress corrosion cracking (SCC) as compared to fully austenitic microstructure. SCC is main advantage of DSS over austenitic stainless steel. UNS S32404 having 20-35% of ferrite, came in to existence in France. At the end of 1950, a new cast alloy UNS 93370 arise, having poor ductility and toughness. Ductility of this alloy was increased by lowering the Cr content. Grade S31500 may be called the 2nd generation of DSS and these are susceptible to IGC [21-22]. During late 1960,s and early 1970,s , the use and development of duplex alloy was advanced due to following factors-

1. Hike in austenitic alloy was reported due to shortage of Ni. Increase in production work in offshore industries, also demands a new SS grade which can response good in aggressive environmental conditions.
2. By the addition of argon oxygen decarburization (AOD) and vacuum oxygen decarburization (VOD) practices, the steel production techniques were improved. This further led to steels with low carbon, oxygen and sulphur contents. This also allows a greater control of composition especially for Ni [21-22].

In Sweden and Germany, the newly developed grade of DSS (UNS S31803 with 22%Cr) was developed in earlies of 1970, s. This newly developed grade of DSS contains a balance equivalent ratio of Cr/Ni and also not sensitive to IGC. To withstand the aggressive environment, a highly alloyed grade of DSS were developed in 1980, s, which contains 25% Cr, 6.7% Ni, 3-4% Mo, 0.2-0.3% N, 0.2%Cu and 0.2% W. Tungsten is added to improve pitting resistance. These newly developed grades were having pitting corrosion equivalent number (PRE_N) more than 40. In 1980, s a grade namely lean alloy steel (S 32304) was developed, which contains lower value of Mo [21].

Effect of Alloying Elements on DSS- Different alloying elements show particular effect on DSS, as described below

1. **Chromium-** The main advantage of addition of Cr is that it improves localized corrosion resistance by formation of a passive chromium-rich oxyhydroxide film. Addition of Cr stabilize the ferrite content. Addition of Cr after a certain limit may form detrimental intermetallic phases in DSS [23-25]. The Cr_{eq} for DSS is given by equation-
   Cr_{eq} = %Cr + % Mo +0.7% Nb (1)
2. **Molybdenum-** Mo increases the passive potential range and lower the corrosion current density in active range. 3 % Mo is preferred to prevent the crevice corrosion [21,26]. Higher value of Mo leads to, detrimental chi (χ) and sigma (σ). phase formation at high working temp [27].
3. **Nickel-**Ni in DSS acts as austenite stabilizer and its main role is to control element partioning and phase balance [25]. Ni addition primarily depends on the Cr content. Excessive amount of Ni will increase the austenite to 50%, results of which boost Mo and Cr in remaining ferrite. The higher value Ni, accelerates the formation of prime-α phase in ferrite, which further leads to embrittlement of material [27]. Ni_{eq} for DSS is given by-
   Ni_{eq}= %Ni + 35% C + 20% N + 0.25% Cu (2)
4. **Nitrogen-** It shows multiple effects on DSS i.e. increased pitting corrosion resistance, strength and austenite content. PRE_N of nitrogen for DSS is 16. Nitrogen acts as stabilizer and promote austenite reformation in DSS [21]. Nitrogen addition reduce Cr partitioning and stabilize the DSS against the precipitation of intermetallic phases [26-27]. Addition of nitrogen generally increase crevice corrosion resistance of DSS [28].
5. **Manganese-** For austenitic steel Mn acts as a stabilizer, while for DSS it shows mixed results. Mn increases the tensile strength, wear and abrasion resistance of DSS. There is no loss of ductility with addition of Mn [29]. Mn addition to DSS, increases the formation rate and temp. range of σ phase [30].
6. **Copper-** Addition of Cu in high alloy austenitic SS is preferred, because it reduces the rate of corrosion in non-oxidizing environments (like H_2SO_4). In DSS, addition of Cu is limited to 2 %, because high value of Cu reduces the hot ductility and tends to increase precipitation hardening [21,31].
7. **Tungsten-**Tungsten addition in DSS, improves its pitting resistance. W increases the crevice corrosion resistance of DSS in heated chloride solutions. In the temp. range of 700^{0}C-1000^{0}C, W encourages intermetallic formation. 1-3% value of W restricts the σ formation at phase boundaries. Addition of W makes rapid forming of χ phase [21].

8. **Silicon-** Si is used for enhancing the high temp. oxidation resistance. Si is found to be beneficial for concentrated nitric acid service. High value of Si (3.5-5.5%) in DSS prevents stress corrosion cracking and increase pitting resistance. General limit for Si is 1 % and it enhance σ formation [21].
9. **Titanium-** Addition of Ti in steel, stabilize the austenite, which further improve HAZ and corrosion resistance. 0.4% of Ti was added to steel to make it stabilize (reducing the intergranular corrosion frequency). Ti addition also join the grain boundaries and prevent the excessive growth of ferrite in HAZ [21].
10. **Carbon and Sulphur -** 0.02-0.03% of Carbon is limited for most of the DSS. This may stop the formation of Cr rich carbides (responsible for pitting corrosion and inter-granular attack). Similarly small amount of sulphur is required for weld bead penetration [21].

Corrosion behavior of duplex stainless steel- Cr, the main element of SS is mainly responsible for increase or decrease the corrosion resistance properties of SS. Final ratio of ferrite to austenite in WM is greatly affected by the base metal Cr variation [32]. During the investigation of effect of isothermal aging on DSS (UNS S31803), it may be concluded that regularly occurrence of σ phase precipitation may reduce the corrosion resistance of DSS [33]. Due to non-uniform thermal field and uneven heating and cooling during the welding, there is variation in microstructure of WM [7,34]. In welding of DSS, the corrosion resistance can be restored due to increase in Cr_2N (formed due to rapid cooling) dissolution, formation of austenite followed by post welded heat treatment (PWHT) in the temp. range of 1050^0C-1100^0 C [12,35]. Stress corrosion resistance (SCC) in WM of DSS is found to be varied directly with N_2 and SCC is inversely proportion to cooling rate [36].

Welding of Duplex Stainless Steel- DSS can be welded by various welding techniques. A brief review of different welding methods has been explained here.

1. Submerged Arc Welding (SAW)- Generally, SAW is used in industries for fabrication purpose, due to its versatile properties i.e. reliability, deeper penetration, and higher productivity. SAW process shield the both, liquid metal and unfused fluxes. For getting deeper penetration, welding current is main parameter, but too high value of current may result in burning of material [37]. SAW process can provide 90% thermal efficiency with minimum heat losses. SAW weldments are having low value of nitrogen and hydrogen elements, thus giving weldments of high ductility and high strength too [38]. During the welding of DSS, an arc of energy value greater than 2.3 KJ/mm and a temperature of more than 180^0C for inter-pass can be used. The above energy and temp. setting fulfilled all requirements of mechanical properties, microstructural properties and also of corrosion resistance. The no. of welding passes can be brought to half by using the higher value of arc energy and inter-pass temp., as recommended previously. Also, the above parameter setting can reduce the welding time to half as compared to gas metal arc welding (GMAW) process. Welding of lean DSS (UNS S32304) with cold wire shows that weld metal which is having higher heat input, generally shows higher corrosion resistance [39]. Also, welding with heat input more than 2.5 KJ/mm can produce adequate corrosion resistance. The σ phase precipitation disappears in the fusion zone (FZ) near to HAZ after PWHT. After, PWHT amount of gamma (γ) phase is lowered, while the quantity of σ and delta (δ) phase is increased. Two pick value (one in fusion zone and second in weld center zone) of microhardness appears without PWHT. After the PWHT, the maximum value of microhardness of fusion zone (near HAZ) got disappeared. While other pick value retains at its location [40]. It was found that heat input ranges of 2.5 to 4.0 KJ/mm does not have any negative effect on SAW of DSS. For the welding of 10-23 mm thick plates a value of heat input 3.0 KJ/mm is recommended because its reduces the joint's defects [41]. The quantity of reformed austenite in HAZ of DSS-2205 grade generally prevents the formation of σ phase. Ferrite content average increment occurs in weld metal at HAZ during inter-pass temp. of 150^0C [42].

2. Plasma Arc Welding- Plasma arc welding (PAW) is having more concentrated heat source, which makes it more suitable for welding of critical parts of aircrafts and automotive factories. PAW is less expensive and generally easy to use, which makes it more suitable for diaphragms manufacturing. In PAW a non-consumable tungsten electrode is used for producing plasma of very high velocity. An inert gas in PAW is used for molten pool's shielding [43]. For most of the austenite grains the WM microhardness is found to lower as compared to base metal (BM). The WM's pitting corrosion resistance is comparable to BM, which is due to the fine grain size and higher content of austenite [44]. Balancing of phase during the welding of DSS is main concern for all researcher. PAW provides WM having austenite content of 60% and having a well control over phase balance i.e. 40% ferrite. Grain boundary austenite (GBA) and intergranular austenite (IGA) are the two forms of austenite found in WM. While HAZ generally contains more widmanstatten austenite (WA). The transit region between center and HAZ contains grain of columnar ferrite. WM shows more hardness as compared to BM. The WM shows slight drop in tensile strength in longitudinal direction. WM elongation is 10% more than that of BM [45]. For PAW of DSS-2205 grade, good operative weldability can be achieved by using input energy range of 2500-3200 J/cm. Higher value of ratio of penetration to width, can be achieved due to high temp. range of PAW. Weld produced by using high energy value found to have increased value of ferrite content in FZ [46].

3. Electron Beam Welding- Electron Beam Welding (EBW) is a fusion welding process, having low heat input and high energy-density. In this process electron beam is the heat source, which is utilized to join the materials. The kinetic energy of accelerated beam of electron is converted in to heat for welding [47]. Low welding heat input promote, larger austenite content in weld zone as compared to high welding heat input. Aging at 1700^{0}C/h, the electron beam weld metal gives greater microhardness than BM. Tensile property of DSS-2205 grade was found unchanged during the EBW process. The weld metal shows lower impact strength due to presence of lower austenite as compared to annealed duplex alloy [48]. To reduce the ferrite content of WB and to elongate the cooling time DSS-2205 was welded by using multibeam in EBW process. Cooling time was increased between 1200^{0}C and 800^{0}C (austenite formation occurring range in DSS). Multibeam technology provides the weld of good quality [49]. A uniform weld structure for DSS was obtained by using rotating focused electron beam method. Weld obtained by this method almost contains the balance phase composition equal to BM [50].

4. Laser Beam Welding- Laser beam welding (LBW) uses a high energy density followed by a higher rate of cooling. Mechanical and corrosive properties of DSS-2205 are greatly influenced by the cooling rate [51]. Welding of DSS with LBW process, generally exhibits higher corrosion resistance as compared to gas tungsten arc welding (GTAW) process. The reason behind the higher corrosion resistance is the smaller FZ and HAZ [52]. For getting the welding joints of acceptable mechanical properties and FZ, a study is made on optimization of laser power, type of shielding environment, weld speed and defocusing distance. Higher weld depth/width ratio is obtained by using high welding speed and high power. Mechanical properties are not remarkably influenced by the heat input. Only elongation is found to be increased with the heat input. Use of nitrogen, instead of argon using same flow rate, has provided the improvement in mechanical properties and a decrease in corrosion rate has been noticed [53].

Plates of 4 mm thickness of DSS-2205 were butt welded using LBW method. Microhardness of WM was found to be increased in FZ and HAZ. The obtained WM is having ductility lesser than the BM, while strength of WM is found to be more than BM [54]. During the welding of 8 mm thick plates of DSS-2205, it was found that focusing position is main parameter for achieving good quality weld. Fast heat dissipitation increase the WM ferrite content and also lower the corrosion resistance of WM. Maintaining the balance ratio of ferrite and austenite is the main issue in welding of DSS [55]. Welding of DSS-2205 grade was performed using CO_2 laser. A study on mechanical properties and microstructure reveal that mechanical properties of WM are in acceptable range, while ferrite phase significantly affected the final microstructure of WM (due to low heat input) [56]. Pitting corrosion resistance of DSS can be controlled by controlling the secondary austenitic microstructure. As during welding, precipitation changes the austenite to ferrite ratio [57].

5. Tungsten Inert Gas Welding- Now a days Tungsten Inert Gas (TIG) welding has become the most popular method of welding for stainless steel (SS), aluminum alloys and titanium alloys. TIG is generally a cheaper process which offer good weld bead surface and weld joint of high quality. In TIG, an arc is generated between tungsten electrode (non-consumable) and w/p followed by the shielding of inert gas [58-60]. Mechanical properties and microstructure of WM is being altered with increased heat input [61]. WM strength is found to be depend on HAZ of WM [62]. A significant increase in penetration capability is obtained by using SiO_2, MoO_3 and Cr_2O_3 flux for welding of DSS-2205. A reduction in angular distortion is obtained during the process. A increase in joint penetration and depth to width ratio has been noticed while using the above fluxes. Also, a significant increase in mechanical strength has been noticed [63]. To overcome the problem of lesser penetration and less dilution, the use of activated flux is recommended which produce extra heat energy with same process parameters. Oxygen of activated flux plays main role in voids formation and hot cracking of WM. Also, a considerable change in surface tension of weld pool has been noticed while using oxide-based fluxes [64]. Weld defects in K-TIG of DSS can be completely avoided by using appropriate welding parameters. Increase in heat input results in increased content of WA and a decrease in fine grained intergranular austenite (IGA). Enhancing the heat input generally increase the corrosion rate of WM [65]. DSS-2205 plate of 8 mm thickness were welded by using K-TIG method and finite element method (FEM) was used for simulation. Results of welding simulation shows that combined generally consist of ellipsoid heat source and conical heat source is found to be more suitable for K-TIG. A decrease in grain size of austenite and ferrite was observed with the increase of welding speed from 280 mm/min. to 340 mm/min [66]. Effect of optimal oxide fluxes on corrosion behavior, mechanical properties and structure of 6 mm thick plate of DSS-2205 for ATIG (active TIG) has been investigated. 76% SiO_2-24% ZnO is optimal flux composition giving depth ratio 2.9 times greater than TIG. Obtained weld bead from ATIG can bear more sudden load as compared to TIG. Ultimate tensile strength (UTS) is found to be more (810 MPa) as compare to TIG (having UTS of 766 MPa) and it is near to UTS of BM (825 MPa). However, a decrease in corrosion resistance property has been reported while using ATIG as compare to TIG [67].

6. Friction Stir Welding- Friction Stir Welding (FSW) uses a non-consumable electrode to join the w/p. Heat between the tool and w/p is generated by the friction [51]. FSW is getting attention because of its capability to overcome the problems i.e. solid inclusions, wide range of HAZ, large distortion and porosity [68]. FSW was carried out for butt welding of 6.5 mm thick plates of DSS-2205. The WM microstructure generally consists of alpha (α) and γ phase with grain refining. The optimal groove design makes tool life longer. The WM shows 65% more yield strength, 33% more UTS and 54% more elongation as compared to BM [69]. Grain size of α and γ phase in the stir zone (SZ) of WM, was found to be decreases with the increase in welding speed. Increase in welding speed generally improves the tensile strength and mean hardness of SZ [70]. Welding of DSS by using FSW method may avoid segregation of alloying element, solidification cracks and liquation. FSW, with full penetration, of 6 mm DSS indicates improvement in strength of weld joints and increase the tensile and yield strength of WM. A grain size of 1μm with outstanding grain refinement can be easily obtained by FSW [71]. Welding condition shows a significant effect on the mechanical property and microstructure of lean DSS. Grain size of α and γ phase and peak temp. found to be decreased, with the increase of welding speed. Increased welding speed generally improve the tensile strength and hardness value of SZ [72]. The result of FSW for DSS-2205 at a welding speed of 50 mm/min. and at a rotational speed of 400 rpm shows that grain refinement generally takes place. Furthermore, in SZ simple shear texture was developed in each phase of ferrite and austenite [73]. By the results of remelting and solidification of metal during welding process, the austenite and ferrite ratio got changed and increase in ferrite formation of WM was noticed. This further causes a down fall in corrosion resistance and mechanical property in HAZ [74].

Conclusions- The first part of conclusion consist of review of adding different alloying elements on DSS-2205 grade. The following points may be concluded-

- Cr tends to increase the localized corrosion resistance and also stabilize the DSS ferrite content.
- 3 % Mo addition is preferred to prevent crevice corrosion in DSS.
- Ni addition in DSS acts as austenite stabilizer, its higher value may lead to m/l embrittlement.
- N addition in DSS increases its strength and promote austenite reformation.
- Addition of Mn to DSS helps in increasing its tensile strength and wear resistance with no loss to ductility.
- In non-oxidizing environment the corrosion rate can be reduced by adding the Cu.

The second part of conclusion reviewed the effect of different welding conditions of various welding method on the microstructure, mechanical properties and corrosion resistance of DSS-2205 grade. The following points may be concluded-

- While welding the DSS-2205, the selection of welding parameter should be done in such away that it should not affect the ferrite and austenite ratio.
- In SAW, after PWHT, σ and α phases are increased, while a decrease in γ phase has been noticed. At HAZ, max. microhardness gets diminished.
- High penetration to width ration and smaller HAZ are the main advantage of PAW.
- WM of EBW shows balance phase composition equal to BM. Multi beam welding process reduces the ferrite content of WM.
- In LBW, the high energy density affects the WM corrosive and mechanical properties. Shielding of nitrogen gives better mechanical and corrosion properties as compared to argon shielding.
- In TIG, increased heat input may alter the WM microstructure and mechanical properties. High welding speed may result in poor microstructure of weld joints.
- Weld produced by FSW shows more value of UTS, yield strength, % elongation as compared to BM. Welding conditions shows a significant effect on WM mechanical properties.

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