Recent Trends in Weldability and Corrosion Behavior of Low Nickel Stainless Steels

Prashant Kumar Pandey, Rajeev Rathi, and Jagesvar Verma

Abstract The current nickel supply deficit and continuous change in its expense brought about getting the consideration of researchers to prompt different options of stainless steel which contains less measure of nickel as its alloying component. Among the different existing stainless steel (SS) grades, austenitic stainless steels (ASS) are used in roughly 60–70% of utilizations, however, ASS requires nickel as its major subsequent. One of the better choices to supplant austenitic stainless steel is ferritic grades, which contain less nickel and have fundamentally the same as execution at a generally lower cost. The current examination is an endeavor to feature the different welding methods (fusion/solid-state) which used most, for joining of these ferritic stainless steel (FSS) grades. The literature affirms that because of the metallurgical issues related to fusion welding processes, solid-state joining processes such as forge welding, pressure welding, ultrasonic welding, and friction stir welding (FSW) are advised to be used for joining of ferritic stainless steels depending their suitability. Moreover, the choice of an appropriate welding process for a particular stainless steel grade is also governed by the corrosion-related aspects, and to reduce the adverse effects of corrosion post welding it is recommended to use pre weld and post-weld heat treatment processes.

Keywords Low Ni SS · FSS · Duplex stainless steel · Welding processes · Corrosion behavior

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1 Introduction

In the interest of their excellent corrosion resistance, good mechanical properties at elevated temperature, and better weldability, austenitic stainless steel have traditionally been the most widely used grade for different industrial applications [1]. The major constituents of austenitic stainless steels are chromium (Cr) and nickel (Ni). These alloying elements strengthen the resistance to corrosion, the sustainability of steels at higher temperatures, and other properties. Furthermore, Ni-based stainless steels are more scratch-safe, attributable to their natural work solidifying properties. However, the issues associated with nickel availability and its cost variation allows the development of other alternate grades. Figure 1 displays the fluctuation in Nickel's price for the past two years on the London Metal Exchange. It can be easily seen that at the end of 2018 the price was minimum (close to USD 10,400 per tonne) during this period, while it reached a maximum peak to nearly USD 18,500 per tonne in mid of 2019.

Among the other alternatives available for austenitic stainless steel, ferritic stainless steels are well known for their excellent resistance against stress corrosion cracking resistance, oxidation at high temperature, pitting, and crevice corrosion in chloride environments [2]. Besides, less expansion and contraction due to temperature change, exceptional confrontation against oxidation at elevated temperature, and stress corrosion cracking enhance the application of ferritic stainless steels in various industries mainly covering the automobile sector (exhaust pipes, catalytic converters, mufflers, tailpipes, etc.), the petrochemical sector (refineries), food processing,

Fig. 1 Historical price graph of Ni for the past two years (London metal exchange)

brewery and wine-making equipment [3]. Reduction in the concentration of interstitial elements such as carbon and nitrogen with the addition of stabilizing elements like molybdenum, titanium, niobium, and others enhances the resistance against corrosion/erosion and it helps ferritic stainless steel grades to be even better than most of the austenitic stainless steel grades [4]. Duplex stainless steel comprised of ferrite and austenite is again one of the alternatives that display its strength and corrosion resistance in numerous aggressive environments. Based on the outstanding performance of these grades of SS, it has been brought to the notice of researchers, manufacturers, and end-users over the past 20 years since development.

Further attention is needed to identify better techniques for joining these materials either similar or dissimilar [5]. These steels can be effortlessly joined by fusion welding processes, while studies show that the heat generated during fusion welding processes leads to coarsening of grains as rapid cooling yields the solidification of molten metal to ferrite phase without any intermediate phase transformation. Thus, the conventional liquid-solid welding processes such as fusion welding decreases the useful mechanical properties such as ductility, impact strength, and corrosion resistance [6].

2 Literature Review

2.1 Literature Search Methodology

This paper involves a unified approach to present innumerable research works done on the joining of similar or dissimilar stainless steel joints with fusion and solid-state welding processes. The literature of the past 10 years is collected (Fig. 2) and an effort

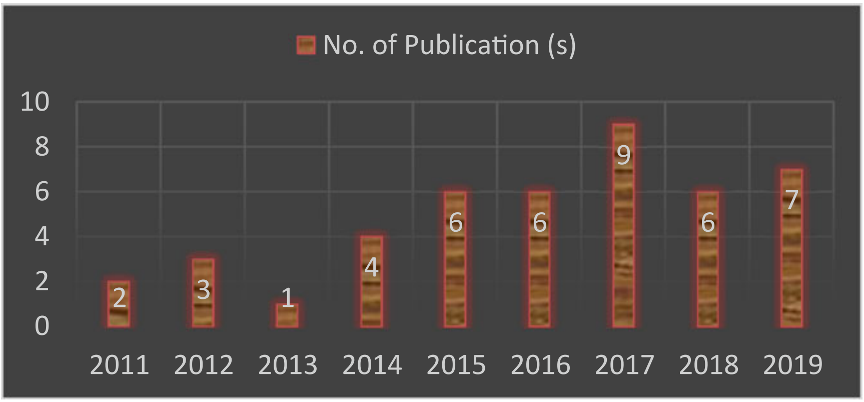

Fig. 2 Number of publication (s) considered for literature (year wise)

has been made to identify the recent advancement in welding of low nickel-based stainless steel.

2.2 Weldability of Low Ni-based SS

Among the various solid-state welding processes, friction stir welding proved to be a successful welding process to develop defects free weld of FSS grade 409 utilizing a polycrystalline cubic boron nitride (PCBN) tool. The microstructure analysis displayed a fine-grained disseminated stir zone (SZ). Further, investigation reveals a considerable rise in the existence of the low-angle grain boundary in SZ when compared with a base metal (BM). It has also been detected that increasing the plunging depth decreases the size of the grain and improves hardness [7]. Keeping the friction stir welding tool rotational speed constant and the welding speed as a variable, various tests comprising optical microscopy, electron back-scattered diffraction (EBSD), scanning electron microscopy (SEM), impact test as well as hardness test indicate that the mechanical and microstructure properties of FSS exhibit a substantial change after welding. The major effect is observed on the low-angle grain boundary which increases as a result of fine-grained equiaxed ferrite [8]. Salemi Golezani et al. [9] used a heavy-duty NC machine to perform FSW for joining FSS grade A430 sheets with thickness measures as 2 mm. They studied the impact of traverse and rotating speed of tungsten carbide tools on mechanical and microstructural properties. The use of a brass chamber assisted with water cooling avoids the wear and damage of the tool. Also, protection applied with argon gas provides shielding to counter tool oxidation at elevated temperature. Varying rotational speed and welding speeds were selected. Results disclosed that increasing the welding speed at constant rotational speed decreases ferrite grain size, which verifies active recrystallization existence in the nugget zone. Mehmet et al. [10] analyzed the effects of the various speed of FSW tools including traverse and rotational speed of ferritic stainless steel grade 430. Two samples of grade A430 of the same thickness as 3 mm were butt welded with friction stir welding. It was detected that the greatest values of mechanical properties were attained at a tool traverse speed of 125 mm/min and rotational speed of 1120 /min (Fig. 3). While the tool angle should be kept as 0^0 and a continual pressure force of 3.5 kN needs to be applied.

The rapid cooling done on FSS after its friction stir welding transforms the ferrite grains from coarse to the fine structure since rapid cooling in addition to frictional stirring initiates severe plastic deformation which further develops a high strain. The fine grains allow the joint to exhibit good impact strength/toughness and ductility as well [11, 12].

Laser beam welding (LBW) is also a useful technique to join FSS sheets and to prepare similar/dissimilar joints. With the increase in welding speed, the heat-affected zone (HAZ) becomes narrower and simultaneously the hardness moves up on the higher side. The varying welding speed does not produce any major change in tensile strength, but at a higher welding speed, greater elongation is achieved [13,

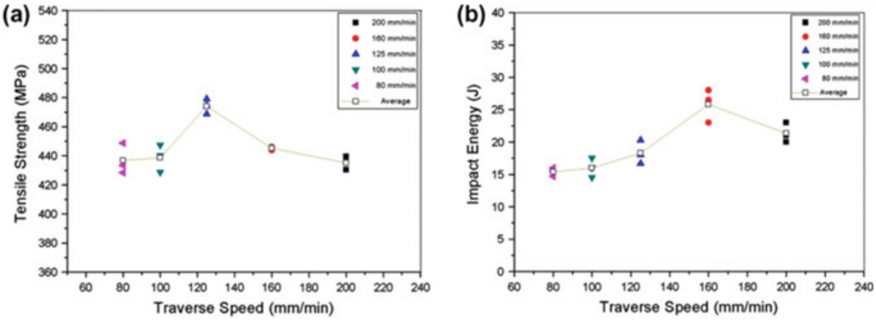

Fig. 3 Effect of tool traverse speed on **a** Tensile strength and, **b** Impact energy [10]

14]. The test results show that the rapid solidification of laser beam welded FSS joints of grade 409 M, reflects excellent bending strength and toughness due to the formation of dendritic grains from the coarse ferrite grains of base metal [15–17].

Once comparing the tensile strength of two different ferritic stainless steel grades, i.e., 444 and 429L, butt welded with the help of gas metal arc welding (GMAW), it has been found that 429L has more tensile strength [18]. Mukherjee et al. [19] experimentally investigated the process response and the microstructure of dissimilar joints made of low Ni ASS grade and 409 M FSS grade. Elemental mapping indicated that the material flow strategy during FSW relies upon the blend of the adopted procedure parameters. Dynamic recrystallization and recuperation are additionally seen in particular dissimilar joints. The FSS displays increasingly serious powerful recrystallization, bringing about an extremely fine microstructure, likely because of the higher stacking energy among the two distinctive grades of steel selected in the present investigation. Gas tungsten arc welding is a versatile process that is frequently used for industrial purposes [20–22]. The FSS grades can also be easily welded by GTAW/TIG and demonstrate better weldability aspects, while the precipitation of carbide and martensite formation is the major issues experienced with this welding technique. These issues should be controlled to hinder unaccepted grain growth in HAZ. It has been found that the intensity of the heat input selected during this welding technique leaves a great effect on grain growth [23– 25]. Narrow HAZ, an increase in microhardness and grain refinement with additional equiaxed crystals can be achieved by adding nitrogen gas in argon-based shielding gas provided with a double layer shielding since nitrogen gets dissolved into the weld pool. Due to microstructure refinement takes the toughness of the welded FSS joint also increases significantly. It has also been observed that the ductile fracture region normally developed very near to the surface of the weld [26, 27]. The pulse mode used for metal transfer enhances the mechanical resistance and metallurgical properties of FSS. This could be attained as this metal transfer mode expressively modifies the composition of the weld metal as compared to spray mode. In spray mode of metal transfer, the stability of the austenite phase gets promoted and at variable heat inputs, the grain structure features considerable enhancement. Pulse mode upgrades hardness as well as impact toughness of weld metal as compared to spray mode at any given heat input [28].

The relationship derived for the resistance spot welding process and microstructure changes on ferritic stainless steel grade 430 show that numerous parameters like the formation of martensite, carbide precipitates at the grain boundary, and grain growth significantly affect the microstructure of heat-affected zone (HAZ) and fusion zone (FZ). It is worth noted that due to the above facts there is an adverse effect on mechanical properties [29, 30]. Bansod et al. [31] investigated the microstructure of FSS joints (similar/dissimilar) using SEM, XRD, and optical microscopy methods and found that in dissimilar joint (when FSS welded with low carbon steel) Widmanstatten ferrite is formed very near to HAZ. With an increase in welding speed, the hardness of the welded zone is improved and at the same time, the HAZ becomes narrower. Varying welding speed does not have any effect on the ultimate strength of the joint but an improved elongation is attained at a higher speed. The test result of corrosion analysis reveals that dissimilar joint possesses better corrosion resistance which is mainly due to the presence of galvanic corrosion. FSS with low Ni percentage displays good strength and better stress corrosion resistance in various corrosive environments [32]. Experimental results show that HAZ of FSS grade 444 welded with electrode E309MoL-16 (AWS) exhibits considerable grain growth as compared to the base metal. Very fine precipitates of needle-shaped were detected in the partly molten zone which can be judged as Laves phase. Also, finely dispersed precipitates were observed in HAZ and this is due to the weld thermal cycle. The X-ray diffraction (XRD) study established the availability of few carbonitrides and chromium nitrides as well as certain secondary phases like chi and sigma [33]. Figure 4 illustrates some of the major constitution diagrams such as Schaeffler, Delong, and WRC-1992 which are useful to predict the microstructure of when dissimilar metal joining is done. However, for stainless steel with higher nitrogen content, the Schaeffler diagram has not been accounted. In this situation, the WRC-92 gives the result that is nearer to reality than those attained using Delong.

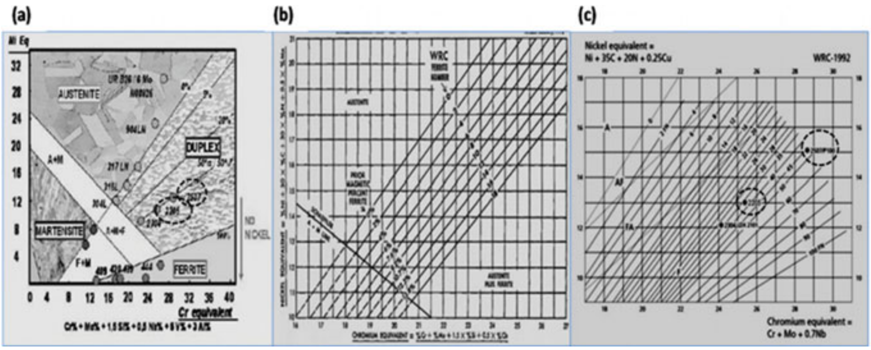

Fig. 4 Constitution diagrams for dissimilar metal joining to predict the weld microstructure **a** Schaeffler, **b** Delong, **c** WRC-1992 [5]

2.3 Corrosion Behavior

Wenyong et al. [34] deliberated the pitting corrosion behavior of FSS grade 444 with the help of electrochemical methods comprising cyclic potentiodynamic polarization, chronoamperometry, and immersion tests besides test to identify corrosion extents. An attempt was made to observe preceding and succeeding corrosion tests, utilizing the scanning electron microscopy (SEM) technique which displays indistinguishable corrosion behavior in all the corroded environments (solutions) subjected to allow the samples for only one minute into the solutions. It is also to be noted that 444 shows improved corrosion confrontation in chloride environments. While in sulphuric acid, it has additional corrosion pits. Khattak et al. [35] analyzed the effect of weld metal interaction on the predisposition of 444 FSS weldment to SCC in hot chloride, by continuous load tests and metallographic investigation. To develop weld joints with unlike chemical configurations in fusion zones, two different filler metals E316L and E309L (both are from austenitic stainless steel domain) were used. The SCC test outcomes revealed the susceptibility of the interface among the FZ and the HAZ. The investigation carried out to find the effect of chloride impurity level and the corrosion mechanism on the susceptibility of FSS and ASS suggests that FSS experiences a substantial mass gain due to the formation of a thick as well as non-protective oxide scale. Furthermore, ASS shows greater resistance to corrosion in high and low chloride salts [36–39].

2.4 Pre Weld Heat Treatment

The analysis was done to examine the effect of annealing on corrosion behavior of FSS and found that annealing may not be able to improve the resistance against crevice corrosion and pitting but it does advance the weldability of the material by hindering carbide precipitations [40–42]. The surface grinding operations are done on FSS to improve the corrosion resistance of the material. These operations hinder the corrosion process at grain boundaries which are located just under the surface layer and also discourage the progression of microcracks when the material is exposed to high loads [43, 44].

3 Discussion of Study

The corrosion-resistant and high-quality materials costs are growing day by day and with this fact, the ferritic steel is a decent option for the utilization in the chloride condition and numerous uranium improvement plants. In these applications welding is the primary procedure for the development of designing structures that debase their properties. In this way, unique consideration is required for the improvement of mechanical properties of FSS during welding which has still a few issues. The use of numerous arc welding processes (like GMAW, SAW, SMAW, etc.) responds in the formation of undesirable precipitates, grain morphologies, and development of residual stresses. While it is shown in earlier works that low-energy welding processes can be preferred but with these, there is an issue of incomplete penetration. In terms of grain refining, intergranular oxidation, and fragility, numerous studies have been conducted on the welding of FSS. Because of these variations, the microstructure and mechanical properties are greatly affected. Among the existing fusion welding processes, GTAW/TIG welding is best suitable to be used for joining of these low Ni stainless steels as this process confirms better weldability as compared to others. Friction stir welding is recommended to be used as a joining technique of various grades of FSS with the thickness of these plates/sheets to be on the lower side. The process parameters should be accurately selected and monitored during the welding. The rapid cooling renovates the ferrite grains from coarse to the fine structure. During the FSW process, argon gas shielding helps to counter tool oxidation at elevated temperatures. Besides, the use of a brass chamber assisted with water cooling avoids the wear and damage of the tool. The literature also illustrates that while performing Laser beam welding (LBW) to join FSS sheets/plates the welding speed should be kept at moderate since it narrows the HAZ is also a useful technique to join FSS sheets and to prepare similar/dissimilar joints. With the increase in welding speed, the heat-affected zone (HAZ) becomes narrower and simultaneously the hardness moves up on the higher side. The research work which is done so far on the corrosion behavior of FSS demonstrates that this steel encompasses better corrosion resistance as compared to most of the current ASS grades. The experimental results for dissimilar weld joints of AISI 304 and AISI 4104 prepared by various welding processes have been summarized in Table 1. It has been observed that the heat affect zone (HAZ) in the GTAW joint is primarily due to the high heat input and low welding speed used during this process. However, the lower heat input and higher welding speed in the case of electron beam welding (EBW) causes the size of the fusion pool to be small and faster cooling rate. As the HAZ is absent in EBW joints that results in better tensile strength. The application of high heat input in GTAW induces the micro-segregation of alloying elements and the formation of chromium depleted zones results in lowering the mechanical properties [45–47].

Table 1 The cumulative mechanical properties of FSS and ASS dissimilar weld joints by FSW, EBW, and TIG [45]

Welding process	Max hardness as weld (HV)	Yield strength (MPa)	%Elongation
Friction welding	305	485.2	18.15
Electron beam welding	400	681	31.97
TIG welding	400	634.5	24.96

4 Conclusion

An attempt has been made to identify welding processes which are suited for joining low Ni SS grades and to study the corrosion behavior of these stainless steel grades in the various corrosive environment. There are various fusion welding processes available that can be utilized for welding of these stainless steel grades, but literature confirms that GTAW/TIG is best suited among those. While using FSW (a solid-state welding process) it is recommended to select appropriate (higher side) plunging depth, as it decreases the grain size and thus improves hardness. Post welding the mechanical and microstructure properties of these grades exhibit an extensive change. Fine-grained equiaxed ferrite contributed to increasing the low-angle grain boundary. The use of an appropriate shielding method (argon gas shielding) helps in getting better weld beads even at higher temperatures.

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