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A Concise Review on Welding Defect Analysis and Remedial Measures of Austenitic Stainless Steel

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Abstract

An industrially viable and commercially available material known for its toughness, magnetic properties, strength, thermal stability and other physical properties which can be made use of in large scale applications is Austenitic Stainless Steel (ASS). Among the top five grades of stainless steel, austenitic stainless steel has exceptional abilities of thermal stability at elevated temperatures and excellent corrosion resistance. Its strength cannot be surpassed at such conditions when compared to the other grades. However, this strength poses challenges to its use in welding. But austenitic stainless steel can withstand welding variations in standard conditions. It poses penetration challenges when suitable solid-state or fusion based welding methods are applied due to its incredible strength and toughness. However, austenitic stainless-steel responds with good compound effects with fusion welding, especially Gas Metal Arc Welding (GMAW). With the variation of temperature, pressure, shielding gas composition used in the weld, environment, and the properties are enhanced. However, mild or large deformations and disruptions in the surface also arise. Variations and the different technological advances at different conditions can also be seen. In this review, it is focused on the response of austenitic stainless-steel variants of different grades to two types of fusion welding processes, which include GMAW and Laser Beam Welding (LBW). The microstructure, tensile strength, bead profile, penetration ability, detainments of corrosion resistance at high temperatures and the fixed durability of the weld at varying conditions are studied.

Keywords

Fusion welding, Weldability, Gas metal arc welding, Laser beam welding, Mechanical properties

Introduction

A brief on austenitic stainless steel

ASS is a type of stainless steel that belongs to the 200 and 300 series. Being cost-efficient and improved properties, these materials have many long-term applications. ASS grades have a high percentage of Cr and Ni so they could offer high corrosion resistance. It plays a major role in industrial and day-to-day applications and thus contributes to the economy of a nation. The main reason for its wide range of applications is because of its high-temperature resistance and can work in any environment. These alloys have excellent microstructural and mechanical properties [1]. A lot of research has been done into optimizing the weld parameters to create defect-free welds and also about the weldability issues in these types of stainless steel. Different grades of austenitic stainless steel were prone to different defects such as solidification cracking, bead quality issue, crevice corrosion, intergranular corrosion, and hot cracking. Austenitic stainless steels are one of the most widely used materials in large volumes among the major five types of stainless steel. The properties of ASS were helpful for intensive welding purposes. High ductility, durability, and high corrosion resistance are some of the highly appreciated properties of ASS. However, during major welding processes, it poses some unfavorable challenges [2].

Fusion-based welding processes

One of the most easily weldable steels in the steel family is ASS [3]. The main areas of focus involve the prevention of hot cracking and the resurrection of the physical and mechanical properties like corrosion resistance even once the welding process is done. Many authors try to understand the response of ASS when it is subjected to different types of fusion welding processes. Comparisons were made between GMAW and LBW by the authors. In this paper, the authors review various types of fusion welding done on ASS and which type of welding provided the best results in the conclusion.

Apart from different fusion welding of ASS, authors mainly focus on variants of GMAW and LBW. In the GMAW process, an electric arc between the electrode and the base metal to create the weld joint, whereas in LBW a laser beam is used to create a heated arc to produce a weld joint. Even though having several similarities the difference between these two methods is the main source that produces the arc which is a laser for the LBW process and electricity for the GMAW process. These processes are reviewed to provide efficient welding joints for various applications.

Application of Austenitic Stainless Steel

With the ability to be easily welded into large scale industrial applications, several grades of ASS find themselves in the food, paper pulp, medical, pharmaceutical, automotive, and chemical industries which is shown in figure 1. The stable properties are exploited for running these applications. Figure 2 shows some of the important properties of ASS.

Effects of Gas Metal Arc Welding Variants in Austenitic Stainless Steel

GMAW technique offers a greater deposition rate and full penetration when compared with gas Tungsten arc welding [4-7], but because of the increased heat input, this does

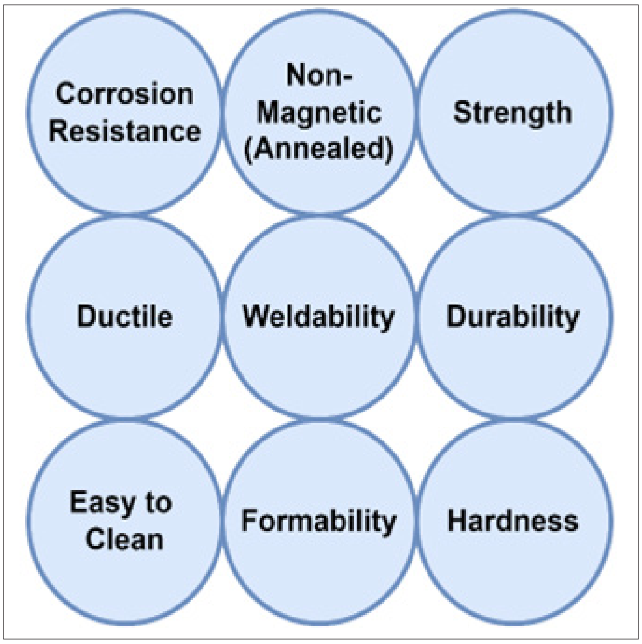

Figure 2: Elementary properties of austenitic stainless-steel.

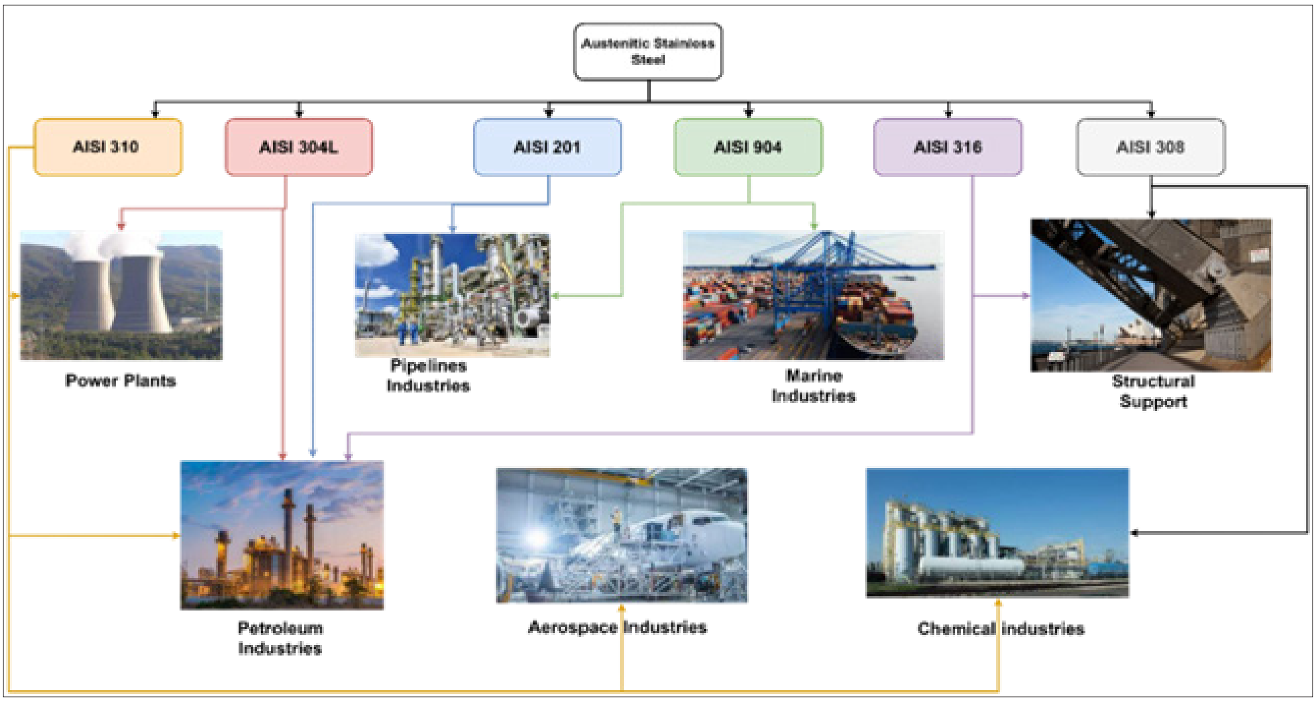

Figure 1: Applications of stainless steel.

not increase the strength of the weldment. While a distinct variation of GMAW, such as the SP-GMAW approach, produces better outcomes since pulsed current is used rather than continuous current. This pulsed current increases the welding speed while lowering spatter, increasing penetration, increasing deposition rates, and decreasing the amount of heat delivered. Sathiya et al. [8] analyzed on the bead geometry, microstructure, and mechanical properties of AISI 904 L Super ASS joint by CO_2 Gas laser–GMAW advanced welding process and determined that the following combination 50% He + 45% Ar + 5% O_2 presented finer refinement and 36% increase in toughness. Finer effects could be drawn from gas combinations at precise compositions.

Singh et al. [9] examined the mechanical property and microstructure of AISI 201LN ASS when welded using GMAW process using ER308L wire spool and assessed that welded joint had higher tensile strength and hardness. Also, the microstructure displayed finer morphology in the HAZ region at lower heat input. Saha et al. [10] conducted an experiment to fabricate AISI 316 ASS weld beads on low alloy steel (E350) by GMAW process. This experiment was successful as it produced uniform, continuous weld beads with a negligible number of spatters. Authors found that the weld bead had low reinforcement and penetration for higher heat input. In some cases, it may be favorable for cladding due to its low dilution. Tasalloti et al. [11] inspected the effect of dissimilar welding wires and the techniques on the quality of microstructure and microhardness of scale weld joints between AISI 304L ASS and S355MC low alloy steel. Weaving had increased penetration on AISI 304 L and decreased penetration in S355MC and this change was due to the lower heat conductivity properties of ASS. In conclusion, the microstructure was found to be consistent using the Schaeffler diagram and microhardness a sharp increase was observed on the ferritic side around the fusion interface. Sathiya et al. [12] carried out an experiment on AISI 904L Super ASS sheets using GMAW to produce bead on plate weld. Important results derived from this experiment were that the HAZ had higher hardness value and in the HAZ region grains were very finer. Also, dendritic microstructures were found in weld metals and also the HAZ. Gio Costanza et al. [13] experimented on the weldability of ASS by GMAW with various gases. The materials used were AISI 304 and AISI 316 ASSs. It was analyzed that the sheets have good weldability with high penetration and right bead profile. However, the welded zone had some lack of mechanical strength, but the joint efficiency was very high while using H_2 and Ag Gases which had about 90% ultimate stress.

Kaewkuekool et al. [14] made a study on the effects of filler material had on the mechanical properties of AISI 304 ASS and they concluded that the interaction effect between current and speed was suggestively varied at levels of ultimate tensile strength and that filler metal only doesn't have add any deviations to the mechanical property. Bayock et al. [15] experimented on welding two dissimilar metals S690QT and 316 ASSs to create a thoughtful bridge between the thermal cycle residual stress and detailed analysis of its chemical composition and microstructure and he derived that a heat input of 10 kJ/cm produced the best mechanical property and inter granular formation in the microstructure. Prasad et al. [16] conducted a detailed review on GMAW of AISI 304 L ASS by varying various weld parameters. They resolved that the crack growth was dependent on the crack propagation directions of the metal. In order to know the adverse effects of variants of GMAW, Single Pulsed (SP) and Double Pulsed (DP) Welding is studied. Kumar et al. [17] performed an experiment on ASS to identify superior weld quality while welded using the Pulsed GMAW process. They determined that the use of Pulsed GMAW process with suitable control parameters presented better resistance to inter granular corrosion and improved mechanical properties when equated to conventional GMAW process. In addition, SP-GMAW lessens porosity and other flaws. In comparison to SP-GMAW, even better outcomes are seen when using the DP-GMAW approach. Each cycle of the thermal strong and thermal weak pulses in this approach contains numerous peaks. A comparison effect on SP- and DP-GMAW is taken into account on ASS. Hu and Xue [1] presented the periodicity of SP- and DP-GMAW on AISI 310S grade ASS using ER2209filler wire and found out that the shrinkage was low for SP-GMAW the mechanical and metallurgical properties were improved during DP-GMAW and these improvements were primarily due to the fluctuations of WFR (Welding fabrication repair). Under microstructure study, Arunkumar et al. [2] studied that DP-GMAW of AISI 310 ASS creates fine grained microstructures as to when compared with other welded samples and the reason was identified to be the thermal pulsation which induced a stirring action on the weld pool. Chen et al. [18] investigated on dynamic behaviour of ASS done by DP-GMAW and identified the size of HAZ in the weld joint mainly depends on the heat input rate and that the length on the oscillation amplitude of the weld pool shows periodic changes within one thermal pulse of DP-GMAW. Mathivanan et al. [19] studied the diagonal shrinkage, metallurgical and mechanical properties of AISI 310 ASS using SP- and DP-GMAW process. They have arrived a conclusion that the shrinkage is low and superior weld joints were obtained during the DP-GMAW process. Hence, the efficiency of DP-GMAW is superior to that of SP-GMAW in terms of grain structure and others. However, the HAZ region was found to be large in the GMAW process. Hence, authors move towards laser beam welding to find better and effective solutions. Table 1 shows the comparison of SP-GMAW and DP-GMAW.

Table 1: Comparison of Single-Pulsed GMAW and Double-Pulsed GMAW.

Single Pulsed GMAW Process	Double Pulsed GMAW Process
Shrinkage Values are Low [1]	Mechanical Properties were enhanced [1]
Higher Fracture Energy Values [19]	Finer Grains [2]
Higher Tensile Strength [15]	Superior welded joints [19]
Increased Hardness [17]	Microhardness and Microstructure were improved [15]
Provides Intergranular Corrosion Resistance [15]	Metallurgical characteristics were improved [1]

Laser Beam Welding Effects in Austenitic Stainless Steel

LBW is a type of advanced welding method in which with the help of a laser beam, two plates of metal are combined or fused together. It is done with the help of precise laser focusing through cavities. High energy capacity of laser beams is exploited, and the property is used to produce heat, which in turn is used to melt the material in which the metal is made [20]. The welded metal plates are then cooled which forms an integral and tough weld of good strength. In typical experiments, three types of main commercial steel are exploited. They were 304L, 316L, and 347 variants. Earlier studies of stainless-steel weldability use showed that in order to commit the highest quality of joints in welding and to reduce defects and distortion produced due to input given in the form of heat, Laser beam welding is most preferred. Based on these elementary criteria, review was carried out in laser beam welding with ASS.

Benyounis et al. [21] investigated the butt joints made out of AISI 304 ASS using laser welding process. They operated in that to know the impact strength and tensile strength capacities of the same. As an outcome, the findings revealed that tensile strength and impact energy could be increased tenfold and highly efficient welds were obtained in LBW. It came with the added advantage of 47 percent reduction in costs when compared to GMAW. Moving on with the microstructural study index, Ragavendran et al. [22] examined the mechanical and microstructure properties through Hybrid Laser-Metal inert gas welding. The inert gas was used to provide a shielding effect from withering chemical reactions. The studies were based on 5.6 mm thick ASS of 316 (N) variant in welded joints. They found that the weld region had become narrow, and the volume of metal welded was reduced in this laser weld as compared to other conventional methods. The final welded metal was free from defects and hot cracking issue. Higher hardness, strength, ductile nature, and required toughness were also imparted to the welded steel material.

Some cases were observed where laser incident angle also affected the weld joints. Kumar et al. [23] had a two-step objective to the study. They investigated the effect of incident angle on the geometry of the entire weld, adding microstructure, and tensile properties of the weld joints. The geometry resulted in elongation of the weld pool in an elliptical form at about 86 degrees to the incident angle. However, other shapes viz., spherical and elliptical weld sections were also observed with the angles of incidence being 89.7 degrees and 83 degrees, respectively. Planar and coarse dendritic microstructures were also observed at other angles. Nguyen et al. [24] made an experimental work to evaluate the influence of Nd:YAG pulsed laser process and kept the process parameters like welding speed, laser power, focal length as the main factor. The temperature gradient was also taken care of in their study. The final metallurgical aspects of the melt pool like particle diffusion, cracking due to solidification and microstructure of the welded zone were also studied. Observations were made that with the increase in welding speed, cracking produced in the fusion zones significantly reduced. With laser power optimized, the line energy had decreased and the effect of heat conduction in copper was transferred to the fusion zone of the weld. However, it induced a certain liability of columnar dendritic growth from the boundaries to the center of the fusion zone which made the weld prone to cracks and defects. A possible doubt arises that with heat causing troubles, would it affect the physical parameters. In order to cure the doubt, Abdel Batahgy et al. [25] made attempts to resolve the concerns with laser welding parameters and their effects on the fusion zone. The final microstructure after solidification of ASS was also seen. The experiments revealed that the parameters like tensile strength, hardness, and bending are unaffected by heat input at room temperatures even at mild cracking situations. However, it showed that the weld profile could not be efficiently handled by laser power. But when compared with other methods this process was found to be more cost-effective and time-consuming.

Weldability Issues

From above literature the authors listed different weldability issues and respective remedial measures during welding of ASS. Solidification cracking was a major issue, and these cracks happen when impurities like sulfur and phosphorus are pushed out of the solid. Because of this rejection, the number of impurities in the remaining liquid keeps going up. These impurities also combine with other elements in ASS to make compounds that melt at a low temperature. At the same time, because of shrinkage during solidification, there will be tensile stress at the center of the weld joint, and weld cracks will form because solidification, tensile stress, and the formation of a low-melting compound all work together [32]. To prevent hot cracking in ASS, it is important to select filler/electrode combinations that cause solidification to occur in FA mode (Primary ferrite solidification), in which the first solidifying ferrite confines the impurities like sulfur and phosphorus. Further, hot cracking can be avoided by increasing nitrogen or by decreasing silicon content. When argon was used as a shielding gas the bead quality was drastically improved. Crevice corrosion in marine areas could be avoided by different coating like 6XN. Intergranular corrosion or sensitization occurs when chromium-rich carbide ($Cr_{23}C_6$) precipitates at the grain boundaries of ASS when they are heated to high temperatures for extended periods of time. Carbide precipitation causes chromium depletion ($Cr < 12\%$) in the vicinity of grain boundaries. Since chromium is the primary factor in corrosion resistance, a grain boundary region that is low in chromium is more prone to corrosion.

Sensitization refers to the process by which carbide precipitation occurs, while inter granular corrosion describes the corrosion that occurs as a result. Inter granular corrosion can be avoided by following methods given table 2. Some intermetallic phases, including G, R, Chi, Lave, Sigma, γ prime and γ double prime, may precipitate out of the matrix during welding when the material is heated to high temperatures and/or held at those temperatures for extended periods of time. These precipitates remove alloying elements from the matrix, which lowers corrosion resistance to a lesser extent. In high-temperature materials, however, intermetallic are sometimes produced

Table 2: Weldability issues and its solutions.

Weldability Issues	Solutions	References
Weld Joint Failures	Eliminating external loading stress	[26]
Solidification Cracking	Ensure an FA or F solidification mode to provide better resistance	[27-29]
Bead Quality Issue	Argon can be used as shielding gas	[30]
Crevice Corrosion	Coating with 6XN	[31]
Intergranular Corrosion/ Sensitization	i. Low-carbon base and filler metal (C < 0.03%). ii. Reduce duration in sensitization temperature range (400 - 850 °C) by reducing heat input, increasing cooling rate, and improving joint design. iii. Stabilized base and filler material. iv. Use high Cr alloy to retain corrosion resistance after precipitation. v. Solution annealing	[31]
Hot Cracking	Adding nitrogen content or by decreasing silicon content	[32]

on purpose to boost creep resistance. ASSs are susceptible to distortion and residual stresses because of their relatively large thermal expansion coefficient (α). Residual strains can be reduced using post-weld heat treatment. But sometimes post-weld heat treatment favors sensitization. Table 2 lists the general weldability issue in ASS and solution for them which have been collected from different literature.

Conclusions

The wide use of ASS has led to mitigation of conventional machining techniques to advanced technological ones. Present day research in this category is involved to minimize the wastes generated in the welding processes along with higher response in terms of retaining the properties imparted to the material after the machining process like welding is finished. Not only being readily available, ASS also forms an integral part of thermal processing units like thermal power plants where the corrosion and thermal resistance properties are used maximum in units like boilers and other heavy equipment. Welding techniques like laser welding are constantly being improved under the banner of eco-friendly and efficient production systems. Based on the literature, this review suggests LBW offers better results when compared to GMAW and its variants. Proper selection filler materials, controlled addition of alloying elements, appropriate heat treatment methods and coating can effectively mitigate the different weldability issues in ASS. The scope for welding in this grade of steel is high, with automation and artificial intelligence techniques to roll out in future, maximal efficiency can easily be achieved in no time.

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None.

Conflict of Interest

None.

Credit Author Statement

None.

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