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A Brief Review of using Gas Metal Arc Welding to Improve the Tribological and Mechanical Properties of Materials

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Abstract: Gas Metal Arc Weld (GMAW) hard facing is renowned for its exceptional mechanical properties and corrosion resistance, making it a favored technique in both industrial applications and research. This method involves creating a thick coating on structural materials, known as substrate materials, which typically possess inferior qualities and are more cost-effective. The primary aim is to enhance the surface attributes of these substrates through welding procedures, thereby achieving desired characteristics. GMAW hard facing significantly improves material properties in two main aspects. Firstly, it enhances surface-dependent features such as corrosion and wear resistance. Secondly, it boosts mass-dependent properties like toughness and durability. This dual improvement makes GMAW hard facing advantageous for various industries, including chemical processing, mining, and power generation. The review of numerous studies presented in this article focuses on different substrates, examining the enhancements in microstructure, corrosion prevention, and mechanical properties achieved through GMAW hard facing. The findings are intended to serve as a valuable resource for both current and future researchers, as well as for industries that employ weld hard facing techniques.

Keywords: Weld hardfacing, Gas metal arc welding, Hardness, Wear resistance, Corrosion resistance.

1. Introduction

Industries often require materials that can withstand diverse climatic conditions to enhance the durability of low-grade components or to substitute more expensive base materials [1]. Weld hard facing is a technique used to create desirable surface characteristics on structural (substrate) materials that are of lower quality and cost [2, 3]. This method typically involves applying a spray coating layer about 120 micrometers thick to develop anti-corrosion properties [4, 5]. The coating process occurs through an electrolytic process, suitable only for electrically conductive materials, which also improves the base material's strength and corrosion resistance [6]. Plating helps prevent spalling and lumping, reduce friction, consolidate surface hardness, and minimize the loss of the parent metal [7]. Another procedure, known as buttering, involves adding a deposit to the base material to facilitate effective bonding of the weld overlap. The buttering deposition pattern differs from both weld and base metals [8]. Unlike coatings, hard facing involves depositing materials of varied thicknesses onto a material prone to rust, preventing corrosion and enhancing the strength and service life of the parent material [9]. The unique composition of the hard-faced layer does not alter the microstructure of the original component. Hard facing typically covers around 20% of the overall plate thickness with the melting metal. Industries such as chemical, oil, nuclear, shipbuilding, and service sectors extensively use hard-faced materials.

Hard facing offers several advantages over other metal deposition methods in terms of corrosion resistance, toughness, adhesion, and improved microstructure. The method increases the material's hardness, with heat input being crucial for achieving high hardness [10]. Weld hard facing involves placing a coating material, either ferrous or non-ferrous, over the existing mother material. One significant drawback is the potential for cracks during the compression of the clad and base material, which can be mitigated by using multi-layer deposition, a buffer layer, and proper electrode preheating.

The current study aims to understand how different welding settings during GMAW hard facing affect deposition characteristics. It provides an overview of how various process factors, including arc voltage, welding current, and travel speed, influence the deposit's integrity, bead shape, and mechanical properties. Additionally, the study examines the effects of these process factors on dilution and corrosion behavior.

2. Literature Review

There are numerous techniques for conducting hard facing activities, including electric resistance arc welding, oxyacetylene welding, gas tungsten arc welding (GTAW), electro-slag welding, gas metal arc welding (GMAW), rolling and strip hard facing, shielded metal arc welding (SMAW), flux-cored arc welding, and plasma arc welding [12-14]. Explosive welding, for instance, forms a junction between two metals using an explosion as a heat source, enabling cladding of materials that cannot be welded by conventional methods, such as 316 low carbon stainless steel [15].

One of the most frequently used manufacturing processes is rolling hardfacing, which accounts for more than 75% of the process in many enterprises involved in hot roll bonding projects or the bonding of collected rollers. Welding is a highly cost-effective procedure for cladding materials. Initially created for maritime applications to provide corrosion and stress resistance and high shock loading resistivity, hardfacing or weld overlaying is now widely used. For instance, in factories, hardfacing of pressure vessels is common because it provides the high rigidity and corrosion resistance needed for challenging conditions. Hardfacing is frequently employed in the industrial sector to restore worn-out sections, thereby extending the lifespan and enhancing the performance of components. It is also commonly used to repair large gears in factories [16].

Laser hardfacing is a modern technique involving direct metal deposition, used for turbine parts, automobile parts, aircraft components, and various wear plates [17]. Explosive welding is another alternative for hardfacing, suitable for large flat plates and also used for pipes and tubes with coaxial joints. However, for coaxial pipes and tubes, techniques such as SMAW, GTAW, and GMAW are more economical. Pulsed GMAW is a typical procedure for hardfacing parts in power plants, including vessels used in refineries, pulp mills, and boilers. Additionally, submerged arc welding is used in hardfacing to extend the service life of spoiled parts [18].

Hardfacing methods restore worn-out components to extend their useful life, with a well-known application being the impeller of a slurry pump. Parts made of low-carbon steel can enhance their resistivity using GTAW and different filler metals [19]. Hot wire GTAW technology is also used to clad heavy nuclear components accurately [12]. Among the many hardfacing techniques, welding is the most adaptable and commonly used method for covering substrates. Several welding processes, including GTAW, different resistance welding, GMAW, and SMAW, are employed. Non-conventional welding techniques like laser welding, hybrid welding processes, and plasma arc welding are also used for manufacturing clad components [20].

The major technique for hardfacing is arc welding, although the specific method may vary depending on the application. For example, resistance welding has been used to encase 1.8 mm thick mild steel sheets in a mixture of Co-Cr alloy and nickel-based alloy, enhancing wear resistance with coatings ranging from 110 to 160 micrometers thick [12]. In ship structural applications, electro-slag hardfacing with strip electrodes is advantageous due to its rapid deposition rate and minimal dilution, making it cost-effective compared to other welding processes [21]. Effective hardfacing of stainless steel using GTAW requires precise process settings [22]. Tungsten Inert Gas (TIG) welding is used to clad the sides of Babcock & Wilcox boilers for corrosion resistance, using mild steel for the base plate and nickel-based alloys for deposition, with a tight gap torch and rotating and weaving approach [23].

GMAW is widely used and reasonably priced for hardfacing. When process parameters are tightly controlled, GMAW demonstrates increased efficiency and superior results. Studies have investigated the GMAW process for joining a layer of duplex stainless steel to low alloy steel, revealing links between heat input and bead morphology, including width, penetration, and height [24]. The adaptability, efficiency, and affordability of GMAW hardfacing distinguish it from other techniques. GMAW offers a higher deposition rate than conventional methods like oxyacetylene welding or submerged arc welding [25]. Additionally, precise heat input control in GMAW minimizes thermal distortion and reduces cracks in the hardfaced layer [26]. Moreover, GMAW hardfacing produces a smooth and clean weld bead, enhancing appearance and reducing the need for post-welding machining.

In several sectors, GMAW hardfacing has proven to be a game-changer, enhancing the performance and lifespan of vital components. For example, the mining industry has demonstrated the use of GMAW hardfacing on excavator bucket teeth [27]. The wear-resistant metals deposited by GMAW significantly improved the endurance of the bucket teeth, reducing the need for replacements and downtime, thereby increasing overall operational efficiency. Similarly, in the oil and gas sector, drill bits treated with GMAW hardfacing have shown reduced abrasive wear and increased longevity.

The use of GMAW hardfacing is based on several tests that involve varying gas compositions, wire thicknesses, and materials. Key factors affecting the quality of a weld include the shielding gas composition, current, torch transverse speed, voltage, and standoff distance. These primary factors determine the effectiveness of the welding process. Minor auxiliary characteristics, such as the flow rate of inert gas and the composition of different gases, do not significantly impact weld quality.

For instance, applying an austenitic stainless steel layer for hardfacing to low alloy steel using GMAW with a transverse speed of 8.71 mm/s, a current of 100A, a voltage of 24V, and carbon dioxide as the shielding gas results in the lowest corrosion rate. The maximum corrosion resistance was observed with a current of 145A, a voltage of 26V, and a transverse velocity of 8.93 mm/s in the same case [28].

The composition of the materials and the shape of the clad beads are crucial parameters for achieving better mechanical resistance when hardfacing with GMAW. Since the goal of hardfacing differs from that of welding, efforts are made to minimize weld bead penetration to reduce strength. Here, the voltage, current, and travel speed of the arc contribute to the heat input, which in turn affects the bead shape. The welding current is essential as it controls the amount of heat entering the

workpiece, impacting the overall quality and characteristics of the hardfacing layer.
Higher currents often lead to higher deposition rates in GMAW hardfacing; however, they must be carefully regulated to avoid distortion and overheating [29]. The electrical potential between the workpiece and the welding electrode, or voltage, influences both the penetration and arc length [30]. Achieving the best bead shape and fusion requires a balanced combination of current and voltage. The flux core filler wire and response surface methodology are used to achieve the desired characteristics in the deposited component [31]. Factors such as the bead height and width, depth of dilution, reinforcing form factor, and penetration shape factor are proportionate to heat input when using GMAW to clad duplex stainless steel over low alloy steel. Regression analysis showed that these findings closely matched real-time data with minimal errors. With an increase in heat input, the weld breadth also increased.

The metal transfer mode, which depends on welding voltage, current, and gas flow, determines the microstructure and geometry of the weld bead seams [24]. The drop separation process in cyclic GMAW was examined using steel and aluminum, revealing the influence of several forces [32]. Another analysis highlighted the significant impact of throbbing parameters on the interaction layer and clad layer characteristics. Pulsed GMAW provides a fine microstructure and minimal clad portion dispersion, achieving superior deposition, lower dilution, better microstructure, and a shorter depth of hardfacing integration. This process also included the mother material of the neighboring hardfacing, comprising an interacting layer with low hardness [33].

In a study using GMAW-P with aluminum foil, the falling velocity and detachment of molten metal were examined, showing that drop transfer significantly influenced weld quality [34]. Research also indicates that variables such as welding current, nozzle-tip distance, and travel speed can affect the curvature index in periodic GMAW. Studies on 65X pipeline steel with pulsed GMAW hardfacing of 316 low-carbon stainless steel examined the effect of process parameters on weld bead configuration. The dimensions of the weld metal expanded in height, width, dilution, and depth as the wire feed rate increased. The contact angle initially decreased but then increased again near its minimum value. As welding speed and dilution values increased, the height, width, thickness, and contact angle of the weld metal decreased. Further research revealed that the average dilution increased by roughly 6%, with a 7% reduction in contact angle when electrode extension dropped. Mathematical models were created to assess the link between fluidized beds and weld shape process factors [35].

When using GMAW for superior stainless steel hardfacing, the results meet strict porosity standards. The fully automated GMAW method produces controlled dilution, employing 308L and 309L filler metals to extend tip change intervals and reduce contact tip wear. Both pulsed GMAW and constant voltage GMAW are evaluated using two shielding gas combinations. The effects of electrode chemistry, welding method, and shielding gas on the porosity of the hardfacing layer are analyzed. Welded wires of class 312 stainless steel (containing up to 30% Cr by weight) and 316 stainless steel are used in these evaluations. When Cr-content up to 19% by weight was used as a recommended overlaying alloy for abrasive group digesters, the Type 312 SS and 316 SS weld overlays appeared vulnerable to solidification cracking, particularly when carbon steel material was welded due to the high chromium concentration. To address this, cyclic spraying GMA welding in a perpendicular orientation was used to create an effective crack-free overlay [36]. Extensive experiments were conducted to examine the effects of developing alternate standards and to assess reaction parameters, operating parameters, and other variables. These included updated welding processes, superior hardfacing materials, and improved mathematical models. Each experiment aimed to produce optimal GMAW processing parameters to control the finest weld bead shape.

One of the main challenges in hardfacing is to create a strong joint between two different metals with minimal filler metal dilution to prevent degradation of the filler material's performance. In a preliminary experiment with automated GMAW, a 12% dilution of the control process parameters was achieved when austenitic stainless steel hardfacing was applied to structural steel [37]. In a recent test, the influence of fluid process factors on austenitic stainless steel GMAW hardfacing over construction steel surfaces was examined. Key welding parameters in this experiment included pinching, welding current, the work distance from the contact tip, and welding speed. A complete design method was used, along with a mathematical formula to obtain data closely resembling real data through an artificial neural network using a particle swarm optimization tool [38].

The GMA welding process variables for austenitic stainless steel hardfacing included welding voltage, current, bead offset, and welding speed. It was discovered that heat inflow impacts the material's microstructure, ferrite content, bead morphology, and corrosive properties. The offset percentage significantly affects the thickness of the deposited layer and filler metal dilution. Bead geometry influences the number of weld passes required to deposit on the surface. Welding speed and wire feed rate significantly impact bead shape under experimental conditions [39, 40].

Research shows that heat inflow significantly affects the properties of super-duplex stainless steel. Geometrical shape variables, such as the reinforcement form factor (RFF) and penetration shape factor (PSF), impact weld bead geometry and are controlled by process parameters, including the torch's average speed, tip-to-nozzle distance, welding current, and welding gun angle. Studies indicate that RFF fluctuations alter the electrode's resistance to heating and melting rate, potentially affecting arc length and arc force. A test on low carbon steel as a duplex stainless steel substrate with all hardfacing parameters achieved the ideal microstructure with a minimal heating rate (0.38 kJ/mm) using 28V, 145A welding current, and 8.6 mm/s nozzle velocity, resulting in a minimal corrosion rate [41].

Various GMAW techniques impact the properties of duplex stainless steel. Preheat treatment was performed on welded samples using engine oil and neem oil for rapid quenching. Results revealed that neem oil quenching with GMA welding affected the mechanical characteristics of the hardfacing parts. Neem oil and lubricating oil quenching had less impact, with stress-relieving heat treatment yielding excellent strength up to 331 MPa. However, an opposite trend was noticed for toughness [42].

Investigating the quality of a single-layer stainless steel overlay was carried out using the mechanized GMA welding method with auxiliary preheating of a solid filler wire, aided by a specially designed torch. Adding arc energy contribution to resistive heating and external preheating of the welding wire significantly reduced the welding current. The analysis concluded that weld beads conveyed minimal dilution. After the system was preheated with the ferrite phase, a significant number of alloying elements, including nickel, molybdenum, and chromium, were added, and the hardfacing was produced. The overlays on the microstructure resulted in higher mechanical and corrosion resistance capabilities. Additionally, the technical quality of the suggested process's final report was outstanding, and its low cost led to higher production. Another experimental study employed the GMAW process to conduct stainless steel hardfacing with preheated filler material using the Response Surface Methodology to ascertain the optimal weld bead shape output [38].

A new type of welding process called Consumable Dual Electrode Single Arc (DESA)-GMAW was proposed. DESA-GMAW supported high discharge rates and regulated the heat input for filler wire. This could be stabilized provided some necessary welding parameters were considered. Using these factors, the filler wire needed to be continuously supplied into the welding pool after short-circuiting occurs in the workpiece, as well as additional filler wires required for routine metal transformation under a steady arc. According to a weld bead examination using a transverse section, the disposable DESA-GMAW process's penetration will drop significantly if the metal deposition rate is high [29].

The GMAW hardfacing technique involves welding two metallic materials with different coefficients of thermal expansion, which can lead to crack propagation at the interface. Different methods were applied at the contact surface to minimize crack development. One of these methods is torch weaving technology, sometimes used in GMA welding. An automated synergic gas metal arc welding process investigated the effect of torch weaving on the combination of structural steel and duplex stainless steel. It was found that the use of weaving technology resulted in a flat deposited layer of the weld and an increase in the ferrite number as the weaving dilution rate dropped. Consequently, weaving technology had no impact on microstructure, porosity, and hardness [43].

Additional crucial factors, such as clad bead shape, eccentricity, and arc rotational speed, were considered in weaving technologies. Research and development were conducted on an automated robotized welding technique, incorporating a procedure where an automated high-speed rotating arc weld and manually rotating wire could be observed. This welding method generally uses many wires and large plates. In contrast to the traditional gas metal arc welding process, the weld bead produced by the torch weaving method is less penetrating, flat, and wide [44].

The arc rotation mechanism was used in another investigation on weld bead shape, where the effects of arc rotational velocity were tested at constant eccentricity [45]. Another investigation used pulsed GMA welding on the weld bead configuration of 5083 aluminum to evaluate the impacts of eccentricity and rotational speed output. The analysis acknowledged that penetration has a relatively greater influence on the feed rate of the wires. Additionally, it was discovered that convexity had the greatest impact on eccentricity, followed by the wire feed speed at the displacement velocity [46].

A recent study found that narrow groove welding can enhance efficiency in the production of thick-walled components because it has perfect control and an automated process that ensures a steady increase in weld strength. It was found that maintaining the faces of small grooves on either side ensures adequate and consistent penetration. Another study showed that when gas metal arc welding is operating, the arc shape and bead properties become narrower if electromagnetic arc oscillation is applied [47]. Consequently, it was determined that groove gas welding and oscillation circumstances both match the criteria for high-quality welds. The wire speed, arc rotation speed, and the ratio of travel speed to wire feed rate affect convexity factors. Additionally, it was determined that penetration was significantly impacted by the relative feed rate of the wire [48].

In various industrial applications, gas metal arc welding (GMAW) hardfacing is a commonly used process to improve the performance and durability of materials. GMAW hardfacing enhances the base material's hardness, wear resistance, and overall mechanical qualities, leading to remarkable long-term performance. The treated materials have a longer service life, lower maintenance costs, and better resistance to corrosion, abrasion, and impact.

The microstructure and its various qualities are the fundamental properties of a clad component. Due to a favorable cooling pattern, a large heat input, and certain alloying components, numerous phases present in both the substrate and the filler are created. These alloying elements and specific aspects are crucial for resistance in corrosive environments and mechanical qualities. The hardfacing mixture is retained in the bead or coalescence with the help of dissimilar welding and material components, resulting in a variety of bead qualities. Often, the impacts of chromium are investigated in the SMAW hardfacing [49]. Chromium, which was found to be an acicular ferrite (AF), increases in percentage due to its influence on hardness. Additionally, the dominant volume fraction of elements made of austenitic material and the inverse relationship between toughness and carbon percent were considered. Consequently, a typical element rises with a layer that has a great deal of resistance property.

In one experiment, transferred plasma boride was applied to a coated steel plate, enhancing the resistance of 1082 steel [50]. The coating procedure was repeated using SMA-Welding technology on the same substrate [51]. 304 stainless steel under Japanese standard (SUS304) and AISI 1045 steel (medium tensile steel) were used to cover the Ti-Ni hardfacing during the GTA welding process. The dendritic character of the overlayer, due to the rapid solidification of the material mixture and the formation of weld beads, is masked by various precipitates formed during the coating process. Examination of the microstructure and concentration of the overlays revealed that the hardness of the coating during processing was three times that of the Ti-Ni intermetallic flux-cored wire. This contributes to the high temperature, durability, and excellent hardness of the coating.

Welding is one of the key elements in developing the proper microstructure. Low carbon steel was coated with stainless steel using three procedures: Tungsten inert gas welding, High current pulsed arc welding, and fine Plasma arc welding, with performance influenced by their efficacy. The stainless steel produced by GTA Weld hardfacing originates from a clad layer where the dilution percentage is less than 50%, and the filler material has a radius not more than 6.4 mm. For hardfacing of the pulsed arc with a material microstructure of stainless steel at a pulse frequency of 500Hz, a larger diameter cored wire is required. Therefore, stainless steel to mild metal substrate transformation occurs with the simple help of plasma arc hardfacing. Both the clad layer and the cell-branched austenite containing d-phase or g-phase at the melt interface can undergo this transformation. According to research, a mild steel layer may be made by utilizing filler metal with a larger diameter if a confined, constricted arc with 50% dilution is employed to produce the stainless steel microstructure [52].

In one study, SMA Welding was performed using a multi-pass hardfacing that had good resistance capabilities and continuous casting rolls of nitrogen alloyed martensitic steel. Additionally, carbide formation can be difficult to prevent, especially in areas between ridges and overheated regions. Tempered martensite is needed to complete the subsequent substantial deposition of carbide in liquid form once welding is complete. The precipitation of chromium-rich carbides inside the material medium may cause chromium deficiency. Sensitization typically refers to the entire process or phenomena. The sensitization zone had hole formation with great susceptibility and produced stress corrosion fractures at the initial point, where resistivity was reduced [21].

The effects of fluctuating temperature levels can be observed during the production process. AISI 304 low carbon L steel, hot rolled on carbon steel, is used as hardfacing to cover ASTM A 515 Gr. 60 [53]. The interface bonding between the stainless steel hardfacing material and base material was accomplished by hot rolling. Similar to earlier studies, this one extensively used the high value of austenitic side carbon inter-diffusion and ferritic side alloying elements. The results reveal that the microstructure is strongly influenced by rolling parameters, cooling rates, and thermal treatment. The microstructure of a thin band-covered hardfacing line, with an austenitic layer separating it from the base metal and tracking ferritic grain characteristics, indicates recrystallized acicular austenitic grains without carbide precipitation. This structure enhances corrosion resistance and mechanical properties in hardfacing applications.

Research on GMAW effects on low-alloy steels in duplex stainless steel clad grades [54] highlights that shielding gas mixture and heat input significantly influence microstructure, nitrogen content, pitting corrosion resistance, and low-temperature toughness of welds. Another study utilized explosive welding to clad 316 low carbon stainless steel with DIN-P355GH vessel steel, showing improved mechanical properties compared to the base materials [55].

Hardfacing methods are crucial for providing abrasion and corrosion resistance. For instance, successful GTAW hardfacing on light alloy steel using Fe and Si-containing filler metals resulted in increased hardness and resistance to abrasion [19]. Similarly, Fe-Cr-C alloys deposited via gas tungsten arc welding demonstrated enhanced mechanical properties and wear resistance [13].

The microstructure of the clad layer and heat-affected zone (HAZ) plays a vital role in determining mechanical and corrosion resistance properties. Dilution during hardfacing significantly affects the microstructure of the base material, altering alloy composition and characteristics. Factors like arc travel speed, electrode diameter, current, and welding parameters influence dilution, affecting weld pool geometry and fusion boundaries.

Studies on weld overlays, where stainless steel is deposited onto low alloy steel surfaces to enhance corrosion resistance, have explored relationships between structure and properties. For instance, AISI 347 grade stainless steel hardfacing on low alloy austenitic stainless steel demonstrated strong mechanical properties near the interface, influenced by microstructural developments like bainite, ferrite, and decarburization.

In conclusion, managing the balance between ferrite and austenite phases is critical for achieving optimal corrosion resistance and mechanical properties in stainless steel hardfacing. Factors like nickel (Ni), nitrogen (N), chromium (Cr), and molybdenum (Mo) concentrations influence phase stability and resistance to intergranular corrosion and stress cracking, emphasizing the importance of proper alloy composition and welding practices.

Hardfacing layers serve a critical role in protecting less expensive substrates from corrosive environments. Clad materials, while not inexpensive themselves, are used to enhance the corrosion resistance and prolong the service life of components. For instance, submerged arc welding has been employed to join butt joints between 316L austenitic stainless steel and 2205 duplex steel using a duplex stainless steel electrode. This process resulted in the formation of needle-like austenite precipitates and coarse ferrite grains due to varying heat inputs, but it did not compromise weld stress corrosion cracking resistance [55].

Research comparing typical weld hardfacing to laser powder hardfacing on identical properties revealed comparable anti-corrosion capabilities, showcasing the effectiveness of both methods [56]. Another study focused on gas metal arc welding of austenitic steel hardfacing on low-alloy steels, which significantly improved resistance to pitting corrosion.

In optimizing the corrosion resistance of duplex stainless steel during GMAW hardfacing, operational tests demonstrated that heat input plays a crucial role. Higher heat input, which correlates with welding current and inversely with welding travel speed, can adversely affect corrosion resistance properties [41].

Corrosion resistance is a critical property influenced by external environmental factors. Studies have evaluated corrosion resistance through various methods including electrochemical tests with cast iron rust, mechanical wear, and exposure to 3.5% NaCl aqueous solutions. Stainless steel has shown resistance to cavitation erosion under these conditions, highlighting its suitability for applications requiring prolonged service life in corrosive environments [6].

Overall, the application of hardfacing materials and welding processes that enhance corrosion resistance contributes significantly to the longevity and performance of engineering components exposed to harsh environmental conditions. Ongoing research continues to explore alloying components, microstructure effects, and testing methodologies to improve corrosion resistance in practical applications.

In a study focusing on the corrosion resistance of boiler pipe components made from overlay 625 low carbon steel alloy, artificial liquid salt was employed to simulate corrosion processes including pitting, internal oxidation, and sulfidation. The research highlighted that a significant amount of iron predisposed the formation of dendritic structures susceptible to selective corrosion within welds. This phenomenon was observed particularly in areas where dendrite cores, depleted in elements like Mo and Nb, were prone to crack formation and accelerated crack propagation when exposed to molten phases. Additional investigations underscored the adverse effects of alloying elements such as Cr and Fe under conditions of high temperature corrosion cracking. To enhance corrosion resistance, substrates are increasingly adopting various hardfacing materials, notably electrodes made of super duplex steel and duplex stainless steel. These materials, rich in alloying metals like molybdenum, chromium, nickel, and nitrogen, enhance the ductility and resistance of austenite and ferrite phases at ambient temperatures. Recent studies combining gas metal arc welding (GMAW) and friction stir welding (FSW) on pressure vessels clad with pure copper revealed that nitrogen content in weld deposits significantly influences microstructure, low-temperature hardness, and resistance to pitting corrosion in duplex stainless steel applied over low alloy steel substrates. The study highlighted the critical role of heat input and shielding gas composition in controlling nitrogen content within weld deposits. Moreover, duplex stainless steel alloy 2209, typically comprising 3% to 5% molybdenum, 19% to 23% chromium, and 6% to 10% nickel, demonstrated improved corrosion resistance and reduced weight loss when alloyed with ruthenium. Electrochemical experiments further confirmed that the presence of ruthenium enhanced passivity against acidic and neutral chloride solutions, making it a promising additive in corrosion-resistant alloys. Previous research has also indicated that duplex stainless steel alloys incorporating secondary ruthenium exhibit enhanced resistance to localized corrosion and improved performance in aggressive environments such as sulfuric acid solutions. Experimental investigations into welding processes revealed that parameters like heat input and cooling rates significantly impact the microstructure and corrosion resistance of super duplex stainless steel weldments. For instance, controlled wire feeding rates during multi-pass welding were critical in optimizing heat affected zone (HAZ) properties and minimizing the development of intermetallic compounds that can compromise corrosion resistance. The study of SAF2205, a commercial-grade duplex stainless steel, highlighted the influence of temperature and chloride ion concentrations on pitting corrosion resistance, emphasizing the critical role of environmental conditions in determining material performance. In welding applications, the choice of filler materials such as austenitic fillers (e.g., ER 316LSi and ER 308LSi electrodes) and duplex fillers was shown to influence mechanical properties and corrosion resistance. Metal arc welding with 309 low carbon stainless steel flux cored electrodes was noted for producing high-quality hardfacing with superior corrosion resistance, particularly in industries requiring resistance to corrosive environments like petrochemical and oil industries. The use of nickel chromium molybdenum alloys in hardfacing applications offers excellent corrosion resistance and creep properties, making them suitable for demanding industrial applications. Similarly, carbon steel Ni-alloys produced through roll bonding or explosive welding provide cost-effective alternatives with substantial corrosion resistance, requiring careful control of Fe content to optimize welding chemistry. Studies utilizing Alloy 625 electrode wire in GMAW hardfacing underscore its effectiveness in enhancing corrosion resistance across various industrial applications.

3. Conclusion

The critical elements for achieving a high-quality welded junction include the shape and geometry of the weld bead, which influence parameters such as bead width, height, and penetration depth. In hardfacing applications, minimizing dilution while ensuring adequate penetration is crucial. Gas metal arc welding (GMAW) processes, known for their high deposition rates and heat input, often require techniques like pulsed GMAW to control penetration depth effectively. Alternatively, rotating arc devices can enhance penetration structure. Factors such as welding current, voltage, speed, arc standoff distance, arc force, and welding gun angle significantly impact weld quality and performance, influencing mechanical strength, wear resistance, and corrosion resistance of the final structure. Tailoring these parameters to specific applications can optimize welding outcomes. Thermal management, including external heat treatments, plays a pivotal role in enhancing material properties during and after welding. Various materials are utilized for weld hardfacing, with some demonstrating superior anti-corrosive properties due to the formation of specific precipitates and intermetallic compounds that alter the microstructure. Achieving an optimal weld bead shape and microstructure, often with a controlled ferrite phase, is essential for enhancing corrosion resistance through systematic research and development. Despite low penetration in hardfacing layers, ensuring sufficient shear strength to prevent separation from the base material is critical. While GMAW hardfacing is effective in improving surface wear resistance, it faces challenges such as susceptibility to cracking under high-stress conditions. Effective pre-weld and post-weld strategies, along with meticulous surface preparation and parameter selection, are essential to mitigate these challenges and ensure the desired properties of hardfaced materials.

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