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IDENTIFICATION OF THE INFLUENCE OF GAS METAL ARC WELDING METHODS ON THE MECHANICAL CHARACTERISTICS OF DUPLEX STAINLESS STEEL

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This study evaluates the effect of various Gas Metal Arc Welding (GMAW) methods on the mechanical properties of duplex stainless steel. The main objective is to identify the most effective GMAW process parameters in improving the mechanical properties of the material, including tensile strength, hardness, and corrosion resistance.

The results of this study provide valuable insights into improving the weld quality, mechanical properties, and durability of duplex stainless steels in high-performance environments and corrosive conditions. Industries such as oil and gas, shipbuilding and chemical processing can greatly benefit from these findings by adopting optimized GMAW parameters to produce stronger and more durable weld joints.

The findings also highlight the significant impact of welding and heat treatment on the alloy's mechanical properties. The strength of the control material was recorded at 811.47 MN/m², whereas the welded samples exhibited strengths between 177.07 and 257.32 MN/m². The impact energy of the control material was 162.70 J, while the welded samples showed values ranging from 38.64 J to 56.20 J.

Additionally, the study reveals that stress relief heat treatment resulted in the highest strength (A3=331 MN/m²) compared to quenching in lubricating oil (A2=329 MN/m²) and neem oil (A1=222 MN/m²), although variations in material toughness were observed. The uniqueness of this research lies in its systematic approach in correlating GMAW parameters with changes in microstructure and mechanical properties. The distinctiveness of this research stems from its structured methodology in linking GMAW parameters to variations in microstructure and mechanical properties, facilitating the identification of optimal welding conditions

Keywords: gas metal, duplex, mechanical, impact, welding, material, tensile strength, corrosion

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1. Introduction

Duplex stainless steel (DSS) is widely used in industries that require a superior combination of high strength, durability and corrosion resistance, such as marine engineering, chemical processing and the energy sector. The two-phase microstructure consisting of austenite and ferrite provides an optimal balance between mechanical properties and resistance to stress corrosion cracking. However, the DSS welding process presents its own challenges, because uncontrolled heat input and inappropriate shielding conditions can cause phase imbalance, which impacts mechanical performance and corrosion resistance [1].

Analysis of the microstructure in the weld interface and heat-affected zone (HAZ)includes testing of mechanical properties such as hardness, tensile strength, and potential impact toughness. Assessment of corrosion resistance and quality of weld joints produced by the double-coating method is done, especially in high-temperature or corrosive environments. Dilution degree, formation of intermetallic compounds, and potential cracking at the interface between the coating layer and the base metal is studied [2]. Long-term high-temperature material performance includes aspects such as creep behavior, resistance to thermal fatigue, and resistance to oxidation over time. Analysis of residual stress distribution and distortion mapping that occurs in the protective layer and its base metal are also performed. Coating testing is generally limited to the initial stage due to cost and time constraints for conducting long-term environmental or mechanical tests. Tests such as high-temperature corrosion or thermal fatigue require special equipment, environmental conditions that mimic the actual application, and relatively long test times [3].

Gas Metal Arc Welding (GMAW) is a technique commonly used in joining duplex stainless steel because of its efficiency, high deposition rate, and flexibility in various industrial applications. However, variations in welding parameters, such as heat input, shielding gas composition, and current setting, can affect the microstructure of the material, potentially reducing its mechanical properties. With the increasing need for high-performance welded structures in extreme environments, optimization of GMAW parameters becomes crucial to ensure the quality, integrity and longevity of welded joints [4, 5]. GMAW is one of the most frequently used welding methods for DSS due to its superior efficiency, high deposition rate, and ability to join thick materials with minimal post-welding process requirements. However, variations in welding parameters, such as heat input, type of shielding gas, and current setting, can have a major impact on the microstructure as well as the mechanical properties of the resulting weld [6].

Quantitative analysis of the kinetics of intermetallic phase formation, such as through time, temperature, precipitation (TTP) diagrams is done. Evaluation of mechanical properties in the HAZ is done, especially after multiple thermal cycles, including toughness, impact strength, and fatigue resistance. Evolution of residual stresses in the HAZ is due to repeated heating and cooling processes. Assessment of corrosion resistance in the HAZ is done, especially to types of corrosion such as stress cracking or pitting corrosion after repeated thermal exposure. Use of thermal simulation or modelling describes the effects of multiple heating cycles on the resulting local temperature gradients and cooling rates [7]. Modelling the microstructural evolution during austenitization and cooling processes, including phenomena such as grain growth, twinning, and carbide precipitation, generally requires an approach based on phase field simulations or the CALPHAD method. Although these methods are capable of providing accurate predictions of microstructural changes, their implementation requires high computational resources, so they are often not used in conventional experimental studies. On the other hand, prediction of hardening mechanisms induced by phase transformations, including the transformation-induced plasticity (TRIP) effect during wear processes, requires complex thermomechanical modelling. This complexity includes the interaction between thermal and mechanical variables that occur dynamically during loading, thus demanding a careful and integrated numerical approach [8, 9].

Duplex stainless steel is extensively utilized in industries like oil and gas, marine, and chemical processing because of its exceptional mechanical strength and resistance to corrosion. However, the welding process plays a crucial role in altering its microstructure and mechanical properties, which can result in challenges such as phase imbalance, decreased toughness, and diminished corrosion resistance [10, 11].

GMAW is commonly employed for welding duplex stainless steel because of its efficiency, ease of automation, and versatility in various welding conditions. Different GMAW methods, including pulsed GMAW, spray transfer, and short-circuit transfer, affect the weld's microstructure, heat input, and overall mechanical properties [12].

Therefore, understanding the impact of the GMAW method on the mechanical characteristics of DSS is essential to optimize the welding process and ensure the long-term performance of the welded components which has not been addressed in previous studies, considering the importance of optimizing GMAW techniques to ensure structural integrity and long-term functionality.

The application of these research findings not only improves mechanical properties, but also contributes to structural reliability, economic efficiency, and better environmental impact. Industries such as oil and gas, shipbuilding, energy, construction, and transportation can benefit from safer, stronger, and more cost-effective welding techniques for duplex stainless steels.

2.Literaturereviewand problem statement

Over the last ten years, numerous approaches have been investigated to improve the mechanical strength and corrosion resistance of alloys. These studies prove that welding parameters, such as heat input, type of gas shield, and current setting, have a significant influence on the microstructure and mechanical characteristics of DSS, including tensile strength, hardness, and corrosion resistance. Methodologically, assessing long-term performance and residual stresses would require longer test periods and specialized equipment, which may not be feasible. Furthermore, exploring a wider range of current parameters would increase complexity and duration which could present practical challenges [13, 14].

Most stainless steels manufactured through powder sintering methods exhibit limitations in high-temperature strength. This weakness arises from microstructural factors and inadequate creep resistance, which stem from the presence of impurities and amorphous phases at grain boundaries. Investigating mechanical properties and challenges like hydrogen embrittlement would require supplementary experimental setups and testing procedures, which may not be feasible within the scope of this research [15]. The proposed model represents heterogeneous materials as an assembly of interconnected structural elements, namely the matrix and inclusions. These inclusions, differing in shape, are randomly dispersed within the matrix. The aluminum matrix is characterized as a deformed elastic-plastic medium, whereas the ceramic inclusions are considered deformed brittle solids. The research highlights the emergence of non-uniform stress and strain distributions, contributing to the formation of dissipative structures. Additionally, it identifies possible damage mechanisms, such as cracking of ceramic particles, debonding at the matrix-inclusion interface, and deterioration of the matrix itself [16]. However, there are still challenges in optimizing GMAW parameters to achieve a stable austenite-ferrite balance while reducing the formation of detrimental phases such as sigma and chi.

It operates mechanically, which means that the component is able to withstand mechanical stress, impact, bending, vibration, sliding friction, extreme temperatures, and harsh environmental conditions, while still functioning properly [17]. This is likely due to the complexity of the interaction between heat input and phase transformation, as well as the limitations of comprehensive models that can predict the microstructural evolution under various welding conditions. In addition, deformation at high temperatures significantly accelerates the rate of precipitation while increasing the strength of the material [18].

High-resolution phase identification, such as the detection of small amounts of sigma phase, requires advanced characterization techniques such as Transmission Electron Microscopy (TEM), Electron Backscatter Diffraction (EBSD), or Atom Probe Tomography (APT), each of which requires high technical expertise and sophisticated equipment. Modelling heat flow, phase transformations, and residual stress distribution in Electron Beam Welding (EBW) processes faces significant computational challenges due to the high energy density and rapid thermal cycling. The utilization of phase field-based modelling approaches or the CALPHAD method for duplex steel (DSS) under EBW conditions requires a very detailed thermodynamic database, which is often beyond the scope of conventional experimental studies [19]. Evaluation of long-term performance parameters, such as fatigue or corrosion resistance, is often not a primary focus. Residual stress analysis requires specialized instruments such as X-ray diffraction (XRD) or neutron diffraction, which are not yet standard equipment in most welding laboratories. Meanwhile, corrosion resistance testing especially for localized forms of corrosion requires more complex test procedures and follows specific standards, such as ASTM G48 or G28. On the other hand, high-resolution phase characterization, such as identification of sub-micron carbides or delta ferrite phases, requires advanced techniques such as TEM, EBSD, or APT, which are technically demanding and require specialized expertise [20].

Focusing on phase transformation kinetics and microstructural evolution may restrictthe study's scope in this domain. A thorough evaluation of corrosion resistance and mechanical properties would necessitate additional experimental setups and testing protocols, potentially surpassing available resources. Examining the effects of welding would require replicating welding conditions and analyzing the resulting microstructures, further increasing the complexity. Exploring these unexamined aspects would offer a deeper insight into the impact of sigma phases in SDSS, especially concerning their performance in practical application [21]. The impact of post-processing treatments, such as heat treatment or surface finishing, on the microstructure and mechanical properties of the molded products has not been widely studied. Comprehensive long-term performance testing and in-depth post-processing experiments require significant resources, which may not be available [22].High-value duplex steels are primarily selected for their superior resistance to corrosion in chloride-containing environments. Therefore, the welding technology applied must be able to guarantee adequate corrosion resistance, especially in the weld joint areas that are in direct contact with aggressive media. In single-sided welding processes, such as on pipelines, small vessels, and containers, the weld root and the surrounding heat-affected zone are the areas most susceptible to corrosion. The comparison between duplex steel and other materials commonly used in building structures is primarily focused on corrosion resistance and mechanical properties. Analyzing structural performance under stress and performing a comprehensive comparative analysis may require expertise from multiple disciplines, which could exceed the original scope of the study [23, 24].

The efficiency of DE-GMAW teleoperation is achieved by integrating high-quality camera visuals and precise robotic execution into a VR environment. This approach eliminates the risks associated with manual on-site welding, such as exposure to welding fumes, arc radiation, and electric shock, while increasing precision in observation and operation. While the results demonstrate the effectiveness of human-robot collaboration in enhancing the DE-GMAW process, the process is not entirely automated, indicating room for further development toward full automation. The comparison between the HRC-optimized DE-GMAW process and traditional welding methods is primarily focused on efficiency, quality, and cost-effectiveness, with limited exploration beyond these aspects [25].

Understanding the influence of magnetic field parameters is very important for optimizing the welding process, as it is necessary to analyze how the magnetic field orientation affects the weld formation characteristics and the presence of porosity in the welded joint, as these are the main factors affecting the mechanical properties and integrity of the weld. However, is does not comprehensively assess the mechanical properties of the welded joint, such as tensile strength, hardness, and fatigue resistance, which are very important for evaluating the performance of the weld under operational conditions. Conducting a comprehensive evaluation of the mechanical properties, microstructural analysis, and durability assessment will require additional experiments and advanced techniques [26].

The viscosity of the fluorine-containing silicate melt decreases more rapidly until it reaches a dynamic equilibrium between the dissociation and recombination of species. Compared with the fluorine-free silicate melt, the process of returning to the natural state is slower, because the fluorine ions interact with the silicate network through the formation of new Si-F bonds. The long-term stability of melts with different fluorine and nitrogen levels has not been examined. Evaluating this factor could be crucial for applications that demand sustained thermal stability. Conducting detailed structural analysis and high-temperature studies requires advanced techniques and equipment, which may not have been accessible or feasible for this study [27].

Although there have been many studies on DSS welding, there is still an unresolved issue regarding the extent to which GMAW methods affect key mechanical properties, such as tensile strength, impact toughness, and hardness. Post-welding heat treatments, such as tempering after cooling, that cause changes in mechanical behavior due to welding are still not fully understood. This study aims to address these unresolved issues by systematically analyzing the effects of various GMAW methods on the mechanical characteristics of DSS. By identifying the specific impacts of welding on tensile strength, impact toughness, and hardness, this study seeks to provide important insights for optimizing welding techniques to maintain or even improve the DSS performance in industrial applications.

3. The aim and objectives of the study

This study aims to evaluate the effect of the GMAW method on the mechanical characteristics of duplex stainless steel. This will make it possible to optimization of welding techniques to improve the performance and durability of duplex stainless steel in various industrial applications.

To achieve this aim, the following objectives are accomplished:

– to systematically assess the impact of GMAW on the tensile strength and hardness of duplex stainless steel;

– to effectively analyze the microstructure of duplex stainless steel after GMAW process;

– to assess the impact resistance of duplex stainless steel after GMAW process.

4. Materials and methodology

The object of the study is duplex stainless steel, in particular its behavior during gas arc welding using continuous and pulsed current modes. The main focus of this study is to analyze how variations in GMAW parameters affect the main mechanical properties, such as tensile strength, hardness, fatigue resistance, and overall quality of the welded joint. By evaluating these factors, this study attempts to optimize the welding conditions to improve the performance and durability of duplex stainless steel in various industrial applications.

Differences in GMAW techniques play a crucial role in determining the mechanical properties of duplex stainless steel. Specifically, variations in welding parameters such as heat input, shielding gas composition, and welding speed are believed to influence essential characteristics, including tensile strength, hardness, fatigue resistance, and overall weld integrity. Optimizing these parameters can enhance the mechanical performance of duplex stainless steel, increasing its suitability for industrial applications that demand high strength and corrosion resistance.

The duplex stainless steel rod was sectioned into equal samples, each measuring 100.2 mm in length. These samples were then cut into two equal halves and subsequently welded together using the GMAW process. Various treatments were applied to some of the welded samples, while others were retained as reference standards for comparative analysis. Prior to welding, each sample underwent chamfering to create a 30° half-groove angle on one side, using a milling machine, leaving a 2 mm root face for proper joint formation. The butt joint welding technique was utilized, as depicted in Fig. 1.

Welding parameters such as heat input, type of shielding gas, and welding speed were varied, while other factors were kept constant. To avoid variations due to compositional differences, a single type of duplex stainless steel was used. Evaluation of mechanical properties was limited to tensile strength, hardness, and fatigue resistance, without performing in-depth microstructural analysis or examining long-term durability. Welding processes and testing were carried out under controlled laboratory conditions, without considering real environmental factors such as temperature changes or corrosion exposure.

Tensile strength measurement is conducted using a compact servo-hydraulic system, which enables precise tensile testing. The system is equipped with a load cell to accurately measure force and an extensometer to determine strain during deformation. For hardness testing, a motorized press system with an automatic load application mechanism is utilized. This setup supports multizone scanning, allowing for hardness mapping across different weld regions, HAZ, and fusion zone (FZ). The butt gas metal arc welding process is depicted in Fig. 2.

The samples were cleaned from dirt and oil, then ground using a grinding machine before the welding process to obtain a smooth and even surface. This machine is designed to stretch the sample at a constant speed, while simultaneously measuring the applied load and the resulting elongation using an extensometer. Sample preparation was carried out according to BS18 standards, as shown in Fig. 3.

The Charpy impact test is performed in accordance with ASTM A370, standard methods and definitions for mechanical testing of steel products and ASTM E23 standard method for notched bar impact testing of metallic materials. Optical microscopy reveals the distribution of austenite and ferrite phases in each weld area, while SEM and metallographic provides high-resolution images of grain boundaries, cracks and secondary phases. Mechanical testing and microstructural analysis are correlated to assess the impact of different welding techniques.

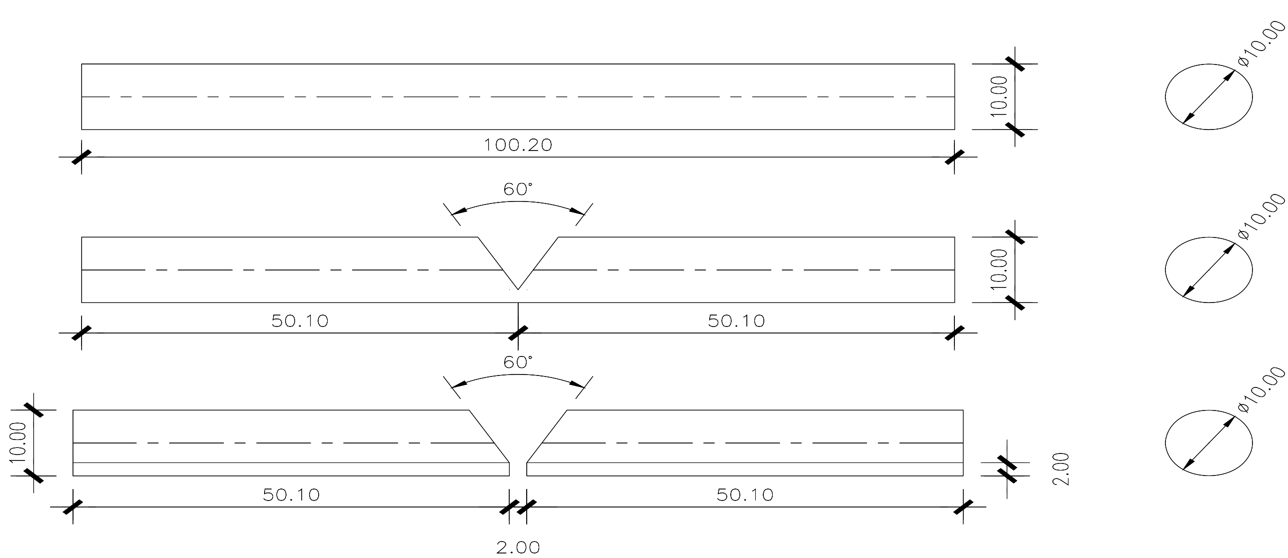

Fig. 1. Joint preparation for groove welding [28]

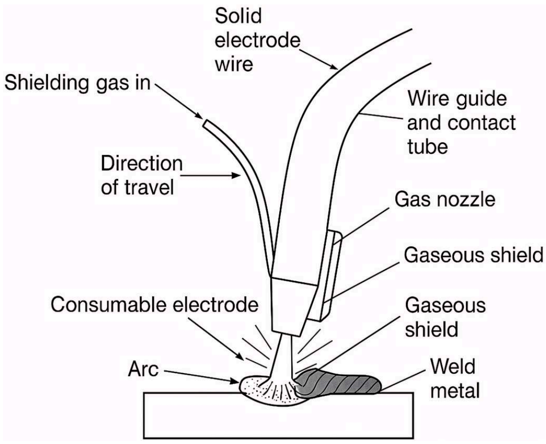

Fig. 2. Gas metal arc welding process

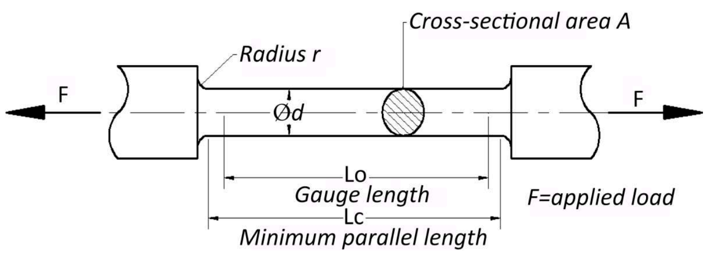

Fig. 3. Standard sample for tensile test [28]

5. Research on the influence of GMAW process variations on the strength and ductility of duplex stainless steel

5. 1. Results of the impact of GMAW variations on the properties of duplex Stainless steel

The results this research show that welding parameters in the GMAW process play an important role in determining the tensile strength and hardness of stainless steel. Variations in heat input during the welding process affect the microstructure of the weld metal and the HAZ, which ultimately leads to differences in the mechanical properties of the materials. The tensile strength of the welded specimens was measured to evaluate their ability to withstand tensile loads. The results are summarized in the Table 1.

LHI (low heat input) produced the highest tensile strength of 610 MPa, due to the formation of finer grains that contribute to increased strength and ductility. MHI (Medium Heat Input) showed a decrease in tensile strength to 580 MPa, indicating slight grain coarsening in the HAZ. Meanwhile, HHI (High Heat Input) recorded the lowest tensile strength of 540 MPa, which was caused by excessive grain growth, carbide precipitation, and possible formation of sigma phases that can weaken the material structure. Hardness measurements were performed on the weld metal, HAZ, and base metal using the Vickers Hardness Test. A summary of the results is presented in Table 2.

Table 1

Effect on tensile strength

Welding condition	Heat input (J/mm)	Tensile strength (MPa)	Fracture location
Low heat input (LHI)	792	610 MPa	Weld metal
Medium heat input (MHI)	1375	580 MPa	Heat-affected zone (HAZ)
High heat input (HHI)	2333	540 MPa	Heat-affected zone (HAZ)

Table 2

Result effect on hardness

Welding condition	Weld metal (HV)	HAZ (HV)	Base metal (HV)
Low heat input (LHI)	210 HV	220 HV	200 HV
Medium heat input (MHI)	195 HV	205 HV	200 HV
High heat input (HHI)	180 HV	190 HV	200 HV

LHI produced the highest hardness value, especially in the HAZ zone (220 HV), which was caused by the fine microstructure resulting from the rapid cooling process. MHI showed a slight decrease in hardness value, indicating moderate grain coarsening but still maintaining structural integrity. Meanwhile, HHI recorded the lowest hardness because slower cooling triggered grain growth and softening of the material, thus increasing its susceptibility to deformation.

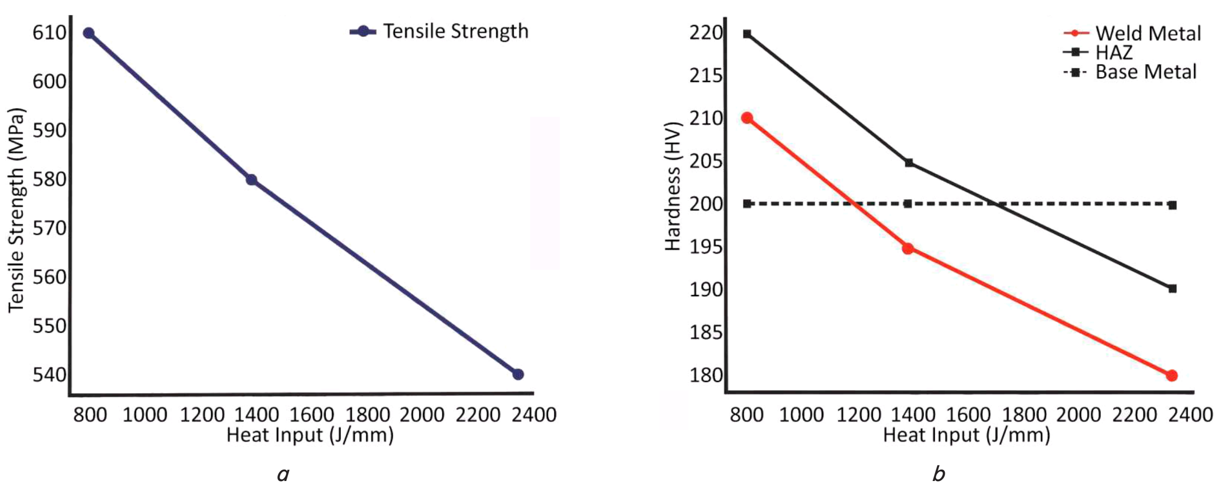

Fig. 4. The tensile strength and hardness: *a* – tensile strength vs heat input; *b* – hardness vs heat input

As the heat input increases, the tensile strength tends to decrease due to grain coarsening and softening in the HAZ. The hardness of the weld metal and HAZ also decreases with increasing heat input, while the base metal remains stable. This indicates that excessive heat input causes a decrease in hardness due to slower cooling and larger grain growth.

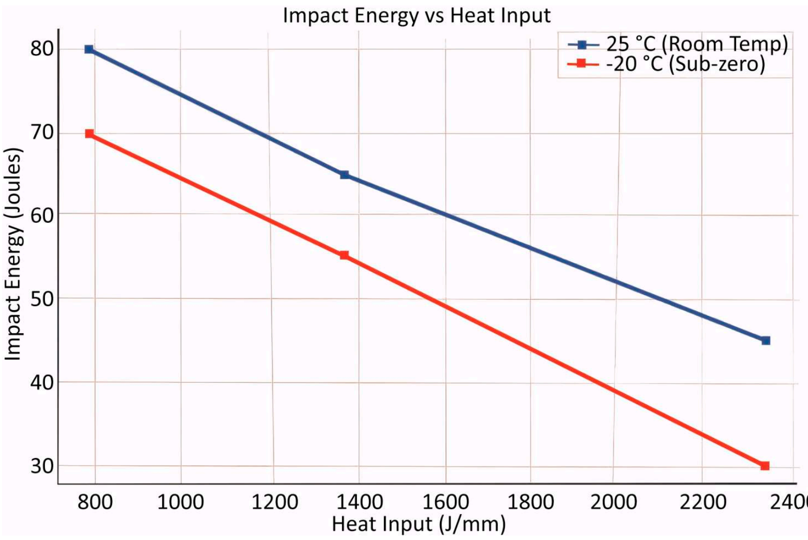

Fig. 5. Impact resistance decreases with increasing heat input

The graph shows the relationship between impact energy and heat input at two different temperatures. The blue line represents the impact energy at room temperature (25 °C), while the red line represents the impact energy at cold temperature (–20 °C). From the graph, it can be seen that the impact resistance decreases with increasing heat input. This decrease is more significant at lower temperatures, emphasizing the importance of controlling welding parameters in cold environments.

5. 2. Results of microstructural changes in duplex stainless steel after GMAW welding

The weld metal (WM) exhibits a dendritic solidification structure, with elongated ferrite grains formed along the solidification area. The HAZ experiences grain coarsening due to thermal cycling, with an increase in ferrite content in the high-temperature region. Meanwhile, the base metal (BM) maintains a balanced duplex microstructure, with austenite and ferrite phases evenly distributed. The increase in ferrite content is observed in the WM and HAZ may affect the mechanical properties, especially in terms of toughness and corrosion resistance. The dendritic ferrite structure with the formation of interdendritic austenite reflects the characteristics of rapid solidification during the welding process. In addition, the presence of ferrite along the grain boundaries indicates an incomplete phase transformation due to the high cooling rate. The microstructure of the analyzed samples shows smooth grain boundaries and shows a more homogeneous mixing between the parent metal and alloy elements, as seen in Fig. 6 below.

The observed microstructures clearly show that the morphological changes caused by the welding process have a significant impact on various material characteristics, including mechanical strength, toughness, corrosion resistance, and thermal behavior. These changes can affect the long-term performance and reliability of welded joints in real applications as seen in Table 3 below.

The result shown in Table 4 reveal that it is possible to improve higher hardness of the weld metal (WM) due to the dominance of ferrite, which is harder but also more brittle than austenite. The HAZ shows a slightly higher hardness increase compared to the base metal due to grain growth and phase changes during the welding process. Meanwhile, the BM has the lowest hardness level, but still maintains the best toughness and ductility due to its balanced duplex structure. To improve the mechanical properties of duplex stainless steel after GMAW process, optimization of key welding parameters is required to maintain the balance of ferrite-austenite ratio, minimize hardness variation, and improve toughness and corrosion resistance.

Moderate corrosion resistance is due to the potential formation of secondary phases such as chromium nitride (CrN) and sigma (σ), which can weaken the protective properties of the material in the weld area. The use of optimization corrosion resistance is increased due to a more uniform phase distribution and minimal fouling precipitation. Proper selection of filler metal, use of optimized shielding gas, and effective post-weld cleaning help prevent the formation of CrN and σ phases, thereby increasing corrosion resistance. By fine-tuning welding parameters, adjusting shielding gas composition, controlling cooling rates, and applying appropriate post-weld treatments, the mechanical performance and corrosion resistance of duplex stainless steel can be greatly enhanced. These enhancements make the material more suitable for demanding industrial applications, including offshore platforms, pipeline systems, and chemical processing facilities.

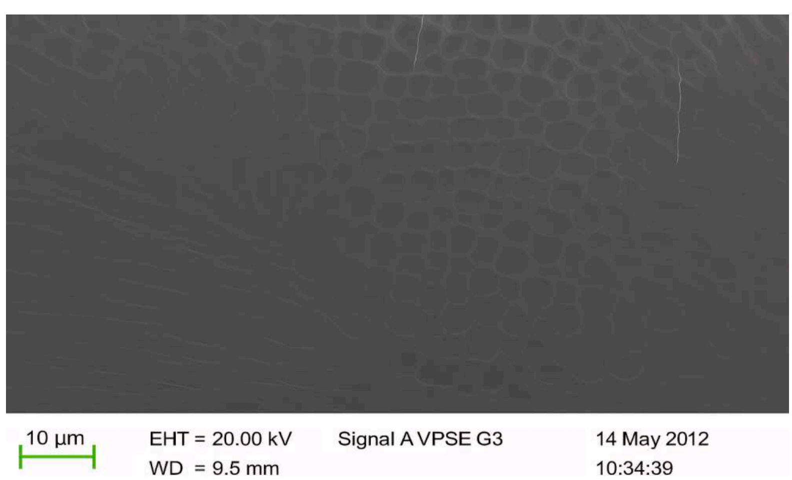

Fig. 6. Microstructural sample

Table 3

Vickers hardness (HV) measurements

Region	Hardness	Observation
Base metal (BM)	230–260 HV	Balanced ferrite-austenite ratio (~50:50), fine-grained structure
Heat affected zone	250–280 HV	Grain coarsening leads to moderate hardness increase. Higher ferrite content (~60 %)
Weld metal (WM)	280–320 HV	Higher ferrite (~65-70 %) results in increased hardness but lower toughness

Table 4

Expected improvements with optimization

Property	Without optimization	Optimization process
Ferrite-austenite ratio	~65–70 %ferrite	50–55 %ferrite, 45–50 % austenite
Tensile strength (MPa)	~820–860 MPa	~750–800 MPa (more balanced)
Hardness (HV)	280–320 HV	230–270 HV (more uniform)
Elongation (%)	280–320 HV	~25–30 %
Corrosion resistance	Moderate (CrN, σ-phase issues)	High (reduced impurities)

5. 3. Results of impact resistance of stainless steel after welding using GMAW

The impact resistance of stainless steel after the GMAW process is influenced by various factors, such as welding parameters, heat input rate, type of filler material, and post-welding treatment. Impact resistance measurements are usually carried out by the Charpy V-Notch (CVN) Test, which assesses the energy absorbed by the material before it fractures as seen in Table 5 below.

Table 5

Impact test results low temperature

Zone	Impact energy (*J*) at room temperature	Impact energy (*J*) at – 40 °C	Observation
Base metal	180–220 J	150–180 J	Maintains superior toughness as a result of a well-balanced ferrite-austenite microstructure
Heat affected zone	100–140 J	60–100 J	Lower toughness caused by grain growth and accumulated residual stresses
Weld metal (WM)	80–120 J	40–80 J	Exhibits the least impact resistance due to a high ferrite content and possible defects

At subzero temperatures, toughness decreases in all areas, but the weld metal (WM) is most affected. This is due to the higher ferrite content, which becomes more brittle at low temperatures, and the absence of austenite transformation, which reduces the ability to absorb energy. In addition, the presence of weld defects acts as a crack initiation point, further reducing impact resistance. WM has a higher ferrite content (~65–70 %), which leads to decreased impact resistance, especially at low temperatures. High heat input results in grain growth in the HAZ, reducing the toughness of the material. Rapid cooling promotes the formation of larger amounts of ferrite, further reducing impact resistance. In addition, the HAZ and WM experience higher residual stresses, making them more susceptible to brittle fracture under impact loads. The presence of porosity and inclusions in the WM can also act as a crack initiation point, contributing to reduced impact energy absorption.

As shown in Table 6, increasing temperature causes the material to become more effective in absorbing impact energy due to increased ductility and decreased residual stress. However, exposure to excessive high temperatures can trigger microstructural damage, phase transformation, and increase the brittleness of the material.

At 400 °C, duplex stainless steels generally experience increased impact resistance due to stress relaxation and phase stability. However, areas such as the weld metal and heat-affected zone need to be optimized to reduce residual stresses and phase imbalances, thereby ensuring better toughness and mechanical performance in high-temperature applications. Impact resistance is generally assessed by the Charpy V-Notch (CVN) Test, which measures the energy absorbed by a material before it fractures.

Table 6

Impact resistance at high temperatures

Zone	Impact energy (J) at – 400 °C	Observation
Base metal	240 J	Enhanced toughness as a result of stress relief
Heat affected zone	150 J	Balanced toughness, though potential phase imbalance may arise
Weld metal (WM)	120 J	Reduced impact resistance caused by residual stresses

6. Discussion of the impact of heat input variation on the mechanical properties and microstructure of welded joints in duplex stainless steel

Experimental data presented in the Table 1 reveal a clear correlation between the magnitude of heat input during GMAW process and the tensile strength characteristics and fracture location of duplex stainless-steel welded joints. Increasing the heat input from 792 J/mm (LHI category) to 2333 J/mm (HHI category) is accompanied by a gradual decrease in the tensile strength. Specifically, the tensile strength decreases from 610 MPa at LHI to 580 MPa at MHI category, and further decreases to 540 MPa at HHI. The weld metal hardness measurement data listed in Table 2 regarding the effect on hardness, HAZ, and base metal at various levels of heat input show a uniform trend: the higher the heat input in the GMAW process, the lower the hardness values produced, especially in the weld metal and HAZ. At the low heat input (LHI) level, the highest hardness values were recorded, namely 210 HV for the weld metal and 220 HV for the HAZ, while the hardness of the base metal remained constant at 200 HV. Fig. 4 shows that higher hardness values tend to occur due to low heat exposure, which allows the formation of fine grain structure and maintains the balance of ferrite-austenite phase distribution. This condition contributes to the increase in local strength. However, when the heat input is increased to the MHI level, there is a decrease in the hardness of the weld metal and HAZ to 195 HV and 205 HV, respectively. This decrease indicates that the increase in thermal energy triggers microstructural changes, such as grain growth and possible reduction of the strengthening phase, especially in the weld area and its surrounding zones.

Fig. 5 shows that increasing heat input results in a decrease in impact strength. The graph on the left shows a consistent decrease in tensile strength with increasing heat input. At the lowest heat input level, which is about 792 J/mm, the material reaches a tensile strength of 610 MPa. However, when the heat input increases to 1375 J/mm and 2333 J/mm, the tensile strength decreases gradually to 580 MPa and 540 MPa. This inverse relationship indicates that increasing heat input has a detrimental effect on the mechanical strength of the welded joint. The decrease is most likely related to excessive thermal exposure, which can result in grain growth, imbalance of the ferrite-austenite phase ratio, and decrease in the amount of strengthening phase, thereby reducing the integrity of the joint. Meanwhile, the graph on the right illustrates the effect of heat input on hardness in three main areas: weld metal, HAZ, and base metal. A significant decreasing trend in hardness is observed in the weld metal and HAZ with increasing heat input. These two graphs together emphasize the importance of controlling heat input during the welding process of duplex stainless steel. Lower heat input has been shown to increase the tensile strength and hardness of the material, while excessive heat input actually decreases these two important properties. Therefore, the setting of welding parameters, especially the amount of heat input, is crucial to ensure optimal joint quality, structural reliability, and long-term durability, especially in applications in extreme working environments, where duplex stainless steels are widely used. The graph also highlights the effect of temperature on the impact performance of the material. At each level of heat input, the impact energy measured at subzero temperatures shows a significant decrease compared to the value at room temperature. For example, at low heat input conditions, the difference in impact energy reaches about 10 joules, while at the highest heat input, this difference increases to 25 joules. These findings highlight the sensitivity of duplex stainless steels to low temperatures, where a drastic decrease in temperature increases the brittleness of the material, especially when combined with high heat input during the welding process.

The emergence of ductile fracture characteristics is in line with the high values of impact energy and tensile strength recorded at low heat input conditions, as explained in the previous section regarding the mechanical test results. These findings strengthen the conclusion that welded joints made with optimized heat input, especially at low levels, are able to maintain favorable microstructures, such as fine grain size and balanced austenite-ferrite phase distribution, which significantly support the improvement of mechanical performance. The results of this SEM analysis serve as a complement to the mechanical data and provide visual validation that the use of low to moderate heat input during the GMAW process tends to produce a ductile fracture mechanism in duplex stainless steels. These characteristics are highly desirable in structural applications, especially for components operating in environments that demand high toughness and reliability against sudden failure. Thus, controlling the heat input to maintain an optimal welding thermal profile is a crucial factor to ensure superior mechanical quality and long-term stability under extreme service conditions.

Based on Table 3, the weld metal recorded the highest hardness value in the range of 280 to 320 HV, which is closely related to the significant increase in the ferrite fraction to around 65–70 %. This increase in the ferrite fraction is a common consequence of the rapid cooling and solidification process during welding. Although increasing the ferrite content can increase hardness, this condition also tends to decrease toughness, making the weld metal more susceptible to brittle fracture, especially when subjected to shock loads or in low-temperature environments. In addition, excessive ferrite content can reduce resistance to pitting corrosion, especially in environments with high chloride content. Overall, the test results show a clear hardness gradient from the base metal, through the HAZ, to the weld metal, reflecting the variation in the degree of thermal exposure and the accompanying microstructural changes. These findings emphasize the importance of controlling the heat input and selecting the filler material composition during the welding process, in order to achieve an optimal balance of ferrite and austenite phases. This balance is critical to maintaining the combination of mechanical properties and corrosion resistance required to ensure the long-term reliability of duplex stainless-steel welded joints, especially in extreme operating environments.

Based on Table 5, the HAZ exhibits a significant reduction in toughness, as indicated by impact energy values ranging from 100 to 140 joules at room temperature, decreasing to 60 to 100 joules at 40 °C. This reduction in toughness is primarily due to excessive grain growth, detrimental microstructural transformations, and the formation of residual stresses due to rapid heating and cooling cycles during the welding process. The lower impact energy in this region indicates an increased propensity for crack initiation and propagation, especially under dynamic operating conditions or extreme low temperatures. All zones of the material exhibited a reduction in impact energy when tested at –40 °C, which can be attributed to reduced atomic mobility and increased brittleness due to low temperatures. However, the extent of this reduction differed between zones, with the weld metal showing the highest sensitivity to extreme cooling, while the base metal experienced the least degradation. This pattern emphasizes the importance of maintaining microstructural integrity to ensure joint toughness, especially in applications in cryogenic or sub-arctic environments.

As seen in Table 5, the weld metal exhibited the lowest impact energy value of 120 J, indicating a significant decrease in the impact load capacity at extreme low temperatures, such as 40 °C. This decrease in toughness is most likely due to the presence of residual stresses due to the welding process and the high ferrite fraction, which are generally known to reduce toughness in duplex stainless steels. In addition, the weld metal was more susceptible to the formation of weld defects, which can act as initiation points for crack propagation under cryogenic conditions. These findings highlight the importance of microstructural stability and residual stress management in maintaining toughness at ultra-low temperatures. The superior performance of the base metal in the impact test indicates that effective stress relaxation processes contribute significantly to mechanical integrity. Conversely, the low toughness of the weld metal underscores the need for proper welding parameter settings and the application of post-weld heat treatments to reduce the potential for brittleness in low-temperature or cryogenic service environments.

This study investigated the effect of various GMAW methods on the mechanical properties of duplex stainless steel. The results of the analysis showed a significant relationship between welding parameters and the resulting mechanical characteristics, thus enriching the understanding of the effect of GMAW techniques on tensile strength, hardness, and overall quality of welded joints. However, there are several limitations that need to be considered. This study only covers certain welding conditions and one type of duplex stainless steel, which may limit the generalization of the results. In addition, important aspects such as corrosion resistance and long-term fatigue performance, which are crucial in practical applications, have not been discussed in this study. The characterization of mechanical properties also still relies on conventional test methods without involving advanced techniques such as microstructure or phase analysis that can provide a deeper understanding of the behavior of welded joints. Awareness of the limitations of this study opens up opportunities for further research in the future. Further research can include various welding parameters as well as comparison with other arc welding techniques. The use of advanced analytical methods such as EBSD and TEM will allow a deeper exploration of the microstructural changes. In addition, investigations into the effects of post-weld heat treatment and studies on long-term corrosion and fatigue resistance under real-world conditions will provide a more comprehensive understanding of the effectiveness of the welding technique used. Computer simulation and thermal modeling can also provide a predictive picture of the welding results under various operational conditions. Overall, this study provides a strong foundation for scientific development and industrial applications. The direction of further research is directed at identifying the limitations and optimal parameters in the application of the GMAW process on duplex stainless steels for various application needs.

7. Conclusions

1. Heat input during GMAW significantly affects the mechanical properties of stainless steel, including tensile strength, hardness, and impact resistance:

– tensile strength: 792 J/mm, reduced: 580 MPa (MHI), 540 MPa (HHI);

– hardness (in HAZ): 220 HV, 205 HV, 190 HV;

– impact energy, 25 °C: 80 J (LHI) to 45 J (HHI); –20 °C: 70 J (LHI) to 30 J (HHI).

2. The presence of fine and evenly distributed grains in the heat-affected zone (HAZ) contributes to enhanced tensile strength, hardness, and toughness. Utilizing a low heat input helps preserve the base metal's original microstructure, whereas higher heat input can lead to the development of a brittle structure particularly harmful in low-temperature environments.

3. Temperature has a significant influence on fracture behavior. All specimens show a significant decrease in impact energy at –20 °C, where the degree of this decrease is negatively correlated with the grain fineness and microstructural stability maintained during the welding process. The transition from ductile to brittle fracture is clearly observed in samples welded with high heat input.

Conflict of interest

The author declare that he has no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors affirm that no artificial intelligence technologies were utilized in the creation of this work.

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