An Investigation of AISI 304 Stainless Steel Using SEM - EDS by Gas Metal Arc Welding

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***Abstract*—**The welding process presents significant fabrication difficulties when dealing with thicker materials, particularly those with a thickness of 12 mm and above. Joining such large thicknesses is a considerable challenge, as numerous issues arise during the welding process. To address these challenges, the current study focuses on the welding of thick plates made of AISI SS 304 grade. The study aims to investigate the problems and challenges encountered during welding using the GMA Welding process. Additionally, the study aims to examine various mechanical properties of the 12 mm thick plates. The primary objective of this study was to examine the impact of Gas Metal Arc Welding (GMAW) on the microstructure of the weld metal and the Heat-Affected Zone (HAZ) under varying welding conditions. Furthermore, the study aimed to determine how these changes in microstructure affected the mechanical properties, The Energy Dispersive Spectroscopy (EDS) testing was conducted on AISI 304 stainless steel welds produced using various Gas Metal Arc Welding (GMAW) methods, including Constant Current (CC-GMAW), Pulsed Current (PC-GMAW), Double Pulsed Current (DPC-GMAW), and Cold Metal Transfer (CMT-GMAW). The EDS analysis aimed to evaluate the elemental composition of the weld zones for each technique. Results indicated variations in elemental distribution, particularly in chromium, nickel, and iron content, which are critical to the corrosion resistance and mechanical properties of AISI 304 stainless steel. These differences were attributed to the distinct thermal cycles and metal transfer characteristics associated with each welding method. Overall, the CMT-GMAW process exhibited more uniform elemental .

Keywords—component, formatting, style, styling, insert (key words)

1. Introduction

Stainless steels are iron-based alloys containing at least 12% chromium, which prevents rust and imparts the “stainless” quality by forming an invisible chromium oxide layer that self-heals in the presence of oxygen. Their composition often includes nickel, manganese, molybdenum, copper, silicon, titanium, niobium, and other elements to improve specific characteristics such as corrosion resistance, toughness, or machinability. Carbon content in stainless steels varies from less than 0.03% to over 1.0%, depending on the grade and desired properties. These alloys are versatile and can be produced in cast, powder metallurgy, and wrought forms, with common wrought products including sheets, strips, plates, wires, and pipes. Cold-rolled flat products dominate the market, accounting for over 60% of production.

The manufacturing process of stainless steels involves two main stages: melting scrap and ferroalloys in an Electric Arc Furnace (EAF), followed by refining via Argon Oxygen Decarburization (AOD) to adjust carbon content and remove impurities. Alternative methods like vacuum induction melting or electron beam melting are also used in specialized applications. Final processing steps, such as hot reduction, cold rolling, annealing, and cleaning, refine the materials to achieve specific dimensions and surface finishes. Classification of stainless steels is based on their microstructure, categorized into austenitic, martensitic, ferritic, duplex, and precipitation- harden able types. They are widely used in industries like chemical processing, power generation, and food manufacturing due to their durability, corrosion resistance, and adaptability. Stainless steels find applications in products ranging from reactor vessels and heat exchangers to kitchen utensils and automotive components, making them integral to modern industry and everyday life

Historically, stainless steels have been classified based on their microstructure into four main categories: austenitic, martensitic, ferritic, and duplex (a combination of austenitic and ferritic). Each of these groups offers distinct characteristics that make stainless steels versatile for various applications. Austenitic stainless steels, the largest family, are recognized for their excellent corrosion resistance and high-temperature strength, primarily composed of iron-chromium-nickel or iron-chromium-manganese-nickel alloys.

Martensitic stainless steels have higher carbon content and lower chromium levels, making them hard enable through heat treatment, suitable for applications requiring strength and wear resistance. Ferritic stainless steels, on the other hand, are non-hard enable iron-chromium alloys that perform well in moderate corrosion environments. Duplex stainless steels combine both austenitic and ferritic structures, providing enhanced strength and resistance to stress-corrosion cracking. In addition, a fifth category known as Precipitation-Hardenable (PH) stainless steels is classified based on the heat treatment used rather than their microstructure, offering high strength and corrosion resistance through controlled precipitation of compounds.

II. Literature Review

A. Shielding Gases

Nicseresht et al. (2010) studied the effect on the microstructure due to heat treatment and corrosion behaviour of Al 6061 TIG welded joints. The corrosion behavior is studied in 3.5 wt percentage NaCl aqueous solution and the result indicated that the base metal consists of Fe rich coarse inter metallic particles which act as cathodic region. The result also indicated that the heat treatment leads to displacement of the base metal corrosion.

Jiangetal (2010) investigated the micro structural and mechanical properties of TIG welded steel joints subjected to PWHT (Post Welding Heat Treatment) at 740° c for one hour. They conducted the mechanical & micro structural tests on the welded joints and the result showed that the mechanical properties and micro structural of the steel welded joints can be improved by a reasonable Post Welding Heat Treatment.

B. Shielding Gases Process

Hidetoshi Fuji et al. (2008) investigated the effect of mixed shielding gas He- O2 and He-CO2 on TIG welding process for the welding of SUS304 stainless steel, in which the effect of concentration of O2and CO2 on the shielding gas of the weld shape was studied. They stated that the addition of oxygen through the shielding gas in the molten pool controls the marang on convention because oxygen is a surface active element for stainless steel.

Cayetal, (2011) analysed the effect of hydrogen as shielding gas on the microstructure and abrasive wear behavior for the surface modification process by applying TIG method. Two different types of shielding gas compositions were selected and it was observed that the microstructure and hardness of the specimen is modified when the shielding gas composition varies.

C. GTA Welding Process

Lothongkumetal. (2001) have studied the effect of pulsed TIG welding parameters such as welding speed, pulse-base currents, pulse frequency, percentage on time, change in volume percentage of shielding gas (argon,nitrogen), flow rate of shielding gas and welding position on the delta ferrite content, shape factor and bead quality in orbital welding of AISI 316l Stainless steel plate. It has been concluded that for 6 h welding position, the optimum welding parameters are base current of 61 A, pulse frequency of 5Hz, 65% on time as constant, varying the weld speed 2-8 mm/sec and 0- 4 volume percentage of nitrogen in argon shielding gas and they are examined until good weld bead geometry with complete penetration occurred.

Jaime Hinojosa-Torres et al. (2008) carried out TIG welding on Zn-22Al- 2Cu alloy plates. Their search from the investigation revealed that crystalline phases are present in the parent metal as well as in the fusion zone. Similarly near the fusion line equiaxed grains surrounded by a network are observed..

III SExperimental Plan

The welding process for AISI 304 stainless steel plates involves meticulous preparation to ensure high-quality results. The base metal, consisting of 12 mm thick plates with dimensions of 300 x 75 mm, is cleaned thoroughly by wire brushing to remove the oxide layer and wiped with acetone to eliminate contaminants. A 60° single V-groove angle is created, and a gap of 0.8 mm is maintained between the plates for proper penetration during welding. The filler wire used is ER308L, with a diameter of 1.2 mm, which ensures compatibility and corrosion resistance. Shielding gases like pure argon or an argon-helium mix are typically employed to protect the weld zone from oxidation. Key parameters such as welding current, travel speed, and post-weld cleaning are adjusted to optimize the process, ensuring a strong and durable weld free from defects.

Double V joint design with 2mm root face and 2.5mm root gap with a groove angle of 60 degrees was used for the present study. Using a welding current of 90-105A the root pass was given to the plates with GMAW.

It is a well-established fact that among all the welding variables in arc welding processes welding current is the most influential variable since it affects the current density and thus the melting rate of the filler as well as the base material. So in accordance with this fundamental fact two different welding processes were used corresponding to different welding currents. The two plates to be welded were tacked. Welding was carried out by an experienced welding operator. MIG wires of 1.2mm diameter were used to weld 304 stainless steel plates. The electrodes were baked in the oven for 45 min before welding to remove moisture. The numbers of passes taken for gas metal arc welding were 8 respectively.

The experiment has been carried out using different variants of GMAW. The variants used here are Constant Current-GMAW (CC-GMAW), Pulsed Current-GMAW (PC-GMAW), Double Pulsed Current-GMAW (DPC- GMAW), and Cold Metal Transfer-GMAW (CMT-GMAW).

Fig 1 : Welding Plate

Tack welding was carried out by a skilled operator using 1.2 mm MIG wire. Prior to welding, electrodes were baked for 45 minutes to eliminate moisture. The Gas Metal Arc Welding (GMAW) process involved a total of eight passes. During welding, the interpass temperature was carefully maintained between 175°C and 200°C, with a 2-minute interval between passes to allow for slag removal and proper cooling. This controlled approach ensured stable weld conditions and consistent quality. After completion, all welded plates were visually inspected to verify the integrity of the welds. The inspection confirmed that the weld beads were free of defects and demonstrated good geometric consistency throughout. This systematic procedure contributed to high-quality and reliable weld joints

. IV. Welding Methods

A. Constant Current

Constant Current Welding Methods: These are welding processes where the machine maintains a steady current despite changes in arc length. This is crucial for ensuring stable heat input and consistent weld quality. Common methods include Shielded Metal Arc Welding (SMAW) and Gas Tungsten Arc Welding (GTAW/TIG)..

B. Pulse Current

This technique alternates between peak current for penetration and background current to reduce overall heat input. It ensures improved weld quality, minimized thermal distortion, and better control over the heat- affected zone. Commonly used in processes like TIG and MIG welding for thin or heat-sensitive materials.

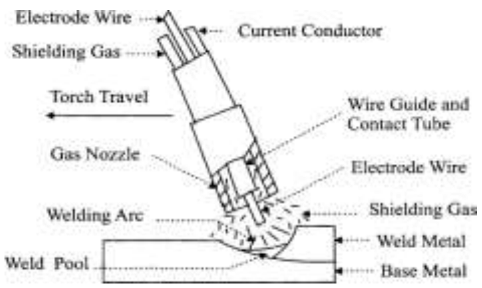

Fig 2 : Welding Mechanism

C. Double Pulse Current

This technique alternates between two levels of pulsed currents to refine weld quality. It ensures deeper penetration, reduced heat input, improved weld bead appearance, and minimized heat-affected zones. It is commonly used for high-precision welding in industries like aerospace and automotive.

D. Cold Metal Transfer

This advanced welding process minimizes heat input using controlled current and precise wire movement. It allows spatter-free and distortion-free welding, making it ideal for joining thin or heat-sensitive materials, such as aluminum and dissimilar metals. Commonly used in automotive and aerospace industries.

V. MICROSTRUCTURE

The four GMAW variants, CC-GMAW, PC-GMAW, DPC-GMAW, and CMT-GMAW, produced full-penetration welds. The width and the fusion area of the four joints differ from one another. Different welding speeds and heat inputs used in the four welding processes are responsible for the differing widths and fusion areas.

Fig 3 : Micrograph of The Base Material AISI 304 Stainless Steel

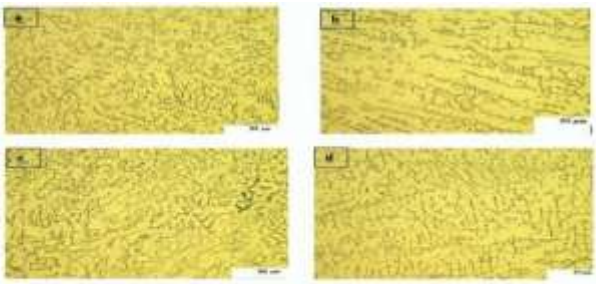

Fig 4 : Mico Optical Image of Weld Region (acc-gmaw (dpc-gmaw (c) dpc-gmac (d) cmt-gmaw

Comparative images of weld joint regions for four GMAW variant CC-GMAW, PC-GMAW, DPC-GMAW, and CMT-GMAW—are shown.
These highlight the differences in grain structures and heat-affected zones (HAZ) due to variations in welding techniques.

VI. *Result and Discussion*

A. ENERGY-DISPERSIVE X-RAY SPECTROSCOPY

Energy-Dispersive X-ray Spectroscopy (EDS) is an analytical technique used to identify and quantify the elemental composition of a material. When a sample is exposed to a focused electron or X-ray beam, it emits characteristic X-rays. These X-rays are unique to each element, allowing EDS to determine the elements present and their relative amounts.

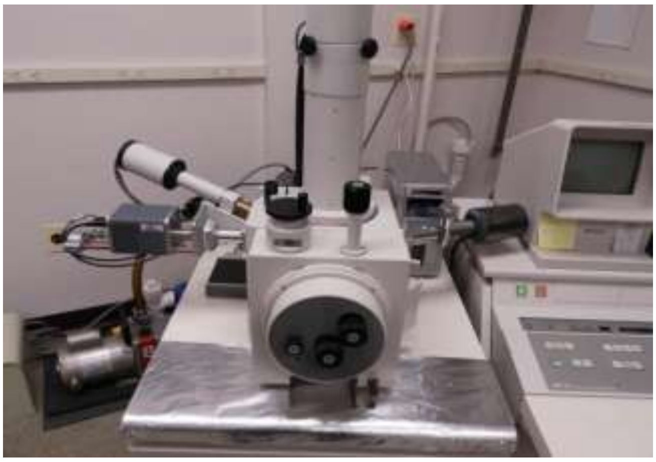

Fig 5 : Energy-dispersive X-ray spectroscopy

A.EDC Testing Result

The Energy Dispersive Spectroscopy (EDS) testing was conducted on AISI 304 stainless steel welds produced using various Gas Metal Arc Welding (GMAW) methods, including Constant Current (CC-GMAW), Pulsed Current (PC-GMAW), Double Pulsed Current (DPC-GMAW), and Cold Metal Transfer (CMT-GMAW). The EDS analysis aimed to evaluate the elemental composition of the weld zones for each technique. Results indicated variations in elemental distribution, particularly in chromium, nickel, and iron content, which are critical to the corrosion resistance and mechanical properties of AISI 304 stainless steel.

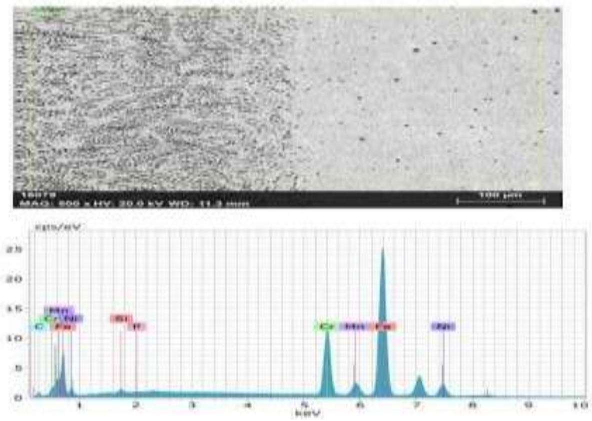

Fig 6 : Eds Alanlyis For Fuction Zone - Pc-Gmaw

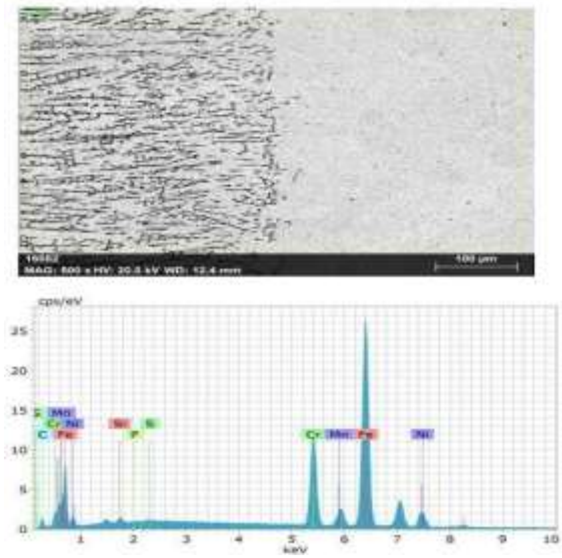

Fig 7 : Cold Metal Transfer Current Testing

VII. TESTING AND EVALUATION

The microchemical analysis of the welded joint, as revealed by Energy Dispersive X-Ray Analysis (EDAX), provides essential insights into the material's composition and its influence on weld performance. The results indicate that iron (Fe) constitutes the majority of the material (67.16 wt.%), serving as the structural backbone and ensuring overall stability. Chromium (Cr), present at 16.79 wt.%, plays a vital role in enhancing corrosion resistance by forming a protective oxide layer. Nickel (Ni), at 7.96 wt.%, contributes to toughness and resistance to oxidation. Carbon (C), accounting for 6.35 wt.%, boosts strength and hardness, though its concentration must be carefully managed to avoid negative impacts on corrosion resistance. Minor elements like manganese (Mn), silicon (Si), phosphorus (P), and sulfur (S) appear in trace amounts and influence weldability, machinability, and overall quality. The precise balance of these elements underscores the importance of controlling composition to achieve optimal mechanical properties and ensure

Fig 8 :Elements Distribution Image Of Mn , Ni , Fe, Si ,Sf ,Se

The welded joint's reliability under varying conditions. This analysis demonstrates the significance of microchemical evaluation in advancing welding techniques and material performance.system's accuracy, responsiveness, and user experience all meet its design objectives.

These differences were attributed to the distinct thermal cycles and metal transfer characteristics associated with each welding method. Overall, the CMT-GMAW process exhibited more uniform elemental distribution, likely due to its lower heat input and controlled droplet transfer,

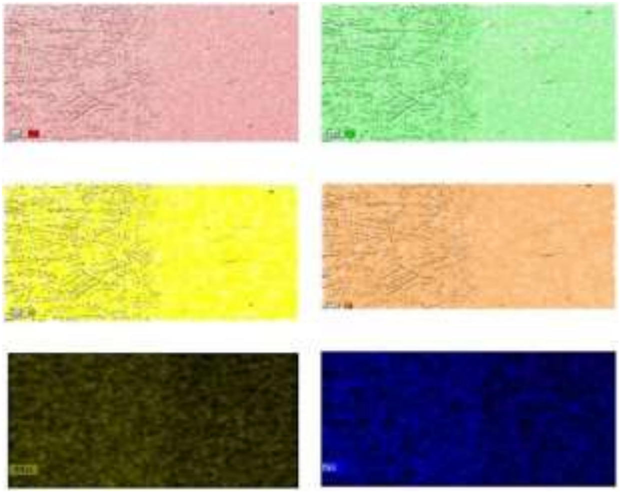

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Fig.9 Elements Distribution Image Of Mn , Ni , Fe, Si ,Sf ,Se

VIII. Analysis Of Spectrum

A. Constant Current

Spectrum A3 reveals a unique elemental distribution that defines the characteristics of the welded joint. Iron (Fe) constitutes 68.68 wt.%, offering robust structural integrity, while Chromium (Cr), at 17.08 wt.%, ensures corrosion resistance by forming a stable oxide layer. The Nickel (Ni) content, 8.09 wt.%, enhances the weld's toughness and resistance to thermal stress. Carbon (C), at 4.46 wt.%, strengthens the weld, whereas Manganese (Mn), at 1.42 wt.%, aids in weldability by stabilizing the molten pool. Trace elements like Silicon (Si) (0.21 wt.%) and Phosphorus (P) (0.07 wt.%) contribute to the weld quality, ensuring smooth operation and minimal defects. This analysis highlights the composition's ability to deliver excellent mechanical properties and chemical stability.

B. Pulse Current

Spectrum B1 presents a distinctive composition that balances strength, corrosion resistance, and toughness. Iron (Fe), at 65.30 wt.%, provides the foundational strength and durability required for structural applications. Chromium (Cr), contributing 18.00 wt.%, elevates corrosion resistance, making it ideal for environments with moderate exposure to oxidizing agents. Nickel (Ni), at 8.80 wt.%, improves both toughness and resistance to oxidation. Carbon (C), with a relatively higher weight of 5.68 wt.%, enhances the hardness of the weld, while Manganese (Mn) (1.96 wt.%) supports weldability by preventing cracking. Minor elements such as Silicon (Si) and Sulfur (S), present in trace amounts, improve machinability and weld consistency. The results reflect the balanced elemental distribution required for high-quality AISI 304 stainless steel welds.

C. Double Pulse Current

The Spectrum C3 analysis offers valuable insights into the material's performance under different welding techniques. With Iron (Fe) at 67.31 wt.%, it serves as the foundation of the material's structural stability. The Chromium (Cr) content, at 17.25 wt.%, provides excellent corrosion resistance, making the weld durable in harsh environments. Nickel (Ni), contributing 8.26 wt.%, enhances toughness and prevents oxidation under high temperatures. Carbon (C), at 5.20 wt.%, improves the strength of the weld but requires careful balancing to avoid compromising corrosion resistance. Other elements, such as Manganese (Mn) (1.73 wt.%), Silicon (Si) (0.22 wt.%), and Sulfur (S) (0.06 wt.%), appear in trace amounts yet play essential roles in ensuring weldability and reducing spatter during the welding process. This composition showcases the adaptability of AISI 304 stainless steel for various applications.

D. Cold Metal Transfer

The analysis of Spectrum DW reveals a well-balanced composition crucial for high-performing welded joints. Iron (Fe) dominates the composition at 67.16 wt.%, serving as the primary structural element that ensures strength and durability. Chromium (Cr), present at 16.79 wt.%, significantly enhances corrosion resistance by forming a passive protective layer. Nickel (Ni), at 7.96 wt.%, contributes to toughness and oxidation resistance, making it suitable for high-temperature applications. Carbon (C), with a weight percentage of 6.35, strengthens and hardens the weld, though care is required to manage its concentration to prevent adverse effects on corrosion resistance. Minor elements like Manganese (Mn) (1.41 wt.%), Silicon (Si) (0.21 wt.%), Phosphorus (P) (0.05 wt.%), and Sulfur (S) (0.08 wt.%) collectively influence weldability, machinability, and overall quality.

IX conclusion

Based upon the present work the following conclusion has been drawn.

- GMAW can be used for welding 12mm thick AISI 304 SS plates that are capable of withstanding appreciable levels of stress.
- Based upon this comparative study it was found that the UTS at room temperature for GMAW welded joints was higher than the UTS at elevated temperature.
- Ductility of the welded joints measured as % elongation in the present case was found to be higher in case at room temperature (45.64%) joints as compared to the elevated temperature (11.48%) joints.
- This comparative study further shows

that GMAW welded joints possessed maximum yield strength of 349.57MPa followed by the base metal yield strength of 385MPa and GMAW welded joints possessing 321.4 MPa yield strength.

- Fractographic images revealed a ductile profile at all studied deformation temperatures. The mechanisms related to ductile fracture are closely related to the nucleation and growth. The absence of large dimples at 500 ºC is related to the suppression of martensite at high temperatures.

Finally it could be concluded that although the GMAW process can be effectively used for welded 12mm thick AISI 304 SS there is a variation among different properties of these joints.

Scalability and Future Scope

The investigation of AISI 304 stainless steel using SEM-EDS and Gas Metal Arc Welding (GMAW) offers strong potential for scalability and future research. The methodology can be expanded to other stainless steel grades and industrial welding applications due to the high adaptability of GMAW in automated processes. Insights from SEM-EDS analysis can help optimize welding parameters, improve joint quality, and even support machine learning models for defect prediction and process control. In the future, this research can be extended to include mechanical and corrosion testing, advanced characterization techniques like TEM or XRD, and studies on the heat-affected zone. Additionally, it can contribute to sustainable manufacturing practices and the development of predictive simulation models, with applications in emerging fields such as wire arc additive manufacturing (WAAM).

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