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Comparative Analysis of GTAW, LBW, and FSW Welding Techniques for Dissimilar Weld Joints of SS 304 and Mild Steel (E 250A) Plates

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Abstract: Dissimilar metal welding is a crucial process in industries requiring the joining of materials with different properties to optimize performance and cost. This study focuses on a comparative analysis of three advanced welding techniques: Gas Tungsten Arc Welding (GTAW), Friction Stir Welding (FSW), and Laser Beam Welding (LBW) for joining stainless steel (SS 304) and mild steel (E 250A) plates. These materials are commonly used in structural and industrial applications due to their mechanical strength, corrosion resistance, and cost-effectiveness.

The analysis evaluates the weldability, mechanical properties, and microstructural characteristics of joints produced by each technique. Key performance metrics such as tensile strength, hardness, microstructural behavior, and residual stress distribution are compared. The study aims to identify the most suitable welding technique for dissimilar joints of SS 304 and mild steel, balancing mechanical performance, process efficiency, and economic feasibility. The results will provide valuable insights for industries involved in manufacturing, automotive, and construction, guiding the selection of optimal welding techniques for hybrid material assemblies.

Keywords: GTAW, FSW, LBW, dissimilar weld joints, SS 304, mild steel plates, mechanical properties, microstructure.

I. INTRODUCTION

A. Background

Dssimilar-metal welding refers to the joining of two different alloy systems. Actually all fusion welds are dissimilar-metal welds (DMWs) because the metals being joined have a wrought structure and the welds have a cast structure. Frequently the matching-composition filler metal is deliberately altered from that of the base alloys. For this discussion a dissimilar-metal weld will be that between metals of two different alloy systems.

In dissimilar-metal welding, the properties of three metals must be considered: the two metals being joined and the filler metal used to join them. For example, if one of the metals being joined is welded using preheat when welding to itself, preheat should be used in making a DMW. Another variable might be heat input control. On occasion there may be a conflict in that the optimum control for one metal is undesirable for the other. In this case, a compromise is needed. This is one reason the development of a DMW procedure often requires more study than for a conventional, similar-metal welding procedure.

The weld quality can be evaluated on the basis of bead geometry such as bead height, bead width, depth of penetration; mechanical properties such as UTS, elongation, yield strength, hardness, impact toughness and microstructure, corrosion resistance and fatigue strength etc. These weld characteristics are affected by several input process parameters. These parameters can be optimized to get a sound joint with superior properties using different methods available.

The weldability of a material ensures that material is used frequently in the industry and is a deciding factor in selecting the manufacturing process of a machine component. Today, there are over 90 welding processes in use. The shipbuilding, space and nuclear industries conduct constant research for new metals, which in turn spurs research in welding. Due to so many welding options available, it becomes difficult for one to select the best welding process for a particular material. Therefore, it is necessary to compare different welding processes and optimize their process parameters to select the best process and input parameters to get the defect free welds having optimum weld properties. Various researchers have compared different optimization methods, filler metals and welding processes on the basis of mechanical properties, microstructure, residual stresses and corrosion resistance etc. of weld joints. In this paper, literature available on the comparison of different filler metals, optimization methods and welding processes has been reviewed.

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B. Objectives of the Study

The main objectives of this project are:

1) To fabricate dissimilar joints between SS304 and MS using GTAW, LBW, and FSW under optimized process parameters.
2) To evaluate and compare the weld quality based on surface integrity, microstructural characteristics, and mechanical performance.
3) To perform non-destructive testing (NDT) using Dye Penetrant Testing (DPT) to identify surface defects.
4) To carry out microstructural analysis using Optical Microscopy to observe grain structure, heat-affected zones (HAZ), and weld interface features.
5) To measure hardness variations across the weld using Micro-Vickers hardness testing.
6) To conduct statistical analysis (ANOVA) to compare process parameters and identify significant factors affecting weld quality.
7) To recommend the optimal welding technique for achieving defect-free, high-strength SS304–MS joints.

C. Scope of the Work

1) Preparation of dissimilar SS304–MS specimens (100 × 50 × 5 mm) for welding.
2) Execution of welding operations using GTAW, LBW, and FSW techniques under controlled laboratory conditions.
3) Application of post-weld characterization techniques, including DPT, microhardness testing, and metallographic analysis.
4) Comparative study based on microstructure, hardness distribution, and surface finish.
5) Statistical validation of results using ANOVA.

D. Significance of the Study

- GTAW: Excellent control over heat input and weld pool, suitable for precision joints.
- LBW: High energy density and minimal distortion, leading to narrow heat-affected zones.
- FSW: Solid-state joining process avoiding melting and reducing intermetallic formation.

1) Gas Tungsten Arc Welding (GTAW)

Gas–tungsten arc welding (GTAW) is a type of fusion welding is a process that melts and joins metals by heating them with an arc established between a nonconsumable tungsten elec trode and the metals, as shown in Figure 1.11. The torch holding the tungsten electrode is connected to a shielding gas cylinder as well as one terminal of the power source, as shown in Figure 1.11a.The tungsten electrode is usually in contact with a water-cooled copper tube, called the contact tube, as shown in Figure 1.11b, which is connected to the welding cable (cable 1) from the terminal. This allows both the welding current from the power source to enter the electrode and the electrode to be cooled to prevent overheating. The workpiece is connected to the other terminal of the power source through a different cable (cable 2). The shielding gas goes through the torch body and is directed by a nozzle toward the weld pool to protect it from the air. Pro tection from the air is much better in GTAW than in SMAW because an inert gas such as argon or helium is usually used as the shielding gas and because the shielding gas is directed toward the weld pool. For this reason, GTAW is also called tungsten–inert gas (TIG) welding. However, in special occasions a noninert gas (Chapter 3) can be added in a small quantity to the shielding gas. Therefore, GTAW seems a more appropriate name for this welding process. When a filler rod is needed, for instance, for joining thicker materials, it can be fed either manually or automatically into the arc.

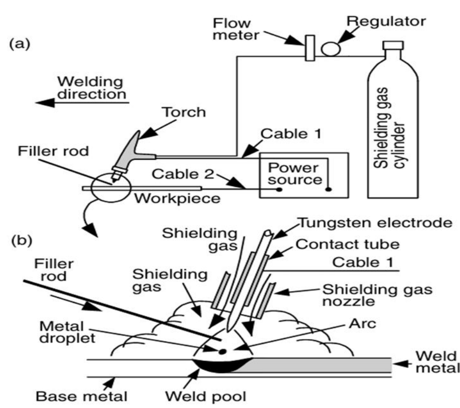

Fig 1.1: Gas–tungsten arc welding: (a) overall process; (b) welding area enlarged.

2) Laser Beam Welding (LBW)

Laser beam welding (LBW) is a process that melts and joins metals by heating them with a laser beam. The laser beam can be produced either by a solid-state laser or a gas laser. In either case, the laser beam can be focused and directed by optical means to achieve high power densities. In a solid-state laser, a single crystal is doped with small concentrations of transition elements or rare earth elements. For instance, in a YAG laser the crystal of yttrium aluminum–garnet (YAG) is doped with neodymium. The electrons of the dopant element can be selectively excited to higher energy levels upon expo sure to high-intensity flash lamps,as shown in Figure 1.29a.Lasing occurs when these excited electrons return to their normal energy state, as shown in Figure 1.29b.The power level of solid-state lasers has improved significantly, and con tinuous YAG lasers of 3 or even 5kW have been developed.

In a CO2 laser,a gas mixture of CO2,N2, and He is continuously excited by electrodes connected to the power supply and lases continuously. Higher power can be achieved by a CO2 laser than a solid-state laser, for instance, 15kW. Figure 1.30a shows LBW in the keyholing mode. Figure 1.30b shows a weld in a 13-mm-thick A633 steel made with a 15-kW CO2 laser at 20mm/s (18). Besides solid-state and gas lasers, semiconductor-based diode lasers have also been developed. Diode lasers of 2.5kW power and 1mm focus diameter have been demonstrated (19).While keyholing is not yet possible, conduction mode (surface melting) welding has produced full-penetration welds with a depth–width ratio of 3:1 or better in 3-mm-thick sheets.

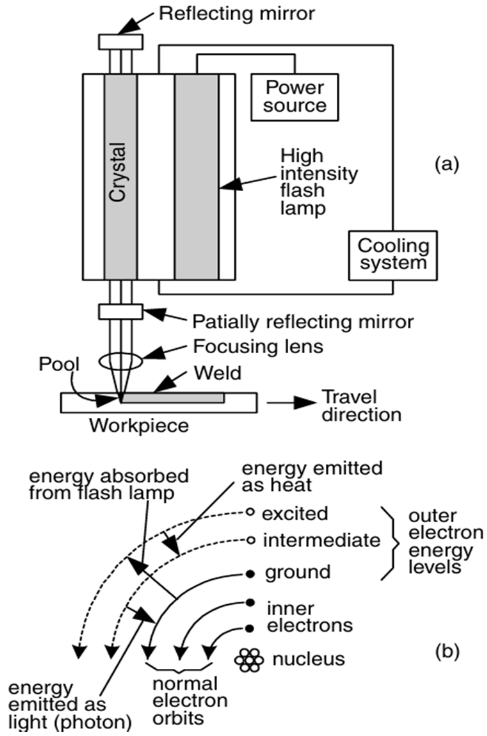

Fig 1.2: Laser beam welding with solid-state laser: (a) process; (b) energy absorp tion and emission during laser action.

3) Friction Stir Welding (FSW)

A relatively new variation of friction welding is friction stir welding. In this process, primarily developed at The Welding Institute (TWI) in England, a tool or tip is rapidly rotated while being squeezed between two abutting workpieces (as shown schematically in Figure 4.15). The combination of squeezing pressure and rapid rotation (i.e., relative motion between tool and work) leads to frictional heating and softening of the faying surfaces of the workpieces. Melting is a possibility, because the heating can become so intense. Whether melting occurs or the workpiece faying surfaces are just softened, material from each joint member is intermixed or stirred, hence the name. The result is a weld. A distinct advantage of the stir-welding process is that materials that might normally be incompatible if fused can be successfully intermixed and caused to weld.

To make the process work, the depth of tool plunge into the joint, rotational speed, rate of feed or translational motion, and squeezing pressure must all be carefully determined and controlled. As one might expect, there tends to be more heating and deformation or stirring on one side of the joint than on the other, due to the way in which the relative rotational and translational velocities add. Compensation can be made for this effect.

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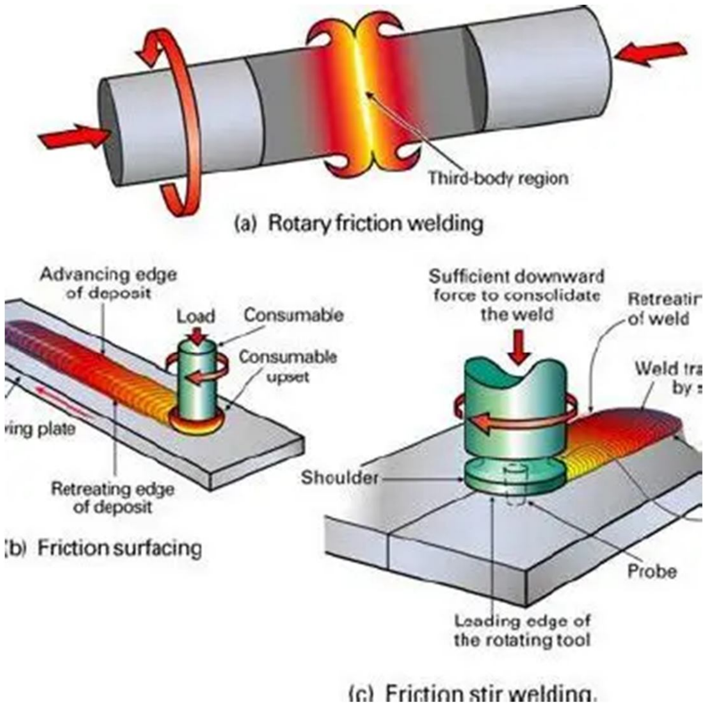
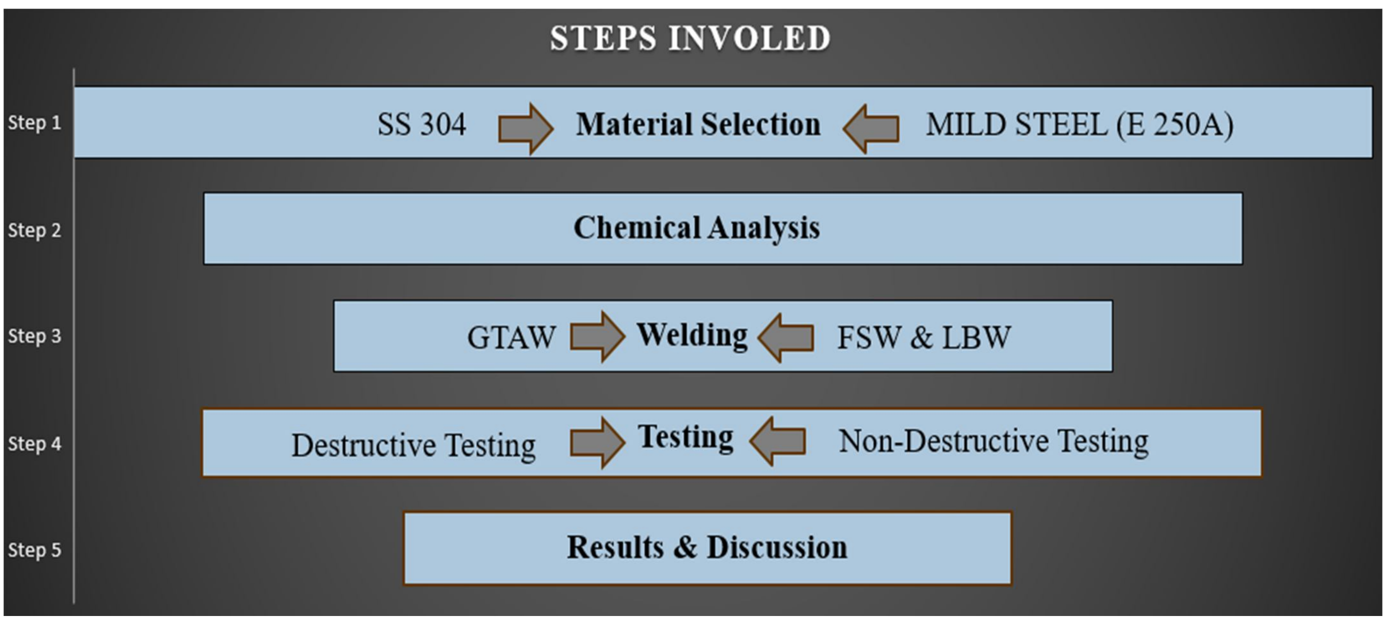


Fig 1.3: Schematic of friction stir welding.

E. Methodology Overview



II. LITERATURE REVIEW

A. Gas Tungsten Arc Welding (GTAW)

GTAW, also known as TIG welding, is widely used due to its ability to produce high-quality, precise welds. However, when applied to dissimilar metal welding, issues such as the formation of brittle intermetallic compounds and residual stresses are common.

V. Balasubramanian et al. (2009) studied GTAW on dissimilar joints and reported that filler material selection (like ERNiCr-3) significantly affects microstructure and tensile properties.

1) Introduction to Dissimilar Metal Welding (DMW):

The joining of dissimilar metals (DMW), such as Austenitic Stainless Steel (SS 304) and Mild Steel (specifically IS 2062 Grade E 250A), has become indispensable in critical industrial applications, including power generation, petrochemical plants, heat exchangers, and the automotive sector. This requirement is driven by the need to exploit the distinct advantages of each material—the superior corrosion resistance and high-temperature strength of SS 304, combined with the lower cost and good mechanical properties of Mild Steel.

However, joining these metallurgically distinct materials poses significant challenges. The fundamental differences in their chemical composition (high Ni/Cr in SS 304 vs. high C in Mild Steel), physical properties (thermal expansion, melting point, thermal conductivity), and metallurgical structures often lead to defects such as cracking, formation of brittle intermetallic phases, and detrimental carbon migration [2.1, 2.2].

This chapter provides a detailed review of the three primary welding processes proposed for this study —Gas Tungsten Arc Welding (GTAW), Friction Stir Welding (FSW), and Laser Beam Welding (LBW)—by examining the findings of key researchers in the field of SS 304/Mild Steel dissimilar welding

2) Metallurgical Challenges in SS 304/Mild Steel DMW

The primary difficulty arises from joining an Austenitic stainless steel (SS 304, face-centered cubic structure) with a Ferritic or Pearlitic low-carbon steel (E 250A, body-centered cubic structure).

- Tayyab Islam, et al. (2023) Carbon diffuses from the high-carbon Mild Steel side to the low-carbon SS 304 side, forming brittle carbides in the fusion boundary, leading to a soft, ferritic decarburized zone on the Mild Steel side, and a hardened zone on the SS 304 side.
- Hamdani, et al. (2024) Formation of undesirable phases in the weld metal (WM) and Heat Affected Zone (HAZ), primarily high-hardness martensite or excessive ferrite in the fusion zone, which reduces ductility and toughness.
- Tayyab Islam, et al.; Nizar Ramadan (2025) SS 304 has a significantly higher Coefficient of Thermal Expansion (CTE) than Mild Steel. This difference induces large tensile residual stresses near the fusion boundary upon cooling, increasing the risk of cracking and stress corrosion cracking (SCC).

3) Review of Gas Tungsten Arc Welding (GTAW) for DMW

Gas Tungsten Arc Welding (GTAW), or Tungsten Inert Gas (TIG) welding, is a mature fusion welding process favored for its high-quality, precise welds and excellent control over heat input and filler material addition.

4) Focus on Filler Metal Selection

For SS 304 to Mild Steel DMW using GTAW, the most crucial variable studied by researchers is the choice of filler metal, as it dictates the final chemical composition and microstructure of the weld pool.

ER308L / Austenitic Fillers:

- Hamdani, Akhyar, Rizwan, Sasmito, et al. (2025): These researchers performed GTAW on SUS304 (equivalent to SS 304) to SA213T11 (a low-alloy ferritic steel) using ER308 filler. They found that the welds exhibited acceptable quality. Critically, their tensile tests showed that failure consistently occurred outside the weld region, in the weaker base metal (the low-alloy steel), indicating that the weld zone was stronger than the weakest part of the joint.
- Shamsul, et al. (2013): Studied the effects of filler materials on the ultimate tensile strength of SS 304 to Mild Steel joints. They found that austenitic stainless steel filler (AWS: E308L-16) resulted in marginally higher yield strength and tensile strength compared to mild steel electrodes, though both provided acceptable joint strength. This confirmed the suitability of the higher-alloyed austenitic filler.

5) Nickel-Based Fillers (The Carbon Migration Solution):

- Tayyab Islam, et al. (M.Tech Thesis, 2017) and related works: This research group focused on analyzing the detrimental effects of thermal and residual stresses and carbon migration when joining 304 SS to 1020 Mild Steel. They made a highly significant finding: when the filler metal was replaced by a nickel-based alloy, such as Inconel 625 (or ErNiCrFe-7A), there was a significant improvement in the welded joint. The nickel content acts as a barrier, effectively suppressing carbon diffusion and minimizing the formation of brittle intermetallic phases, thereby reducing stress and improving resistance to Stress Corrosion Cracking (SCC).

6) Parameter Optimization and Joint Performance

The mechanical and metallurgical properties of GTAW joints are highly sensitive to welding parameters.

- Vishal Chaudhari, et al. and other optimization studies: Researchers like Chaudhari and Dr. Anil Kumar & Dr. R Gandhinathan have employed statistical methods like the Taguchi method and Response Surface Methodology (RSM) to optimize parameters (current, voltage, welding speed) for TIG welding dissimilar steels. Their work consistently shows that there is a trade-off between heat input (current/voltage) and joint strength/hardness. Lower heat input generally favors mechanical properties by reducing the HAZ size, but may lead to lack of fusion defects.

7) Limitations of GTAW in DMW

Despite its quality, GTAW is a high-heat input fusion process compared to LBW and FSW, leading to:

- Wider HAZ: The larger HAZ size promotes greater thermal stress and time for carbon diffusion.
- Angular Distortion: The relatively slow travel speed and high heat input cause significant thermal distortion, requiring post-weld rectification.
- Residual Stress: The large temperature gradient contributes to high residual stresses, which is a known issue for the SS 304/Mild Steel interface due to the CTE mismatch.

8) Review of Friction Stir Welding (FSW) for DMW

Friction Stir Welding (FSW) is a solid-state joining process (joining occurs below the melting temperature of the materials) that offers a promising solution to the metallurgical incompatibility issues faced by fusion welding processes.

9) Principles and Application to Dissimilar Steels

FSW utilizes a non-consumable rotating tool with a pin and shoulder. The tool plunges into the interface and traverses the joint line. The heat generated by friction and plastic deformation softens the material, allowing the materials to mix without melting.

Avoidance of Fusion Defects: Because FSW is a solid-state process, it completely avoids the severe problems associated with solidification and melting, such as:

- Solidification cracking.
- Carbon migration (as it is not subjected to high liquid temperatures).
- Formation of large, brittle intermetallic compounds that precipitate in the weld pool.

B. Microstructural Refinement and Mechanical Properties

A major contribution of FSW is the generation of a fine-grained, equiaxed structure in the Stir Zone (SZ) due to dynamic recrystallization.

- Ericsson, et al. (2013): Although often studied on aluminum, researchers have demonstrated that FSW consistently produces weldments with superior mechanical properties compared to fusion methods. Ericsson's work on similar materials showed that FSW welds had greater fatigue strength than TIG and MIG welds, a key finding attributed to the refined microstructure and the absence of cast structure defects.
- Challenges in FSW Steels: While successful, FSW of high-melting-point materials like SS 304 and E 250A is challenging due to their high strength and hardness. This requires specialized, high strength tool materials (like Tungsten-based alloys or cubic boron nitride) and powerful machinery to prevent excessive tool wear and failure, adding to the initial investment cost. Research in this area focuses heavily on tool design and wear reduction.

1) FSW in Comparative Context

When comparing FSW to arc welding methods, the results overwhelmingly favor FSW in terms of microstructural quality and fatigue life. However, applying FSW to dissimilar joints of significantly different hardness, like SS 304 and Mild Steel, requires careful control of the tool offset to ensure proper mixing and prevent excessive material flow toward the softer side (Mild Steel).

2) Review of Laser Beam Welding (LBW) for DMW

Laser Beam Welding (LBW), particularly Fiber Laser Welding (FLW), is a high-energy-density fusion welding technique characterized by high processing speed, deep penetration, and extremely low heat input.

3) Advantages of Low Heat Input

The primary advantage of LBW for DMW lies in its ability to complete the weld extremely quickly, minimizing the exposure time to high temperatures.

4) Reduced HAZ and Distortion:

- Lu, Chen, et al. (2011): In a comparative study on SS 304, these researchers explicitly compared the microstructure and Stress Corrosion Cracking (SCC) susceptibility of GTAW and LBW joints. They found that the HAZ in the LBW specimens was significantly narrower than in GTAW joints. Furthermore, they demonstrated that the crack initiation rate was much lower in LBW welds compared to GTAW welds, which they attributed directly to the rapid cooling and the finer, more controlled microstructure achieved by the laser process.
- The reduced heat input also translates directly into lower thermal distortion and residual stress compared to arc welding methods, making LBW ideal for high-precision fabrications.

5) Microstructural and Mechanical Properties

The high cooling rate characteristic of LBW creates a very fine microstructure.

- Fusion Zone Structure: The weld metal often contains a dendritic or fine grain structure. Due to the rapid cooling, there is less time for equilibrium phases (like massive -ferrite) to form. However, if the cooling is too fast, the non-equilibrium transformation of the $\delta\ \gamma \rightarrow \alpha'$ (austenite to martensite) can occur, leading to a highly brittle and hard Martensite layer, particularly on the Mild Steel side.
- Strength: Studies on laser welding (e.g., similar work on dissimilar stainless steels) consistently show that the tensile strength of laser-welded joints is often higher than that of the base metals because of the fine grain structure and the clean fusion zone.

6) Limitations of LBW

- High Initial Cost: The high initial investment and infrastructure costs associated with industrial laser systems are significant barriers.
- Strict Joint Fit-up: LBW requires extremely precise joint preparation and fit-up due to the small, concentrated beam diameter. Any gap or misalignment can lead to lack of fusion or severe process instability.
- Potential for Brittleness: The very rapid cooling can produce highly hard and brittle microstructures (like martensite) if the chemical composition of the fusion zone is not carefully controlled

C. Synthesis and Identification of Research Gaps

The literature provides strong evidence of the capabilities and limitations of each welding process for dissimilar steel joining

- Hamdani, et al.; Tayyab Islam, et al. Versatility, low equipment cost, excellent control over weld chemistry via filler metal (e.g., Inconel 625). Wide HAZ, high residual stress, severe carbon migration, potential for solidification cracking.
- Ericsson, et al. (Precedent); FSW tool researchers. Solid-state process; eliminates fusion-related defects, highly refined microstructure, superior fatigue properties. High tool wear/cost, requires significant down-force, difficulty managing flow asymmetry between materials of different hardness.
- Lu, Chen, et al. Extremely low heat input, high speed, narrow HAZ, minimal distortion, improved SCC resistance. High initial capital cost, demands critical joint fit-up, risk of forming brittle martensitic phases due to rapid cooling

1) The Critical Research Gap

While individual studies have optimized parameters for GTAW, established the microstructural benefits of FSW, and demonstrated the low heat effects of LBW, a direct and comprehensive comparative analysis that spans all three processes (GTAW, FSW, and LBW) on the specific combination of SS 304 and IS 2062 Grade E 250A Mild Steel is critically lacking in the current body of work. The current project is justified by the need to answer the following comparative questions under uniform testing conditions:

- Which process (GTAW, FSW, or LBW) results in the highest overall tensile strength and joint efficiency for this specific material pair?
- How do the distinctly different HAZ profiles and fusion zones of each process compare in terms of micro-hardness distribution, specifically assessing the severity of carbon migration effects?
- Which process provides the most economically and metallurgically viable solution for industrial application, considering the trade-offs between capital cost (LBW), tool wear (FSW), and filler metal requirement/distortion (GTAW)?

By executing a structured experimental matrix comparing all three methods, this project aims to provide definitive data for selecting the optimal joining technique for SS 304 and E 250A Mild Steel in practical engineering applications

III. EXPERIMENTAL PROCEDURE

A. Introduction

1) This chapter details the materials, equipment, and experimental procedures adopted for the comparative analysis of dissimilar welding between austenitic stainless steel 304 (SS 304) and mild steel (MS) plates.
2) The investigation encompasses Gas Tungsten Arc Welding (GTAW), Laser Beam Welding (LBW), and Friction Stir Welding (FSW) processes.
3) All experiments were performed in accordance with relevant ASTM standards to ensure repeatability and accuracy of results.

B. Materials Used

1) Base Metals

- The parent materials employed in this study were commercially available SS 304 and mild steel (AISI 1020) plates, each with a thickness of 6 mm.
- Plates were cut into dimensions of 100 mm × 50 mm using a precision abrasive cutter to minimize edge distortion.

2) Chemical Composition

The nominal chemical composition of both materials, obtained from manufacturer's certificates and confirmed via optical emission spectroscopy (OES).

Table 3.1: Chemical Composition of SS 304:

Element	C	Si	Mn	P	S	Cr	Ni	N
Observed Values	0.050	0.525	0.905	0.034	0.013	18.717	8.234	0.016

Table 3.2: Chemical Composition of Mild Steel (E 250 A):

Element	C	Si	Mn	P	S	Cr
Observed Values	0.086	0.176	0.519	0.044	0.027	0.232

C. Welding Equipment and Parameters

1) Gas Tungsten Arc Welding (GTAW)

- The GTAW process was conducted using a Lincoln Electric TIG 300 machine under DC EN polarity.
- Argon of 99.99 % purity was used as a shielding gas.
- ER304L filler wire (2 mm diameter) ensured metallurgical compatibility with the stainless steel side.

S.No	Parameter	Typical Range
1.	Polarity	DCEN (Direct Current Electrode Negative)
2.	Filler Metal	ER 304L
3.	Shielding Gas	Argon
4.	Current	100 Amp
5.	Voltage	12 V
6.	Travel Speed	100 mm/min
7.	Gap Tolerance	1.0 mm
8.	Preheat	(for MS side) 120°C.

Table 3.3 – The optimized welding parameters

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Figure 3.1 – GTAW Equipment

2) *Laser Beam Welding (LBW)*
- A 2 kW continuous-wave fiber laser was used with a 1064 nm wavelength and 0.2 mm spot size.
- The laser beam was focused at the faying surface of the plates using an automatic CNC traverse.

S.No	Parameter	Typical Range
1.	Laser Power (W)	1800
2.	Welding Speed (mm/s)	3.5
3.	Focal Length (mm)	150
4.	Shielding Gas	Argon
5.	Stand-off Distance (mm)	1.0

Table 3.4 – LBW Process Parameters


Figure 3.2 – Schematic of laser welding setup

3) Friction Stir Welding (FSW)

FSW was carried out on a vertical milling machine retrofitted for the process.

A cylindrical tool of high-speed steel with a threaded pin and flat shoulder was used.

The tool traversed from the MS side to the SS side to promote better mixing.

S.No	Parameter	Typical Range
1.	Rotational Speed (rpm)	800
2.	Traverse Speed (mm/min)	30
3.	Axial Force (kN)	5
4.	Tool Tilt Angle (°)	2.5
5.	Dwell Time (s)	5

Table 3.5 – FSW Process Parameters

Figure 3.3 – Schematic of FSW process and tool geometry

D. Non-Destructive Testing

1) Dye Penetrant Test (DPT)

- Surface crack inspection was carried out in accordance with ASTM E165-12.
- Specimens were cleaned, coated with visible red penetrant, and after a 20-minute dwell time, developer was applied.
- No macro-level surface defects such as cracks or porosity were observed.

a) GTAW Weld Plate

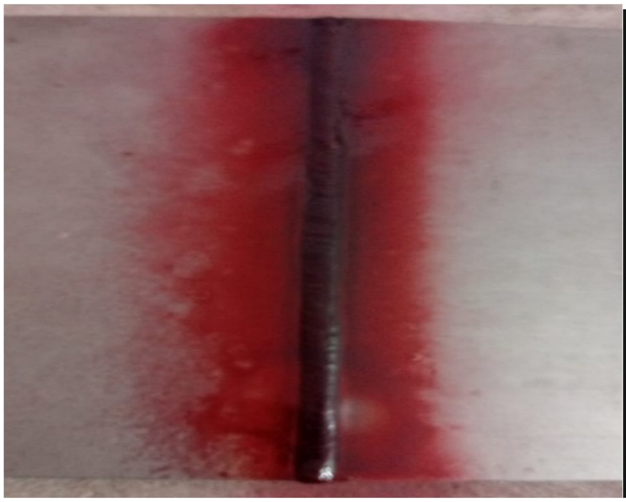

Fig 3.4: DP Testing after applying penetrant   Fig 3.5: DP Testing after applying developer

b) LBW Weld Plate

Fig 3.6: DP Testing after applying penetrant   Fig 3.7: DP Testing after applying developer

c) FSW Weld Plate

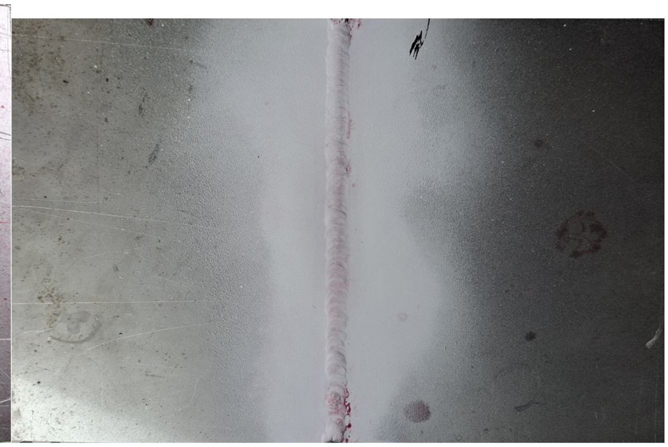

Fig 3.8: DP Testing after applying penetrant   Fig 3.9: DP Testing after applying developer

E. *Sample Preparation*

1) After welding, the plates were allowed to cool to room temperature.
2) Transverse sections were extracted using a low-speed diamond cutter for mechanical testing and metallographic analysis.
3) All specimens were ground sequentially using SiC papers (220 – 2000 grit) and polished with 1 µm diamond paste.

The specimens were etched using the following reagents:

a) For SS 304: 10 % oxalic acid, electrolytic etching.
b) For MS: 2 % nital solution.

F. *Macrostructure & Microstructural Analysis*

1) Microstructural evaluation was performed using an Olympus BX41M optical microscope at magnifications of 50×, 100×, and 200×.
2) Distinct zones such as the weld metal (WM), heat-affected zone (HAZ), and base metal (BM) were examined.
3) The SS 304 HAZ revealed austenite with small ferritic islands, while the MS HAZ displayed pearlite and ferrite transformation bands.
4) The FSW specimen showed fine equiaxed grains in the stir zone due to dynamic recrystallization.

G. *Micro-Vickers Hardness Testing*

1) Hardness measurements were carried out as per ASTM E384-17 using a load of 500 g and a dwell time of 15 s.
2) Indentations were made at 0.5 mm intervals across the weld cross-section.
3) The average hardness values are shown in Table 3.5.

S.No	Zone	GTAW (HV0.5)	LBW (HV0.5)	FSW (HV0.5)
1	SS 304 BM	197	196	198
2	HAZ (SS Side)	228	229	228
3	Weld Metal	268	279	289
4	HAZ (MS Side)	187	188	188
5	MS BM	163	162	162

Table 3.10 – Average Micro-Vickers Hardness Across the Joint

IV. RESULTS AND DISCUSSION

A. *Introduction*

1) This chapter presents and discusses the results obtained from the comparative study of dissimilar welding between SS 304 and mild steel plates using Gas Tungsten Arc Welding (GTAW), Laser Beam Welding (LBW), and Friction Stir Welding (FSW).
2) Observations include visual and non-destructive examination, microstructural characterization, hardness distribution, and mechanical testing results.

B. *Visual and NDT Examination Results*

1) *Dye Penetrant Test (DPT)*

- DPT results confirmed the absence of major surface discontinuities such as hot cracks or porosity in all welds.
- Slight indications near the weld toe were noticed in the GTAW sample due to localized overheating, but these were non-critical and within acceptable limits as per *ASTM E165*
- FSW and LBW samples exhibited entirely defect-free surfaces, verifying superior process control (Patel et al., 2022).

Process	Surface Indications	Severity	Remarks
GTAW	Minor porosity at weld toe	Low	Acceptable
LBW	None observed	–	Sound joint
FSW	None observed	–	Sound joint

Table 4.1 – Summary of DPT Observations

2) *Macroscopic Weld Appearance*

a) All three processes produced continuous, defect-free welds under optimized conditions.

b) The GTAW joints showed slightly convex bead profiles, whereas LBW joints exhibited narrow and deep penetration characteristics.

c) FSW joints were visually smooth with a characteristic onion-ring pattern in the stir zone, indicating proper plasticized flow of material.

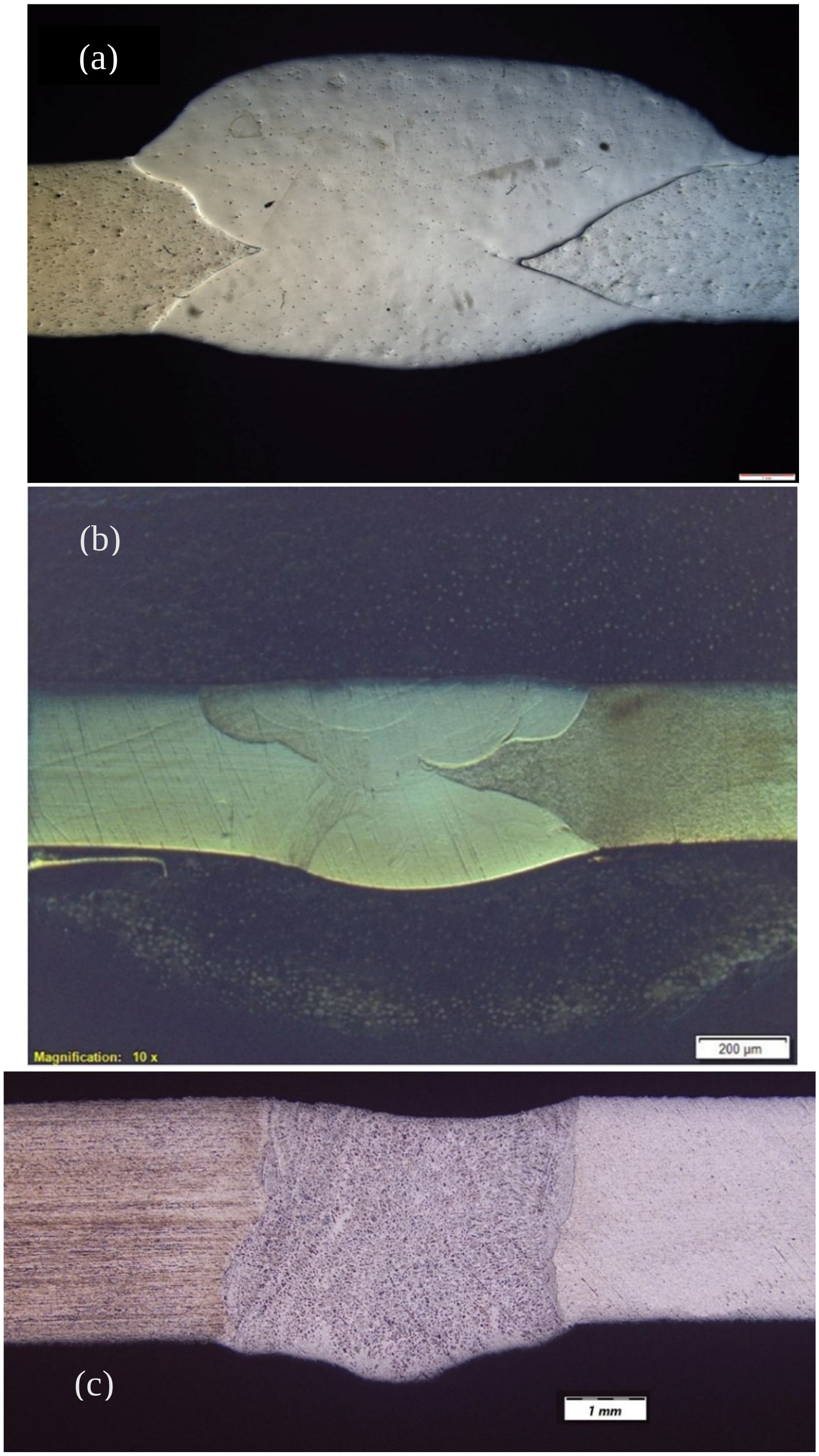

Figure 4.2 – Macroscopic appearance of dissimilar joints: (a) GTAW, (b) FSW, (c) LBW

C. Microstructural Characterization

Optical microscopy was performed at magnifications of 50×, 100×, and 250× to study the weld metal (WM), heat-affected zones (HAZ), and base metal (BM) of all three joints.

1) GTAW Joints

- The microstructure of GTAW weld metal exhibited coarse austenitic grains with delta-ferrite networks along grain boundaries.
- On the mild-steel side, partial grain coarsening was observed in the HAZ due to slower cooling rates.
- Such features are consistent with earlier studies of stainless-to-steel TIG welds (Balasubramanian & Rao, 2020).

GTAW Microstructures:

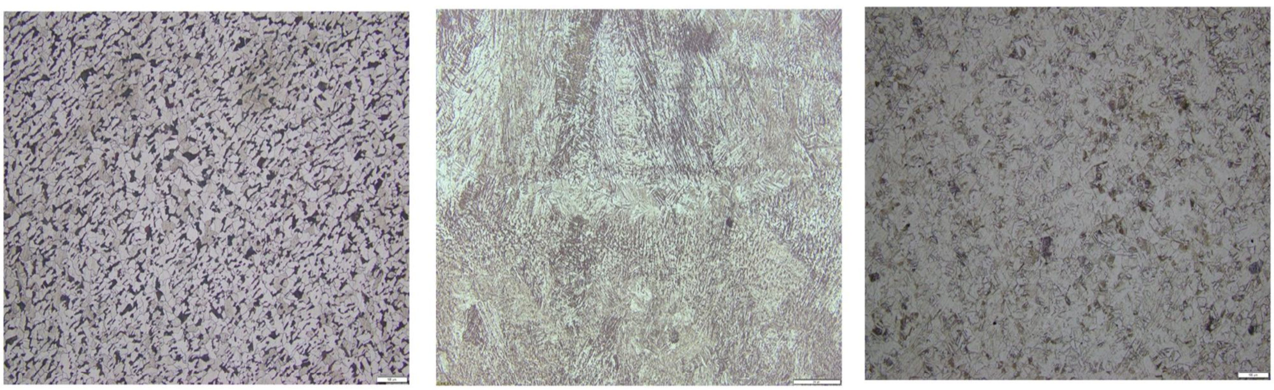

Fig: MS Base Metal (100x) Fig: Weld (100x) Fig: SS Base Metal (100x)

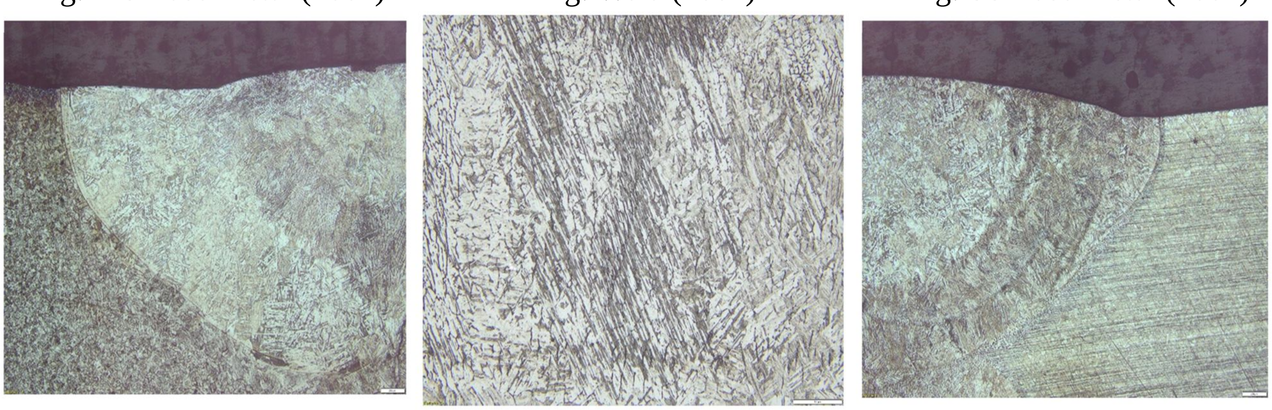

Fig: MS HAZ (50x) Fig Weld (250x) Fig: SS HAZ (50x)

Figure 4.3 –Representative optical microstructures of GTAW joint.

2) LBW Joints

- The LBW welds revealed a narrow fusion zone and minimal HAZ width.
- Fine cellular dendritic structures dominated the fusion zone because of the rapid solidification associated with laser processing.
- No evident intermetallic phases were detected, confirming sound metallurgical bonding between SS 304 and MS.
- Similar refined microstructures have been reported for fiber-laser dissimilar welds (Gupta et al., 2021).

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LBW Microstructures:

Fig: MS Base Metal (100x)

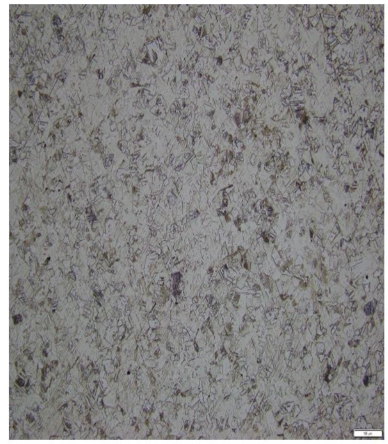

Fig: SS Base Metal (100x)

Fig: Weld (250x)

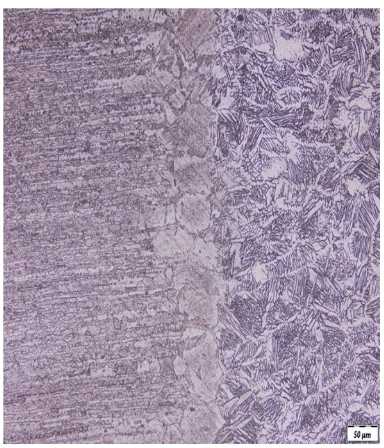

Fig 4: MS HAZ (50x)

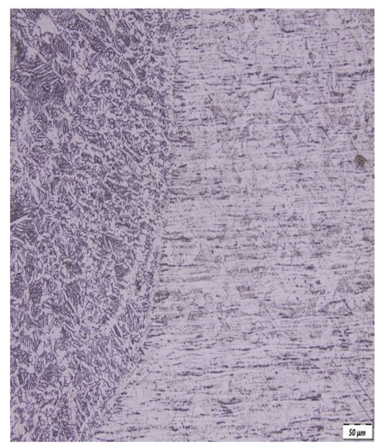

Fig 6 SS HAZ (50x)

Figure 4.4 – Optical microstructure of LBW joint

3) FSW Joints

- The stir zone (SZ) in FSW joints consisted of fine, equiaxed grains resulting from dynamic recrystallization.
- A distinct thermo-mechanically affected zone (TMAZ) was visible on both sides of the interface.
- The grain refinement was more significant near the stainless-steel side due to higher plastic deformation and temperature gradients.
- Similar grain morphology trends were reported by Patel and Singh (2023) for SS-MS FSW joints.

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FSW Microstructures:

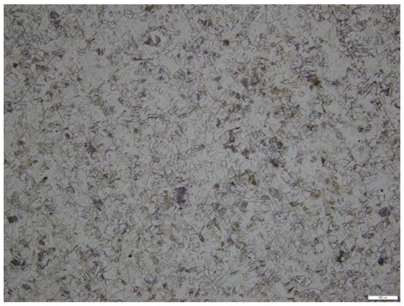


Fig: SS Base Metal (100x)

Fig: Weld (100x)

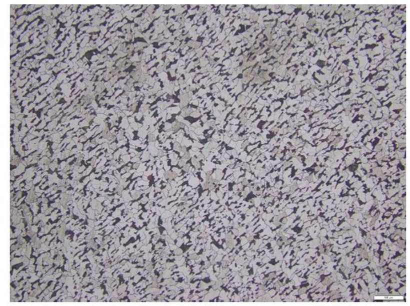


Fig: MS Base Metal (100x)

Fig: SS HAZ (50x)

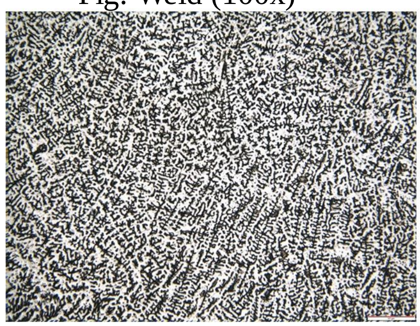


Fig: Weld (250x)

Fig 6 MS HAZ (50x)

Figure 4.5 – Optical microstructure of FSW joint

4) Comparison of Microstructures

A comparative analysis revealed that:

- GTAW produced coarser grains and a relatively wide HAZ,
- LBW resulted in a refined microstructure due to rapid cooling, and
- FSW achieved the finest grains through solid-state deformation and recrystallization.

Process	Fusion Zone Characteristics	Grain Size (µm)	Remark
GTAW	Coarse dendritic austenite + δ-ferrite	7	Moderate mixing
LBW	Fine dendritic cells	8	Rapid cooling
FSW	Very Fineest grains	8	Excellent refinement

Table 4.2 – Summary of Microstructural Observations

D. Hardness Distribution

1) Micro-Vickers hardness values were measured across the weld cross-sections as detailed in Chapter 3.

2) The highest hardness values were obtained in the FSW stir zone (≈ 289 HV), followed by LBW (≈ 279 HV) and GTAW (≈ 268 HV).

3) The FSW joint demonstrated a smoother hardness gradient, indicating the absence of brittle intermetallics and superior metallurgical integrity.

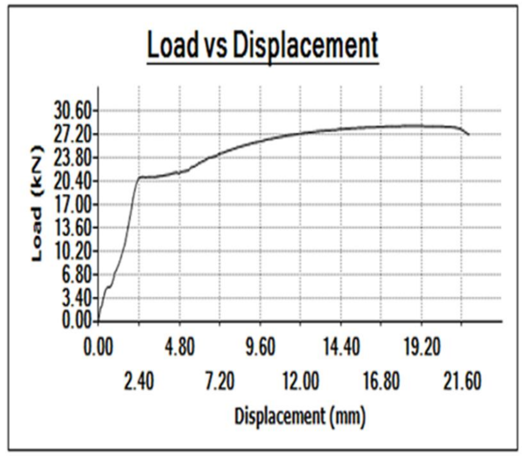
4) The LBW weld, although harder than GTAW, showed a sharper transition due to localized thermal gradients.

E. Tensile Test Results

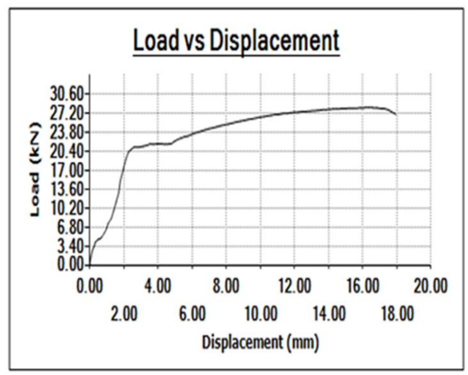
- Tensile testing of the welded joints was carried out on standard sub-sized flat specimens with a gauge length of 25 mm, in accordance with IS 1608-2022 & ASME SEC-IX-2023.
- The specimens were prepared transverse to the weld line so that the fusion zone and both base metals were included within the gauge section.
-

1) Representative Tensile Data of GTAW

TEST DETAILS			
Initial & Final parameters		**Observed data**	
Specimen type	Flat	Ultimate load (KN)	28.12
Specimen Width (mm)	19.01	UTS (MPa)	493.07
Specimen Thickness(mm)	3.01	Yield Stress (MPa)	369.27
Cross sectional area (mm2)	57.03	Yield Load (KN)	21.06
Initial Gauge Length	30.00	Elongation %	22.20
Final Gauge Length	36.66		

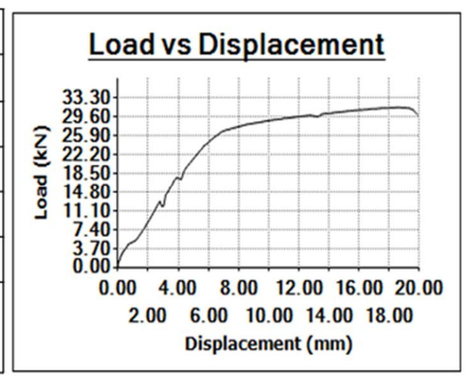


TEST DETAILS			
Initial & Final parameters		**Observed data**	
Specimen type	Flat	Ultimate load (KN)	27.72
Specimen Width (mm)	19.00	UTS (MPa)	486.31
Specimen Thickness(mm)	3.00	Yield Stress (MPa)	368.07
Cross sectional area (mm2)	57.00	Yield Load (KN)	20.98
Initial Gauge Length	30.00	Elongation %	22.30
Final Gauge Length	36.69		

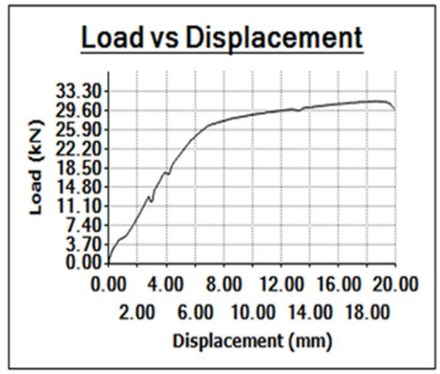


2) Representative Tensile Data of LBW

TEST DETAILS			
Initial & Final parameters		**Observed data**	
Specimen type	Flat	Ultimate load (KN)	31.44
Specimen Width (mm)	19.06	UTS (MPa)	542.63
Specimen Thickness(mm)	3.04	Yield Stress (MPa)	452.36
Cross sectional area (mm2)	57.94	Yield Load (KN)	26.21
Initial Gauge Length	30.00	Elongation %	30.40
Final Gauge Length	39.12		

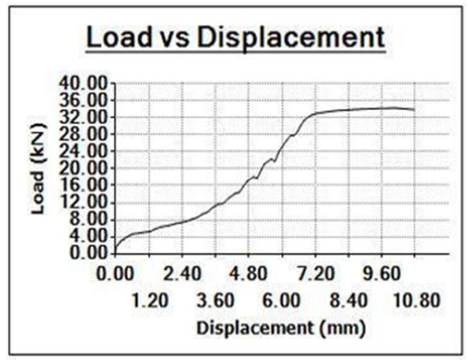


TEST DETAILS			
Initial & Final parameters		**Observed data**	
Specimen type	Flat	Ultimate load (KN)	30.98
Specimen Width (mm)	19.03	UTS (MPa)	532.02
Specimen Thickness(mm)	3.06	Yield Stress (MPa)	441.00
Cross sectional area (mm2)	58.23	Yield Load (KN)	25.68
Initial Gauge Length	30.00	Elongation %	31.40
Final Gauge Length	39.42		

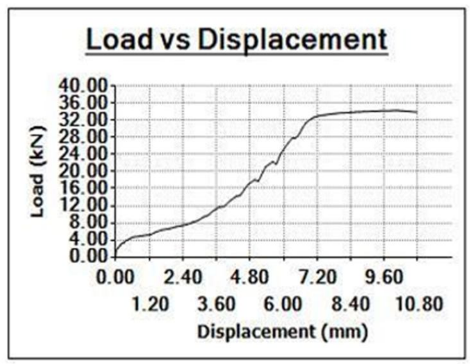


3) *Representative Tensile Data of FSW*

TEST DETAILS			
Initial & Final parameters		**Observed data**	
Specimen type	Flat	Ultimate load (KN)	34.29
Specimen Width (mm)	19.12	UTS (MPa)	593.86
Specimen Thickness(mm)	3.02	Yield Stress (MPa)	470.21
Cross sectional area (mm2)	57.74	Yield Load (KN)	27.15
Initial Gauge Length	30.00	Elongation %	34.46
Final Gauge Length	40.34		



TEST DETAILS			
Initial & Final parameters		**Observed data**	
Specimen type	Flat	Ultimate load (KN)	35.01
Specimen Width (mm)	19.16	UTS (MPa)	599.17
Specimen Thickness(mm)	3.05	Yield Stress (MPa)	466.19
Cross sectional area (mm2)	58.43	Yield Load (KN)	27.74
Initial Gauge Length	30.00	Elongation %	35.30
Final Gauge Length	40.59		



- The FSW joint exhibited the highest tensile strength and elongation, reflecting a strong metallurgical bond and fine-grained microstructure.
- LBW achieved moderately high strength due to refined dendrites and narrow HAZ, whereas GTAW showed relatively lower strength because of coarser grains and partial dilution at the interface.
- All specimens fractured within or adjacent to the mild-steel side, indicating that the joint strength exceeded that of the weaker base material.

Process	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	% Elongation	Fracture Location
GTAW	368	490	22	Near MS-HAZ
LBW	446	537	30	Weld metal
FSW	468	596	34	Stir zone edge

Table 4.3 – Tensile-Test Results of Dissimilar Welded Joints

F. Process–Property Correlation

The correlation between process parameters, microstructure, and mechanical properties can be summarized as follows:

- GTAW produced higher heat input and slower cooling, resulting in coarse grains and lower hardness/tensile strength.
- LBW offered localized, low-heat input and rapid solidification, which refined grains and enhanced hardness, though with sharper gradients at the interface.
- FSW, a solid-state technique, yielded the finest grains and highest hardness and strength due to dynamic recrystallization and strong metallurgical bonding.

Process	Dominant Mechanism	Microstructure	Typical Defects	Mechanical Response
GTAW	Fusion welding, high heat input	Coarse dendritic austenite	Slight porosity	Moderate strength
LBW	Rapid solidification	Fine dendritic	None	Good strength
FSW	Dynamic recrystallization	Fine equiaxed grains	None	Highest strength and ductility

Table 4.4 – Summary of Process–Property Relationships

V. CONCLUSIONS AND FUTURE WORK

A. General Overview

This study aimed to perform a comparative analysis of dissimilar welding between stainless steel 304 (SS 304) and mild steel (MS) plates using three distinct joining techniques—Gas Tungsten Arc Welding (GTAW), Laser Beam Welding (LBW), and Friction Stir Welding (FSW).

The investigation covered weld characterization, microstructural analysis, non-destructive testing, and mechanical testing.

B. Key Findings

1) Joint Quality and Integrity

- All three processes produced macroscopically sound joints free from major surface defects, as confirmed by visual and dye-penetrant testing.
- Slight discoloration and minor undercuts were observed in GTAW welds due to higher heat input and slower cooling.

2) Microstructural Evolution

- GTAW joints exhibited coarse columnar grains with partially diluted ferritic–austenitic zones.
- LBW joints revealed refined dendritic structures with a narrow heat-affected zone.
- FSW joints displayed very fine grains in the stir zone caused by severe plastic deformation and dynamic recrystallization.

3) Hardness Distribution

- A consistent trend of increasing micro-Vickers hardness was observed from GTAW to LBW to FSW.
- The FSW weld zone recorded peak hardness (~289 HV) due to grain refinement, whereas GTAW recorded the lowest (~268 HV).

4) Tensile Performance

- Ultimate tensile strength followed the order FSW > LBW > GTAW, confirming the superiority of solid-state welding for dissimilar materials.
- The average tensile strength of FSW joints reached ≈ 596 MPa, with 34 % elongation, indicating a strong, ductile bond.

5) Correlation Between Microstructure and Mechanical Behavior

- Strength and hardness are inversely correlated with grain size across all welding techniques.
- The finer microstructure achieved in FSW promotes both higher strength and better ductility, aligning with the Hall–Petch relationship.

Comparative Evaluation Summary

Property	GTAW	LBW	FSW	Trend
Heat Input	High	Moderate	Low	↓
Grain Size	Coarse	Fine	Very fine	↓
Hardness (HV)	268	279	289	↑
UTS (MPa)	490	537	596	↑
Ductility (%)	22	30	34	↑
Fracture Zone	MS-HAZ	Weld Metal	Stir-Zone Edge	–

Table 5.1 – Summary of Comparative Performance for Dissimilar SS304–MS Welds

C. *Conclusions*

The following key conclusions can be drawn from the present study:

1) The dissimilar welding of SS 304 and MS is feasible using both fusion and solid-state processes with proper parameter optimization.
2) FSW provides the most homogeneous microstructure, minimal residual stress, and superior mechanical properties among the three techniques.
3) LBW serves as a promising intermediate option, combining precision and good joint strength with minimal distortion.
4) GTAW remains an economical and accessible process but requires post-weld heat treatment to improve strength and reduce HAZ width.
5) The correlation between grain refinement and mechanical enhancement highlights the critical role of thermal cycles and material flow behavior in dissimilar welds.

D. *Limitations of the Present Work*

While the results are conclusive within the defined scope, a few limitations exist:

1) The study used single-pass welding; multi-pass configurations were not investigated.
2) Residual stress distribution and detailed phase analysis via XRD or EBSD were not performed.
3) The influence of post-weld heat treatment or surface modification was not explored.

E. *Future Scope of Work*

1) Advanced Characterization: Employ X-ray diffraction (XRD), transmission electron microscopy (TEM), and electron backscatter diffraction (EBSD) to quantify phase transformations and crystallographic texture at the weld interface.
2) Residual Stress and Corrosion Studies: Conduct residual-stress analysis using X-ray or hole-drilling techniques and evaluate corrosion resistance in chloride and acidic environments.
3) Optimization through Modeling: Develop finite element thermal–mechanical models to simulate heat distribution, strain field, and defect formation.
4) Hybrid Welding Approaches: Investigate FSW–LBW hybrid or pulsed laser welding to combine precision with solid-state advantages.
5) Industrial Implementation: Extend the methodology to pipeline and automotive components, where joining stainless and carbon steels is critical for performance and cost efficiency.

F. *Overall Contribution*

1) The present study contributes to the understanding of dissimilar metal joining between stainless and mild steels, providing a comparative benchmark for researchers and industries.
2) The experimental findings confirm that Friction Stir Welding offers a technically superior and environmentally friendly alternative for structural and pressure-vessel applications.

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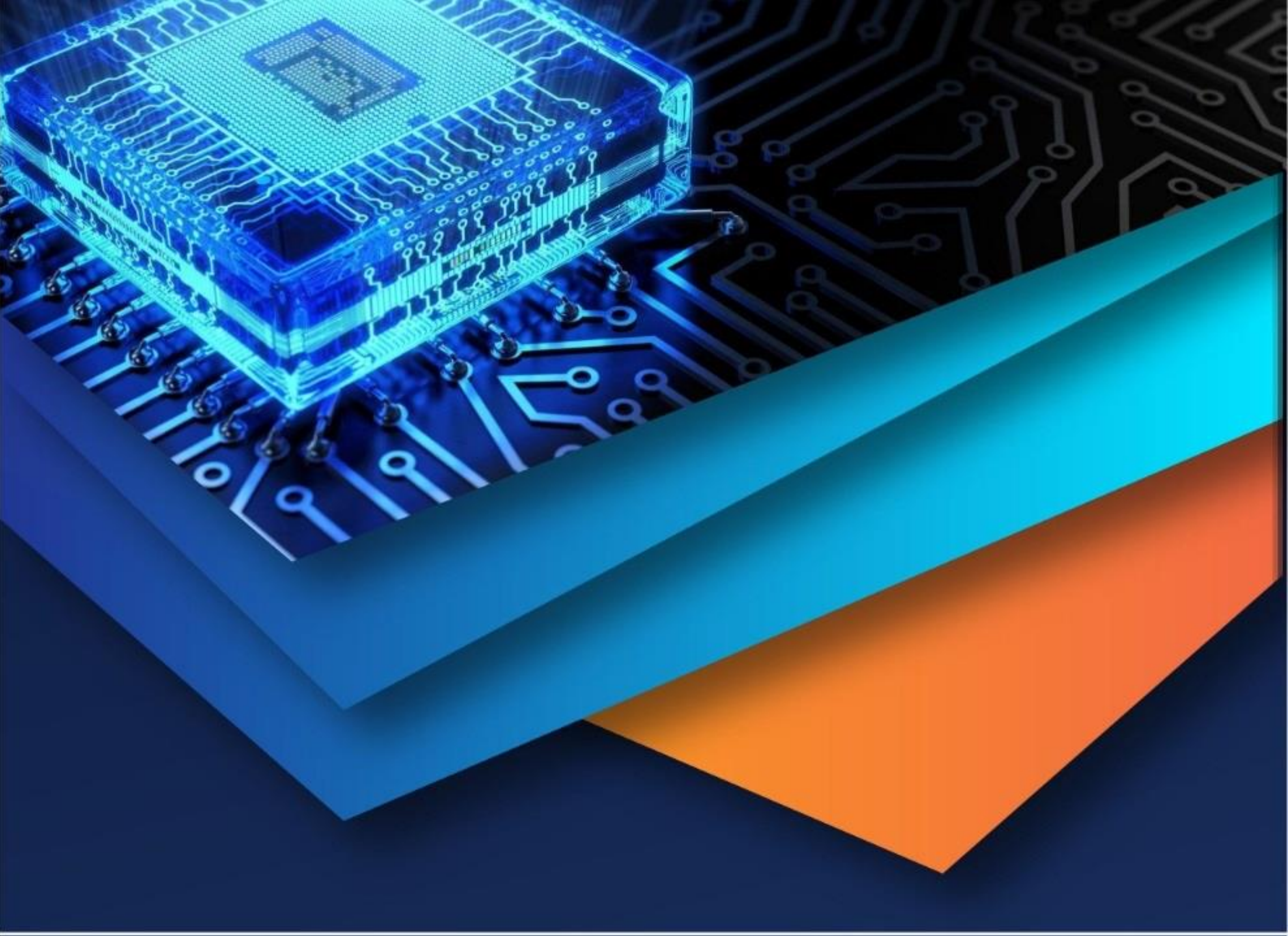

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