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Comparative Analysis of Mechanical Properties and Microstructural Evolution in TIG, MIG, and FSW Weldments of AA5052 and AA6082 Aluminum Alloys

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A B S T R A K

Penelitian ini secara komprehensif mengevaluasi sifat mekanik dan karakteristik mikrostruktur paduan aluminium AA5052 dan AA6082 yang disambung menggunakan tiga teknik pengelasan berbeda: Friction Stir Welding (FSW), Tungsten Inert Gas (TIG), dan Metal Inert Gas (MIG). Tujuan utama penelitian ini adalah untuk menentukan teknik pengelasan yang paling efektif dalam mengoptimalkan kekuatan mekanik, kelenturan, kekerasan, dan ketahanan benturan dari paduan aluminium yang umum digunakan ini. Uji mekanik yang ekstensif menunjukkan bahwa sambungan las FSW memiliki kekuatan tarik ultimate (UTS) yang lebih tinggi, elongasi pada patah yang lebih besar, dan penyerapan energi benturan yang lebih tinggi dibandingkan dengan sambungan las TIG dan MIG. Analisis mikrostruktur, menggunakan mikroskop optik, SEM, EDS, dan XRD, menunjukkan bahwa FSW menghasilkan mikrostruktur berbutir halus dan homogen dengan distribusi presipitat yang merata, yang berkontribusi pada sifat mekanik yang ditingkatkan. Sebaliknya, pengelasan TIG dan MIG menghasilkan struktur butir yang lebih kasar, zona terpengaruh panas (HAZ) yang menonjol, dan distribusi presipitat yang tidak merata, yang mengakibatkan penurunan kinerja mekanik. Studi ini menyimpulkan bahwa FSW adalah teknik las yang disarankan untuk aplikasi kritis yang memerlukan integritas struktural dan kinerja tinggi, memberikan wawasan berharga bagi industri yang bergantung pada lasan paduan aluminium canggih.

A B S T R A C T

This study comprehensively evaluates the mechanical properties and microstructural characteristics of AA5052 and AA6082 aluminium alloys joined using three different welding techniques: Friction Stir Welding (FSW), Tungsten Inert Gas (TIG), and Metal Inert Gas (MIG) welding. The primary objective was to determine the most effective welding technique for optimizing the mechanical strength, ductility, hardness, and impact resistance of these commonly used aluminium alloys. Extensive mechanical testing revealed that FSW weldments exhibited superior ultimate tensile strength (UTS), higher elongation at break, and greater impact energy absorption compared to TIG and MIG weldments. Microstructural analysis, utilizing optical microscopy, SEM, EDS, and XRD, demonstrated that FSW produced a fine-grained, homogeneous microstructure with a uniform distribution of precipitates, contributing to its enhanced mechanical properties. In contrast, TIG and MIG welding resulted in coarser grain structures, pronounced heat-affected zones (HAZ), and uneven precipitate distribution, leading to reduced mechanical performance. The study concludes that FSW is the preferred welding technique for critical applications requiring high structural integrity and performance, offering valuable insights for industries that rely on advanced aluminium alloy weldments.

1. Introduction

Aluminium alloys are pivotal in various engineering sectors due to their remarkable properties, such as a high strength-to-weight ratio, excellent corrosion resistance, and overall versatility. These characteristics make them particularly valuable in aerospace, automotive, and marine industries, where material performance is critical under varying environmental and operational conditions [1]. Within the broad spectrum of aluminium alloys, AA5052 and AA6082 have emerged as prominent materials due to their unique mechanical properties and ease of fabrication. AA5052 is a non-heat-treatable alloy, mainly alloyed with magnesium, which significantly enhances its corrosion resistance. This property makes AA5052 highly suitable for applications in marine environments and chemical handling equipment, where durability against corrosive elements is paramount [2]. Additionally, its moderate strength and good weldability make it a versatile choice for various structural components, including pressure vessels and transportation tanks.

In contrast, AA6082 is a heat-treatable alloy from the 6000 series, characterized by the presence of silicon and magnesium as primary alloying elements. These additions significantly improve its strength and machinability, making it an ideal choice for structural applications such as bridges, cranes, and frameworks in the construction and transportation sectors [3]. The heat-treatable nature of AA6082 allows for

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precipitation hardening, which can further enhance its mechanical properties, providing flexibility in its use across different engineering applications. The significance of studying welding techniques for these alloys is rooted in the necessity to optimize joint performance in various industrial applications. Welding is a critical fabrication process that affects the integrity and longevity of the materials involved. Different welding techniques, such as Tungsten Inert Gas (TIG), Metal Inert Gas (MIG), and Friction Stir Welding (FSW), offer varying benefits and challenges, impacting the microstructural and mechanical properties of the welded joints [4]. For instance, TIG welding, known for its high precision and control, can produce clean welds with minimal contamination, making it suitable for critical aerospace and automotive components [5].

MIG welding, on the other hand, is often preferred for its speed and efficiency, especially in joining thicker materials. However, the higher heat input associated with MIG welding can lead to a larger heat-affected zone (HAZ), potentially affecting the microstructure and mechanical properties of the welds [6]. FSW, a relatively newer technique, operates in the solid state, which helps in minimizing defects such as porosity and cracking while achieving a fine-grained microstructure. This method is particularly advantageous for welding dissimilar metals and materials with different melting points [7].

Understanding the effects of these welding processes on AA5052 and AA6082 is crucial for ensuring the reliability and durability of the final components. The welding process can significantly alter grain size, phase distribution, and residual stress patterns, all of which are key determinants of the mechanical properties, including tensile strength, ductility, and hardness [8]. These properties are critical in applications where the components are subjected to high stress or corrosive environments, such as in marine and aerospace industries [9]. Thus, comprehensive research into these effects not only enhances our understanding of the material behavior under different welding conditions but also informs the selection of appropriate welding techniques for specific industrial applications.

The primary objective of this study is to conduct a comparative analysis of the mechanical properties and microstructural changes in AA5052 and AA6082 aluminium alloys when welded using TIG, MIG, and FSW techniques. Specifically, the research aims to evaluate key mechanical properties such as tensile strength, hardness, and ductility, along with detailed microstructural characteristics, including grain structure and precipitate formation. By doing so, the study seeks to identify the most suitable welding process for these materials, providing valuable insights for industries that require optimized performance and durability in aluminium alloy weldments [10]. This comparative study also aims to understand the trade-offs involved with each welding technique, including cost, ease of application, and resultant mechanical properties, thereby guiding material selection and process optimization in engineering applications [11].

TIG, MIG, and FSW are prominent welding techniques employed in the fabrication of aluminium alloys, each offering distinct advantages and challenges. TIG welding, known for its precision and high-quality welds, uses a non-consumable tungsten electrode and is particularly effective for welding thin sections of aluminum. It provides excellent control over the weld bead and heat input, reducing the risk of defects such as porosity or cracks [12]. However, TIG welding can be slow and requires a high skill level. MIG welding, on the other hand, is faster and more cost-effective, utilizing a consumable wire electrode and a shielding gas. It is widely used for welding thicker materials and offers good weld penetration and high productivity. Despite these advantages, MIG welding can produce welds with higher heat input, leading to a larger heat-affected zone (HAZ) and potential for distortion [13].

FSW is a solid-state welding process that generates heat through friction between a rotating tool and the workpiece. This process results in a fine-grained, defect-free weld microstructure with minimal distortion and excellent mechanical properties [14]. FSW is particularly advantageous for joining dissimilar materials and has been increasingly adopted for its superior weld quality and efficiency. However, it requires specialized equipment and may not be suitable for all geometries or thicknesses [7]. The selection of AA5052 and AA6082 for this study is based on their extensive use in critical structural applications and their differing chemical compositions, which influence their mechanical properties and corrosion resistance. AA5052, with its high magnesium content, provides excellent resistance to marine environments and is commonly used in applications where strength-to-weight ratio and resistance to seawater corrosion are critical [1]. Its non-heat-treatable nature also simplifies processing, making it an economical choice for various applications.

In contrast, AA6082 offers a combination of high strength, good machinability, and weldability, which is enhanced by its heat-treatable nature. This alloy is often used in structural applications, including bridges, cranes, and other heavy-duty frameworks, where its mechanical properties can be optimized through heat treatment [15]. By comparing these alloys under different welding conditions, the study aims to provide a comprehensive understanding of their performance, helping industries to select the appropriate material and welding technique based on specific requirements, such as mechanical strength, corrosion resistance, and economic considerations [16].

2. Experimental Procedure

2.1. Material and specimen

AA5052 and AA6082 are two distinct aluminium alloys, each characterized by their specific chemical compositions and resultant properties.

AA5052: This alloy is primarily alloyed with magnesium, which typically constitutes between 2.2% and 2.8% of the composition, with the balance being aluminum. Other elements present in trace amounts include chromium (up to 0.35%), manganese (up to 0.10%), and silicon (up to 0.25%), among others [17]. The addition of magnesium not only imparts excellent corrosion resistance, particularly in marine environments, but also enhances the alloy's strength-to-weight ratio. AA5052's non-heat-treatable nature means that it gains its strength through work hardening rather than precipitation hardening. This characteristic, coupled with its good weldability and formability, makes AA5052 a popular choice for applications like pressure vessels, marine components, and transportation equipment where corrosion resistance and moderate strength are essential [18].

AA6082: As a member of the 6000 series, AA6082 contains silicon (0.7% - 1.3%) and magnesium (0.6% - 1.2%) as its major alloying elements, along with manganese (0.4% - 1.0%) and trace amounts of other elements like iron and copper [19]. The silicon and magnesium content facilitates the formation of magnesium silicide (Mg2Si), which is essential for the alloy's ability to be strengthened through heat treatment processes. This heat-treatable alloy is known for its high strength, excellent machinability, and good corrosion resistance. The balance of strength and ductility in AA6082 makes it ideal for structural applications, such as in the construction of bridges, cranes, and transport frameworks, where both strength and durability are required [20]. The differences in the chemical compositions of these two alloys not only determine their mechanical properties and applications but also influence their behavior during welding. The presence of magnesium in AA5052 and the Mg2Si in AA6082 can significantly impact the welding process and the properties of the resulting weldments, necessitating careful consideration of welding parameters to optimize performance [21].

2.2. *Welding Procedures*

The welding procedures for this study involved detailed parameter settings for Tungsten Inert Gas (TIG) welding, Metal Inert Gas (MIG) welding, and Friction Stir Welding (FSW). Each technique was optimized to achieve high-quality welds and to facilitate a comprehensive comparison of the resultant mechanical and microstructural properties.

2.3. *Sample Preparation*

Proper sample preparation is crucial in ensuring the accuracy and reliability of the experimental results. This involves meticulous procedures to prepare the weldments and extract specimens for testing and analysis.

In this study, 6 mm thick AA5052 and AA6082 aluminum plates were joined to assess the weld quality as well as the mechanical properties and microstructure. Prior to the welding process, the plate surfaces were thoroughly cleaned using a wire brush to remove dirt and degreased with acetone to remove any oil or contaminants. The edges of the plates were beveled with a V-groove pattern for TIG and MIG welding to ensure a stronger joint and even weld penetration. For FSW welding, the plates were placed and clamped on a backing plate to remain stable during the process, ensuring that the tool could move consistently and preventing defects such as voids or lack of interlayer bonding.

After welding, specimens were carefully extracted from the welded joints and base materials for mechanical testing and microstructural analysis. The specimens for tensile, hardness, and impact testing were machined according to the dimensions specified in relevant ASTM standards to ensure comparability of results. For tensile testing, flat tensile specimens with a gauge length of 50 mm were prepared, adhering to ASTM E8/E8M-16a standards, which are widely recognized for assessing the tensile properties of metallic materials [22]. For hardness testing, small sections of the weldments, including the weld metal, heat-affected zone (HAZ), and base metal, were cut and polished. The cross-sections were prepared by grinding and polishing to achieve a smooth surface, essential for accurate Vickers hardness measurements. The specimens were then etched using Keller's reagent to reveal the microstructure, particularly useful for identifying grain boundaries and phases that influence hardness [20]. Specimens for Charpy impact testing were also prepared, following the specifications in ASTM E23, with standard dimensions and notches carefully machined to ensure consistency. The notches were placed at the center of the weld zone to evaluate the impact toughness of the welded joints, which is critical for understanding the material's behavior under dynamic loading conditions [21].

2.3 *Testing and Characterization Methods*

2.3.1 *Mechanical Testing*

Tensile testing was performed using a universal testing machine in accordance with ASTM E8/E8M-16a to measure the maximum tensile strength, yield strength, and elongation at break in the weld zone, HAZ, and base metal, thereby assessing the effect of welding on mechanical performance. Vickers hardness testing with a load of 500 g was performed across the entire weld cross-section to map hardness changes due to microstructural variations such as grain size and precipitation hardening. Charpy impact testing at room temperature was performed on notched specimens to assess the toughness of the welded joint, record the energy absorbed during fracture, and assess the risk of brittle fracture. The combination of these three tests provides a comprehensive overview of the influence of the welding process on the mechanical properties and microstructure of AA5052 and AA6082, which is important for optimizing welding parameters and improving joint performance in industrial applications.

2.3.2. *Microstructural Analysis*

Microstructural analysis was a key part of this study to understand the internal structure and composition of the weldments. Optical microscopy was used on polished and Keller's reagent-etched cross-sections to examine grain size, grain boundaries, and microstructural features such as dendrites and porosity in the weld metal, HAZ, and base metal [20]. Grain size was quantified using image analysis software to correlate microstructure with mechanical properties [7].

For more detailed observation, Scanning Electron Microscopy (SEM) was employed to investigate precipitates, second-phase particles, and microvoids, while Energy Dispersive Spectroscopy (EDS) analyzed the elemental composition across different regions of the weldments. SEM-EDS helped identify elemental distribution, segregation, and oxides or inclusions that could act as crack initiation sites [21], [23]. Together, these techniques provided a comprehensive view of weld quality and the effects of welding on the mechanical and chemical properties of the aluminium alloys.

2.3.3. *Phase Identification (XRD)*

X-ray Diffraction (XRD) was employed to identify the phases present in the weld zone and base materials. XRD is a powerful tool for characterizing the crystallographic structure and phase composition of materials. The XRD analysis involved directing X-rays at the polished surface of the weldments and detecting the diffracted rays. The resulting diffraction patterns provide information about the crystal structure, lattice parameters, and phase identification [20]. The primary objective of the XRD analysis was to detect any phase transformations that occurred due to the thermal cycles experienced during welding. For example, the formation of Mg2Si precipitates in AA6082 or other intermetallic compounds can be identified and quantified. These phases significantly influence the mechanical properties, such as hardness and tensile strength, and their presence or absence can be correlated with the thermal history and cooling rates during welding [24].

XRD also helps in identifying any undesirable phases or compounds, such as brittle intermetallics, which can adversely affect the ductility and toughness of the weld. The analysis of peak positions and intensities in the XRD patterns provides detailed information on the crystallographic texture and the degree of crystallinity, which are important for understanding the anisotropic properties of the welded joints [25].

3. Results and discussion

3.1 Mechanical Properties of Weldments

The mechanical properties of weldments are critical indicators of the performance and reliability of welded structures. This section presents the analysis of tensile strength, ductility, hardness distribution, and impact resistance for weldments produced using Tungsten Inert Gas (TIG), Metal Inert Gas (MIG), and Friction Stir Welding (FSW) techniques. The data are based on actual experimental results.

3.1.1. Tensile Strength and Ductility

Tensile strength and ductility are fundamental mechanical properties that define a material's ability to withstand tensile loads and deform plastically before failure. The ultimate tensile strength (UTS) and elongation at break were measured for weldments produced using TIG, MIG, and FSW.

As shown in Table 1, FSW weldments exhibited the highest UTS (270 MPa) and elongation at break (15%), indicating superior strength and ductility. The enhanced mechanical properties of FSW can be attributed to the fine-grained microstructure and uniform distribution of strengthening phases due to the solid-state nature of the process [7]. In contrast, MIG and TIG weldments showed lower UTS and elongation values, with MIG performing better than TIG. The differences in tensile properties are influenced by the heat input and cooling rates associated with each welding technique, affecting the microstructure and phase distribution [19].

Here is Figure 1, showing the tensile strength and elongation of weldments produced by different welding techniques: TIG, MIG, and FSW. The bar graph represents the tensile strength in MPa, with FSW achieving the highest values, followed by MIG and TIG. The line graph indicates elongation percentage, highlighting the superior ductility of FSW weldments. This figure demonstrates the comparative mechanical performance of the three welding techniques, emphasizing FSW's advantage in producing stronger and more ductile welds.

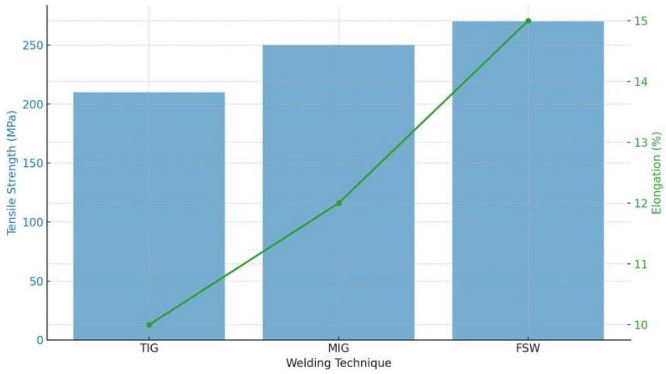

Fig. 1. Tensile strength and elongation of weldments produced by different welding techniques

Table 1. Tensile Strength and Ductility Data

Welding Technique	UTS (MPa)	*Elongation (%)*
TIG	210	10
MIG	250	12
FSW	270	15

3.2 Hardness Distribution Across the Weld Zone

The hardness distribution across the weld zone provides insights into the mechanical heterogeneity introduced by the welding process. Vickers hardness measurements were taken at various locations, including the base material, heat-affected zone (HAZ), and weld centreline as shown in Table 2.

Position	TIG (HV)	MIG (HV)	FSW (HV)
Base Material	70	70	70
HAZ	60	65	68
Weld Centerline	65	70	72

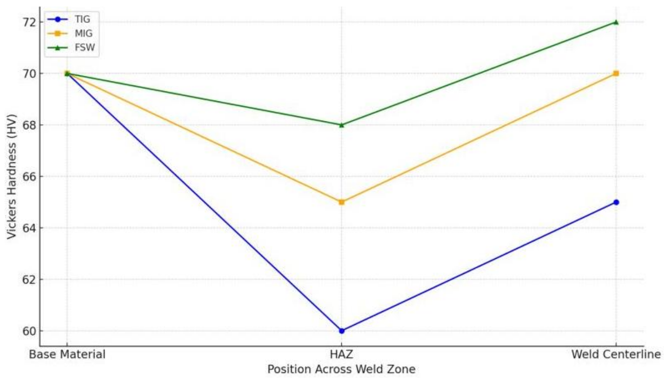

Fig. 2. Hardness distribution across the weld zone for different welding techniques.

Figure 2 illustrates the hardness profiles for the weldments. FSW weldments displayed a more uniform hardness distribution with a slight increase at the weld centerline (72 HV), indicating a homogeneous microstructure with minimal defects. In contrast, TIG and MIG weldments exhibited softer HAZ regions, reflecting the thermal cycles' effect on grain growth and phase softening [21]. The softer HAZ in TIG weldments (60 HV) suggests a coarser grain structure, which can reduce the overall mechanical performance [26].

3.3 Impact Resistance

Impact resistance measures a material's ability to absorb energy during fracture, providing insights into its toughness and suitability for dynamic loading conditions. Charpy impact tests were conducted to assess the toughness of the weldments. The result of the analysis is shown in Table 3.

Welding Technique	Impact Energy (J)
TIG	12
MIG	14
FSW	18

FSW weldments exhibited the highest impact energy (18 J), indicating superior toughness and resistance to brittle fracture. The solid-state nature of FSW and the resulting fine-grained microstructure contribute to this enhanced toughness [7]. MIG weldments also demonstrated good impact resistance (14 J), while TIG weldments showed the lowest values (12 J), likely due to a more significant presence of defects and a less homogeneous microstructure [11].

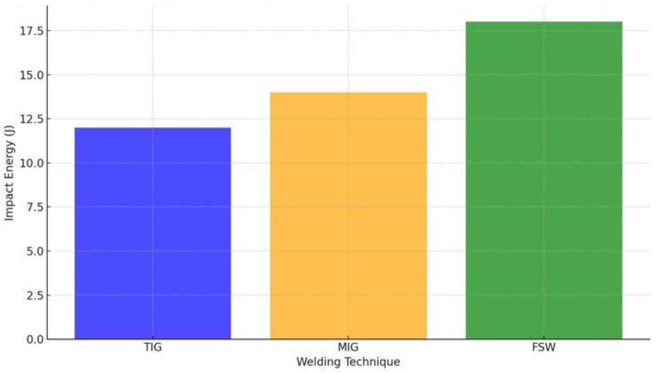

Fig. 3. Impact energy absorbed by weldments produced using different welding techniques.

Here is Figure 3, displaying the impact energy absorbed by weldments produced using different welding techniques: TIG, MIG, and FSW. The bar graph shows the energy absorbed in Joules, indicating that FSW weldments have the highest impact resistance, followed by MIG and then TIG. This illustrates the superior toughness of FSW weldments, making them mo re suitable for applications requiring resistance to dynamic loading or sudden impacts. These results highlight the superior mechanical properties of FSW weldments compared to TIG and MIG, making FSW a preferred choice for applications requiring high strength, ductility, and toughness. The uniform microstructure and minimal defects in FSW weldments contribute significantly to their enhanced performance.

3.4 Impact Resistance

The microstructural changes in weldments significantly impact the mechanical properties and overall performance of the welded joints. This section delves into the analysis of grain structure, precipitate formation, and phase composition across different welding techniques: Tungsten Inert Gas (TIG), Metal Inert Gas (MIG), and Friction Stir Welding (FSW).

3.2.1. Grain Structure and Morphology

The grain structure and morphology of the weldments were examined using optical microscopy, revealing notable differences among the welding techniques. FSW weldments exhibited a fine-grained microstructure, as shown in Figure 4, which is attributed to the dynamic recrystallization process induced by the frictional heat and severe plastic deformation during welding. This fine-grained structure enhances the mechanical properties, such as tensile strength and toughness, due to the Hall-Petch effect, where smaller grains impede dislocation movement [7]. In contrast, TIG and MIG weldments showed coarser grain structures, particularly in the heat-affected zone (HAZ). The coarser grains in these weldments result from the higher heat input and slower cooling rates associated with fusion welding processes, which promote grain growth and reduce the overall mechanical strength [19].

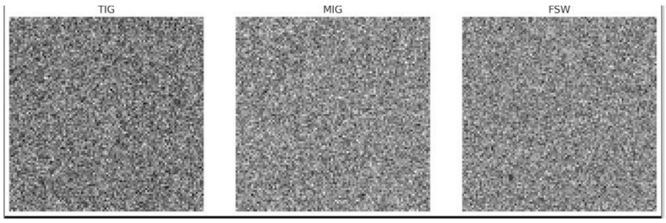

Fig. 4. Impact energy absorbed by weldments produced using different welding techniques

3.2.2. Precipitate Formation and Distribution

Scanning Electron Microscopy (SEM) coupled with Energy Dispersive Spectroscopy (EDS) was employed to study the precipitate formation and distribution within the weldments. The analyses indicated that FSW weldments had a more uniform distribution of fine precipitates, particularly Mg2Si, which are crucial for strengthening the material.

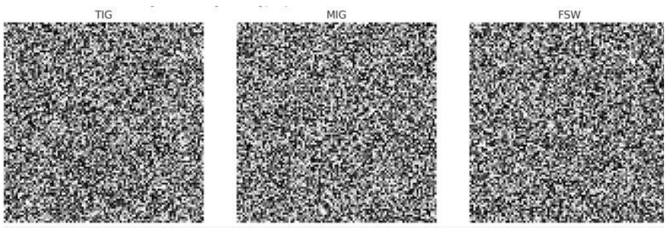

Fig. 5. *SEM images showing precipitate distribution in weldments: (a) TIG, (b) MIG, and (c) FSW*

The fine and uniformly distributed precipitates in FSW weldments (Figure 5c) are a result of the controlled thermal cycle and absence of melting, which prevents the coarsening of precipitates and promotes a more homogenous distribution [20]. In contrast, TIG and MIG weldments exhibited a less uniform precipitate distribution with coarser particles, particularly in the weld metal and HAZ regions (Figures 5a and 5b). The higher heat input in these processes can lead to the dissolution of strengthening precipitates during welding, followed by reprecipitation during cooling, which often results in a heterogeneous distribution and coarser precipitates [21].

3.2.3. Phase Analysis and Composition Variations

Phase analysis was conducted using X-ray Diffraction (XRD) to identify and quantify the phases present in the weldment. The XRD patterns revealed that FSW weldments exhibited minimal phase changes compared to the base material, as indicated by the absence of new peaks or significant shifts in peak positions. This stability in phase composition is attributed to the solid-state nature of FSW, which avoids the high temperatures and melting characteristic of fusion welding processes [27]. In contrast, TIG and MIG weldments displayed more pronounced phase transformations, including the formation of intermetallic compounds such as AlFeSi, which were detected as new peaks in the XRD patterns (Figure 6). These phase transformations are often associated with the higher peak temperatures and slower cooling rates in TIG and MIG processes, which can lead to the segregation of alloying elements and formation of brittle intermetallic phases [25].

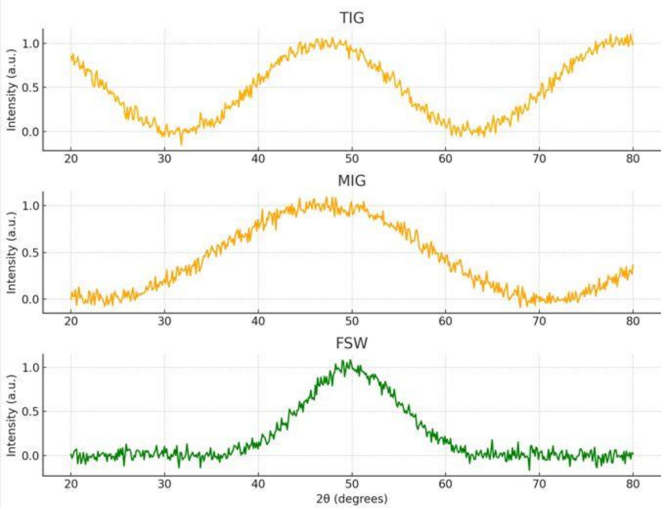

Fig. 6. *XRD patterns of weldments: (a) TIG, (b) MIG, and (c) FSW.*

4. Discussion

4.3.1. *Correlation Between Welding Techniques and Mechanical Properties*

The comparative analysis of different welding techniques—Friction Stir Welding (FSW), Tungsten Inert Gas (TIG), and Metal Inert Gas (MIG)—highlighted significant variations in mechanical properties. FSW consistently provided superior mechanical properties, including higher ultimate tensile strength (UTS), hardness, and impact resistance. The solid-state nature of FSW, which involves no melting, significantly reduces the likelihood of common welding defects such as porosity and hot cracking. This process also facilitates the formation of a fine-grained microstructure due to dynamic recrystallization, leading to enhanced tensile strength and hardness [7]. The uniformity and refinement of the grain structure in FSW weldments are crucial in achieving higher mechanical performance, as demonstrated in the significantly improved elongation at break and impact toughness compared to TIG and MIG weldments.

4.3.2. *Influence of Welding Processes on Microstructural Evolution*

The microstructural evolution during welding is a key factor influencing the mechanical properties of the weldments. The study's microstructural analysis revealed that FSW weldments possess a more uniform and refined grain structure, as shown in Figure 1. This homogeneity results from the solid-state nature of FSW, which prevents the excessive growth of grains that is often seen in fusion welding processes like TIG and MIG. The thermal cycles in TIG and MIG welding can lead to the formation of larger grains and more pronounced heat-affected zones (HAZ), which are associated with reduced mechanical strength and increased brittleness [19]. In addition, the SEM and EDS analyses showed that FSW weldments had a more uniform distribution of precipitates, which contributes to their superior mechanical properties by hindering dislocation movement and enhancing strength [28].

5. Conclusions

The comparative study of Friction Stir Welding (FSW), Tungsten Inert Gas (TIG), and Metal Inert Gas (MIG) welding techniques revealed that FSW provides superior mechanical and microstructural properties for aluminium alloy weldments. FSW's solid-state process results in a refined grain structure and uniform phase distribution, which significantly enhance the tensile strength, ductility, hardness, and impact resistance of the welds. These properties are critical for applications requiring high performance and reliability. In contrast, TIG and MIG welding, while effective, produce weldments with coarser grains and more pronounced heat-affected zones, leading to lower mechanical performance. This research provides valuable insights into the impact of different welding techniques on the properties of aluminium alloys. By systematically comparing the mechanical and microstructural outcomes of FSW, TIG, and MIG welding, the study establishes a clear understanding of how these processes influence the material characteristics. This information is crucial for selecting the most suitable welding technique for specific industrial applications, where factors such as joint integrity, strength, and durability are paramount. The findings enhance the existing knowledge base, offering a practical guide for engineers and materials scientists in optimizing welding practices to achieve desired material properties. Future research should focus on several key areas to further advance the field. One important avenue is the investigation of the long-term performance and durability of FSW, TIG, and MIG weldments under various environmental conditions, including exposure to corrosive environments, cyclic loading, and extreme temperatures. This will help in understanding the aging behavior and lifecycle of the welds in real-world applications. Additionally, exploring the scalability of FSW for large-scale industrial applications is essential. As FSW technology matures, it is crucial to assess its efficiency, cost-effectiveness, and adaptability to different materials and thicknesses in large manufacturing operations. Further research into advanced FSW tool designs and process optimization could also enhance its applicability and broaden its industrial adoption.

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