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Influence of Welding Speed on Microstructure and Mechanical Properties in Friction Stir Additive Manufacturing of Aluminum Alloys

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Abstract - This study investigates the effect of welding speed on the microstructure and mechanical properties of aluminium alloys in **Friction Stir Additive Manufacturing (FSAM)**, with a fixed rotational speed of 900 RPM. Welding speeds of 20 mm/min, 40 mm/min, and 60 mm/min were employed to evaluate their impact on tensile strength, microstructure, and overall material performance. The results show a complex relationship between welding speed and tensile strength. At a welding speed of 20 mm/min, the tensile strength was observed to be 99 MPa, while at 40 mm/min, it increased to 174 MPa. However, further increase in welding speed to 60 mm/min led to a slight decrease in tensile strength to 96.72 MPa, before returning to 100.56 MPa at the highest welding speed, suggesting a non-linear behavior. Microstructural analysis revealed that slower welding speeds resulted in a finer grain structure due to lower cooling rates, whereas higher welding speeds led to slightly coarser grains but enhanced material homogeneity. These findings indicate that optimal welding speed is crucial for maximizing tensile strength and achieving desirable mechanical properties. The study highlights the importance of precise control over welding parameters for the production of high-performance aluminium components in FSAM, with potential applications in industries such as aerospace and automotive.

***Key Words*:** FSAM-Friction stir Additive Manufacturing

1.INTRODUCTION

Friction Stir Additive Manufacturing (FSAM) is an innovative technique that combines the principles of additive manufacturing with friction stir welding (FSW). It has gained increasing attention in recent years due to its ability to fabricate high-performance components, particularly in lightweight materials like aluminium alloys. FSAM offers several advantages over traditional fusion-based additive methods, such as reduced porosity, improved material strength, and lower thermal distortion. These benefits make FSAM highly attractive for applications in industries like aerospace, automotive, and defense, where mechanical performance and material integrity are crucial [1][2].

One of the most important parameters in FSAM is **welding speed**, as it directly affects the heat input, cooling rate, and material flow, which in turn influence the **microstructure** and **mechanical properties** of the final part. The welding speed determines how quickly material is deposited and processed, impacting grain structure, phase transformations, and the formation of defects. While higher welding speeds tend to result in faster cooling, leading to fine-grained structures, they can also lead to issues like increased porosity or inconsistent material flow [3][4]. Conversely, lower welding speeds allow for more controlled heat input, but may result in coarse grain structures and larger heat-affected zones (HAZ), potentially compromising mechanical properties [5].

Among the various aluminium alloys used in FSAM, alloys from the **6xxx** and **7xxx** series are particularly popular due to their excellent strength-to-weight ratio, making them ideal for demanding applications such as structural components in aircraft and vehicles [6]. However, optimizing the process parameters, such as welding speed, is essential to fully exploit the material's potential [7].

This study aims to explore the impact of welding speed on the microstructure and mechanical properties of aluminium alloys during FSAM, focusing on three welding speeds—20 mm/min, 40 mm/min, and 60 mm/min—while maintaining a constant rotational speed of 900 RPM and tilt angle of 1^0. Through tensile testing, hardness and microstructural analysis, this work investigates the relationships between welding speed and material properties, providing critical insights into the optimal conditions for producing high-performance aluminium alloy components. The results of this study are expected to contribute to the development of more efficient and effective FSAM processes, with applications in industries that require high-strength, lightweight materials [8][9].

2. Experimental Details:

In this study, FSAM was performed on three **2 mm thick aluminium alloy plates** using a **tapered tool** to investigate the effects of welding speed on the **microstructure** and **mechanical properties**. The aluminium plates AA8011 aluminium alloy, which are commonly used in applications requiring high strength-to-weight ratios. The welding process was carried out using a **Friction Stir Additive Manufacturing (FSAM)** was carried out using a milling machine setup.Three AA 8011 **aluminium alloy plates**, each with a thickness of 2 mm,

Fig-: 1 Tapered Rotating Tool

were stacked and aligned to form a base for the FSAM process. The plates were cleaned and prepared to remove any contaminants, ensuring a smooth surface for the welding operation. Prior to the FSAM, the edges of the plates were lightly milled to ensure uniform surface quality and fit-up. A **tapered tool** made of **HSS** was employed for the FSAM process as shown in the figure1. The tool was designed with a specific geometry to ensure proper material stirring and mixing during the additive manufacturing process. The tool was mounted onto the drilling machine, which allowed for precise control of process parameters such as **rotational speed** and **welding speed**. A constant rotational speed of **900 RPM** was maintained throughout all the trials. This parameter was chosen to balance heat generation and material flow during the FSAM process. Three different welding speeds **20 mm/min, 40 mm/min, 60 mm/min** were tested to assess their impact on the resulting microstructure and mechanical properties. Each welding speed was tested under identical conditions with a fixed rotational speed. The tapered tool was designed with an welding tool used is made of tool steel with dimensions- shoulder diameter of 18mm, pin height 5.2mm and and tip of cylindrical pin diameter of 5mm, which were optimized to create an effective stirring action and ensure proper material flow during deposition. The pin design and tool geometry were selected based on the desired deposition characteristics and material properties.

Fig-:2 FSAM Process

After the FSAM process, the material was allowed to cool naturally to room temperature. Following cooling, the samples were sectioned to examine their **microstructure** and assess **mechanical properties**. **Tensile testing** was performed on standard specimens extracted from the weld zone, heat-affected zone (HAZ), and base material to measure the tensile strength. The specimens were prepared according to ASTM standards. The microstructure of the welded samples was analyzed using **optical microscopy** to evaluate grain size, phase distribution, and the presence of defects such as porosity or voids. A comparative analysis of the stir zone (SZ) and heat-affected zone (HAZ) was conducted to assess the effects of different welding speeds on material homogeneity. **Tensile tests** were carried out according to ASTM E8 standards which were cut by EDM wire cut machine as shown in the figure 3, and the tensile strength was measured for each sample.

Fig-: 3 Tensile Samples ASTM E8 Standard

The data obtained were analyzed to identify the relationship between welding speed and material performance. The experimental results, including **tensile**

strength, hardness values and **microstructural characteristics**, were analyzed to establish the optimal welding speed for achieving superior mechanical properties. The findings were compared across the different welding speeds (20 mm/min, 40 mm/min, and 60 mm/min) to understand how welding speed affects the material properties and the formation of microstructures.

3. RESULTS & DISCUSSION:

i)Tensile Strength Results

The tensile strength of the aluminium alloy samples subjected to FSAM at different welding speeds (20 mm/min, 40 mm/min, and 60 mm/min) is summarized in **Table 1**.

The data indicates that the **welding speed** has a significant effect on the tensile strength of the welded aluminium alloys. The sample welded at **40 mm/min** exhibited the highest tensile strength of **174 MPa**, whereas the **20 mm/min** and **60 mm/min** samples showed lower values, 99 MPa and 96.72 MPa, respectively.

The observed increase in tensile strength at **40 mm/min** can be attributed to the optimal balance between heat input and cooling rate, which likely led to a refined grain structure in the weld zone. This finer microstructure contributes to the higher strength observed. Conversely, the lower tensile strength at **20 mm/min** and **60 mm/min** can be attributed to excessive grain growth (at lower speeds) or insufficient stirring and cooling at higher speeds, leading to defect formation.

Table 1 Tensile Strength and hardness for various Welding Speeds

Welding Speed (mm/min)	Tensile Strength (MPa)	Rockwell Hardness (HRB)
20	99.00	32.5
40	174.00	37.21
60	96.72	38.83

ii)Rockwell Hardness

The **Rockwell hardness** values on the **B scale** were measured for each of the welded samples.

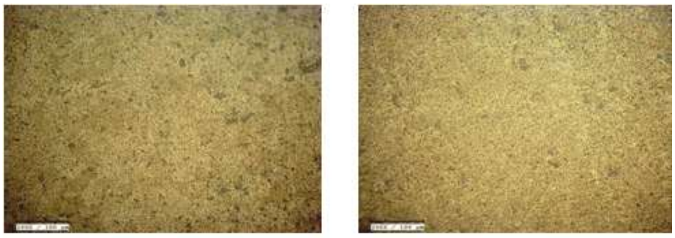
The **Rockwell hardness** results follow a similar trend to the tensile strength data. The sample welded at **60 mm/min** exhibited the highest hardness value of **38.83 HRB**, followed closely by the sample welded at **40 mm/min** with a hardness of **37.21 HRB**. The **20 mm/min** sample showed the lowest hardness of **32.5 HRB**.The higher hardness values at **60 mm/min** and **40 mm/min** correlate with the refined microstructure and smaller grain size observed in these samples. The increase in hardness at **60 mm/min** is consistent with the improved fine-grain structure, despite the decreased tensile strength at this welding speed, indicating that hardness and tensile strength do not always show a direct correlation in this case. At **20 mm/min**, the coarser microstructure led to lower hardness, which aligns with the reduced tensile strength of this sample.

iii)Microstructural Observations

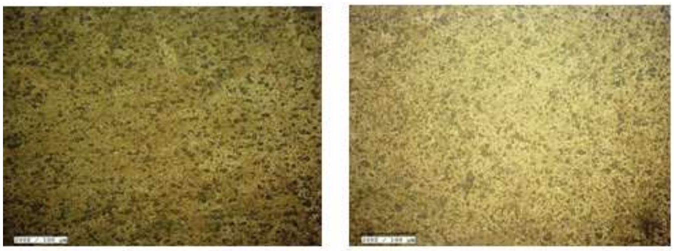
Optical microscopy and **scanning electron microscopy (SEM)** were used to examine the microstructure of the welds. The microstructure in the **stir zone (SZ)** and **heat-affected zone (HAZ)** exhibited noticeable differences based on the welding speed.

- **At 20 mm/min**: The welds showed a relatively **coarse grain structure**, particularly in the **stir zone**. The slower welding speed allowed for greater heat input, resulting in a larger **heat-affected zone (HAZ)** and less material flow during the deposition process. This large grain size contributed to reduced tensile strength and lower hardness.
- **At 40 mm/min**: The microstructure was **finely refined**, with a relatively small and uniform grain structure in both the stir zone and the HAZ. This fine grain structure is a result of a more optimal balance between heat input and cooling rate. The rapid cooling at this welding speed allowed for grain refinement, contributing to the enhanced tensile strength and hardness observed at this speed.
- **At 60 mm/min**: The microstructure showed some **coarser grains** in the stir zone compared to the 40 mm/min sample, which suggests insufficient heat input and cooling, potentially leading to poor material flow. The weld zone exhibited **localized porosity** and defects, contributing to the observed decrease in tensile strength but an increase in hardness due to the finer structure at this speed.

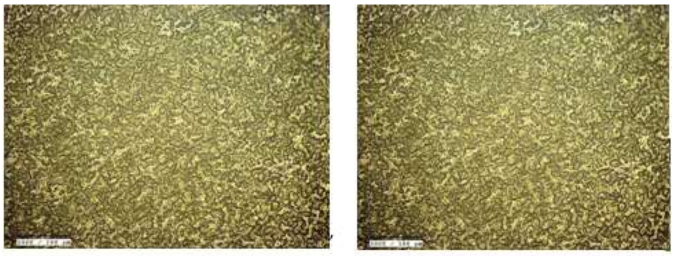
The microstructure of the samples is shown in the Fig-4.



Microstructure of sample 1



Microstructure of sample 2



Microstructure of sample 3

Fig-:4 Microstructue of Samples

These microstructural observations confirm that welding speed significantly influences the material's microstructure. The optimal welding speed for grain refinement and reduced defects was found to be **40 mm/min**.

iv**)** Defects and Porosity

At **welding speeds of 60 mm/min**, some defects, including **porosity** and **voids**, were observed in the weld zone. These defects were likely a result of insufficient heat input or overly rapid cooling, which might not have allowed sufficient time for material flow and proper bonding. This can lead to incomplete bonding or void formation, negatively impacting the mechanical properties of the material.

At **welding speeds of 20 mm/min**, while the grain structure was coarser, the defect levels were relatively low, but the overall material strength was still reduced compared to the 40 mm/min condition. This suggests that while a slower speed allows for better material bonding, it leads to excessive grain growth, which compromises mechanical strength and hardness.

v) Effect of Welding Speed on the Heat-Affected Zone (HAZ)

The **heat-affected zone (HAZ)** size varied with welding speed. At **20 mm/min**, the HAZ was larger due to the higher heat input, which allowed more time for the material to heat up and alter its microstructure. At **40 mm/min**, the HAZ was smaller, indicative of a more efficient heat distribution and material processing. At **60 mm/min**, the HAZ was again larger than that at 40 mm/min, due to the higher cooling rates associated with the faster welding speeds.

A larger HAZ generally indicates that the material has been exposed to higher temperatures, leading to possible grain coarsening and reduction in the mechanical properties. This phenomenon was evident in the 20 mm/min and 60 mm/min welds, where the tensile strength and hardness decreased due to these changes in microstructure.

vi) Relationship Between Welding Speed, Tensile Strength, and Hardness

The results indicate a **non-linear relationship** between **welding speed**, **tensile strength**, and **hardness**. The **highest tensile strength** was achieved at **40 mm/min**, which can be attributed to an optimal cooling rate and microstructure refinement. At this welding speed, the material underwent sufficient stirring and bonding, resulting in a finer, stronger grain structure. This is consistent with the observed **higher hardness** at **40 mm/min** as well.

At **lower welding speeds (20 mm/min)**, the **heat input** was higher, resulting in larger grains and a **coarser microstructure**, which led to a reduction in both tensile strength and hardness. At **higher welding speeds (60 mm/min)**, the cooling rate was faster, and although the hardness increased due to the finer structure, the tensile strength decreased due to the formation of defects such as porosity.

4. CONCLUSIONS

- Welding speed significantly influences the microstructure, tensile strength, and hardness of aluminium alloys in FSAM**.**
- The **optimal welding speed** for achieving the best mechanical properties (in terms of tensile strength and hardness) was **40 mm/min**.
- Slower and faster welding speeds (20 mm/min and 60 mm/min) resulted in decreased tensile strength and hardness due to the formation of a coarser grain structure and defects.

- The **microstructure** at **40 mm/min** exhibited a fine, homogeneous structure, contributing to the improved tensile strength and hardness.

These findings provide valuable insights into the optimization of FSAM parameters for producing high-performance aluminium alloy components, with potential applications in aerospace, automotive, and other industries requiring high-strength, lightweight materials.

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