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Effect of tool travel speed on tensile strength of friction stir welded dissimilar joint of aluminium AA6061 T6 alloy and maraging M250 steel

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Abstract

Friction stir welding (FSW) is a promising welding method to produce dissimilar joints between steel and aluminium. The formation of the intermetallic compound layer at the dissimilar joint interface affects the joint mechanical properties, which are also influenced by the FSW process parameters. In the present research work, M250 Maraging steel and AA6061 T6 aluminium alloy were joined by FSW. The joints were prepared with five different tool travel speeds ranging from 0.33 mm s\(^{-1}\) to 1 mm s\(^{-1}\) using a tapered tool pin made by tungsten carbide material, keeping tool rotational speed constant. The welded joints were analyzed for their tensile behaviour and microstructural change, including hardness measurement. The failed samples are analyzed using a scanning electron microscopy device for their mode of failure. In the Energy Dispersive X-Ray Spectroscopy (EDS) analysis, the formation of intermetallic compound (IMC) layers of Fe\(_3\)Al, Fe\(_4\)Al\(_{13}\), and Fe\(_2\)Al\(_5\) are observed. When the thickness of the IMC layer increases, the joint strength decreases. It is found that the welding speed influences the thickness of the IMC layer formed, causing variation in the strength of the dissimilar joint. Better joint efficiency is obtained at a tool travel speed of 0.67 mm s\(^{-1}\).

1. Introduction

Currently, industries utilize lightweight structural materials instead of heavy structural materials for several engineering applications. Aluminium (Al) and Magnesium (Mg) materials are typically used in the automotive industry due to their high strength and lightweight structure. Many industries apply combinations of Al alloy—steel hybrid structures to manufacture components through the welding process. The honda motor Co. used the hybrid joint of steel with aluminum in engine cradles, and stainless steel and aluminium alloy combination is used in cryogenic fuel storing and transportation [1]. Thus in recent decades, several researchers have researched the combination of various materials to meet industrial needs. Consequently, applying the suitable welding process for joining the dissimilar material becomes essential [2, 5]. IMC’s formation is a significant problem in joining two dissimilar materials by fusion welding as they affect the weldability [4].

Friction Stir Welding (FSW) is a solid-state welding process widely used as a promising technique for joining dissimilar materials that improve weldability. Predominantly, FSW was applied in the joining of Al alloys and magnesium alloys for diminishing the formation of intermetallic compounds in the dissimilar joints. It is difficult to achieve good quality when FSW is applied to dissimilar material combinations, including Al/Cu alloy, Al/Ti alloy, and Al/Fe alloy, due to the difference in material compositions [5–7].

The major issues, namely difference in melting points, tool wear, material flow behaviour, and microstructure of the materials, are affecting the quality of the FSWed joint [8, 9]. Many researchers attempted to enhance the weld quality of dissimilar materials in the past decades. Uzun et al. [10] investigated and found that the stir zone’s microstructure (SZ) has a reinforced composite structure of steel in aluminium alloy. The fatigue property of the joint is lesser than Al alloy. The hardness decreases towards SZ on the advancing side of

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| Material                  | Elements, % by weight |
|---------------------------|-----------------------|
|                          | Ni  | Co  | Mg  | Mo  | Si  | Ti  | C   | Cr  | Cu  | Mn  | Zn  | Fe  | Al  |
| AA6061 T6 Alloy          | —   | —   | 0.90| —   | 0.75| 0.02| —   | 0.18| 0.24| 0.05| 0.07| 0.47| Bal.|
| M250 Maraging steel      | 18.9| 6.8 | —   | 5.5 | 0.21| 0.3 | 0.01| 0.28| —   | 0.32| —   | Bal.| 0.26|

**Table 2. Mechanical properties of AA6061-T6 and M250 Steel.**

| S. No. | Base material | UTS (MPa) | YS (MPa) | % Elongation |
|--------|---------------|-----------|----------|--------------|
| 1      | AA6061-T6     | 310       | 276      | 12           |
| 2      | M250 Steel    | 1800      | 1700     | 8            |

2. Experimental work

Al alloy AA6061-T6 and aged Maraging Steel of grade M250 were used as parent materials for the present research work. The composition of the base materials’ chemical elements and mechanical characteristics are presented in tables 1 and 2. Spectro-chemical analysis by Bruker Q4 TASMAN - Advanced CCD Based Optical Emission Spectrometer was used to estimate the PM chemical composition. Plates of 100 mm × 50 mm × 3 mm were machined normal to PM’s rolling direction to prepare a flat butt weld joint configuration, as shown in figure 1. A compound FSW tool having a plain tapered cylindrical pin profile made of tungsten carbide shown in figure 2 was used for the welding. Tool pin offset distance was fixed as 1.5 mm from the joint interface at the Al side. Five joints were made with different TTS of 0.33, 0.5, 0.67, 0.83, 1 mm s⁻¹, keeping axial force as 7.5 kN, tool tilt angle as 2° (shown in figure 2), and rotational tool speed 500 rpm. A semi-automatic FSW machine setup with a hydraulic unit to control the pressure acting in the Z-axis direction (axial load) and X-direction (welding speed) during the welding process a chiller unit to cool the spindle as shown in figure 3 used for welding. The heat generated is measured by a non-contact type infrared temperature scanner during the welding process.

The microstructural studies of the welds were carried out by an Olympus BX51M optical microscope. The optical microscopy (OM) specimens were polished using the standard metallographic procedure and etched. To reveal the microstructure, AA6061 T6 etched with Keller’s reagent for 10 s to 15 s and modified fry’s reagent for 25 s for M250 Steel, respectively.
To assess the transverse tensile properties of welded joints, FIE made Servo Controlled Electronic Universal Testing Machine UTES-40 was used. Two Tensile specimens from each plate were extracted by the Wire EDM process and prepared using the ASTM E8M standard with a gauge length of 25 mm, as shown in figure 4. The tensile properties, including elongation, ultimate tensile strength, and yield strength, were estimated.

Figure 1. Illustration of weld joint configuration with plate dimensions.

Figure 2. Design of compound tool and pin profile.

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fracture path cross-section of the tested tensile samples was analyzed using Field Emission Scanning Electron Microscope (FESEM) (Zeiss make SIGMA HV machine).

The microhardness measurements were taken (using Mitutoyo MVK-H1 Vickers’ hardness tester) along the mid thickness zone of the cross-section of the welded joint specimen at equal intervals of 1 mm on either side of the joint interface with a load of 0.245 N for 10 s dwell time.

3. Results

3.1. Macrostructure

Figure 5 illustrates the weld appearance at the top surface of the joints. The defect-free top surface is observed for many fabricated joints at TTS, ranging from 0.33 mm s\(^{-1}\) to 1 mm s\(^{-1}\). The weld ripple formations are even and equally spaced in almost every joint. The weld surfaces are soft, and a thin white layer is present next to the SZ on all joints’ retreating side.

The joints fabricated at TTS of 0.33 mm s\(^{-1}\), 0.5 mm s\(^{-1}\), and 0.67 mm s\(^{-1}\) show defect-free SZs, whereas the joints fabricated at TTS of 0.83 mm s\(^{-1}\) and 1 mm s\(^{-1}\) are defective because of incomplete fusion and tunnel defect are observed in the SZ. Therefore, the samples fabricated using TTS of 0.33 mm s\(^{-1}\), 0.5 mm s\(^{-1}\), and 0.67 mm s\(^{-1}\) are considered for further mechanical characterization and metallurgical study. The tensile samples were prepared along the long transverse direction normal to the weld direction and metallographic specimens prepared from a short transverse plane across the joint of welded plates.

3.2. Microstructure

The microstructure of the base AA6061 T6 alloy comprises slightly extended and pancake-shaped grains at the rolling plane. However, the M250 Steel contains prior-austenite grain boundaries and lath martensitic. Figure 6. Shows the photomicrograph of PMs.

The photomicrographs obtained at various regions across the welded joint cross-section are analyzed using the ImageJ software. The grain size measurement was carried out using the line intercept method as per the ASTM E112 standard shown in figure 7. The estimated average grain size in several areas of joint and PMs are
Figure 5. Photomacrographs of FS welded joints fabricated at different welding speeds.

Figure 6. Optical photomicrograph of PMs: (a) AA6061—T6 and (b) M250 Steel.

Table 3. The average grain size of different zones of the FS welded dissimilar joint.

| Tool travel speed (mm s$^{-1}$) | SZ  | TMAZ | HAZ | TMAZ | HAZ | AS    | RS    | PM    |
|-------------------------------|-----|------|-----|------|-----|-------|-------|-------|
| 0.33                          | 5.6 | 58   | 51  | 54   | 52  | 49    | 53    |       |
| 0.5                           | 4.8 | 57   | 53  | 57   | 53  |       |       |       |
| 0.67                          | 3.6 | 51   | 52  | 51   | 52  |       |       |       |
presented in table 3. Figure 8 shows the typical grain boundary maps of the PMs for the FSW process and the weld joint’s various zones, representing the SZ’s morphology and grain size.

The SEM images of the joint interface fabricated at different TTS of 0.33, 0.5, and 0.67 mm s\(^{-1}\) are illustrated in figure 9. The areas marked in figure 9 are analyzed for their quantitative composition by the EDX method, and
the results reveal the presence of the IMC layer at the joint interface. A skinny IMC layer was formed at the interface when TTS is 0.33 mm s\(^{-1}\), shown in figure 9(a). There is no evidence for the IMC layer’s presence at the bottom portion of the joint, but the maximum thickness (about 0.9 μm) of the IMC layer is present at the joint top portion. The IMC layer developed at the interface has an irregular border with micro-fissures towards the joint’s top shown in the figure. In the Al side’s stir zone (SZ), steel scrapings varying from tiny particles to large fragments are distributed.

However, throughout the joint cross-section, the IMC layer thickness is almost equal at the interface when the travel speed is 0.5 mm s\(^{-1}\). Figure 9(b) shows that the maximum thickness of about 2.5 μm is observed at the top portion, whereas 1.4 μm is observed at the middle portion of the joint, and the least thickness of about 0.8 μm is at the bottom portion. The thickest IMC layer, about 7.8 μm, is formed at the joint top portion at the speed of 0.67 mm s\(^{-1}\). As exhibited in figure 9(c), the IMC layer thickness of about 4 μm is observed in the joint’s middle portion. Similarly, the thinnest layer, about 1.9 μm, is formed at the same speed toward the joint bottom portion. This investigation also reveals no micro-fissures, and no distinct linear boundary on the steel side was detected.

The EDS spectrum of the interface shows the presence of IMC layer with its average chemical composition (wt-%) of 34% of Al/66% of Fe, 77% of Al/23% of Fe, and 71% of Al/29% of Fe, at different TTS of 0.67, 0.5, and 0.33 mm s\(^{-1}\) respectively is presented in figure 10. It is also observed that the chemical composition concerning the Fe–Al phase diagram [2] corresponds to IMCs formed are Fe₃Al, Fe₄Al₁₃, and Fe₂Al₅, at TTS of 0.67, 0.5, and 0.33 mm s\(^{-1}\), respectively. Due to the brittleness nature of the IMC layer and its high hardness, the

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**Figure 9.** SEM micrograph images of joint interface region fabricated at different welding speeds (a) 0.33 mm s\(^{-1}\) (b) 0.50 mm s\(^{-1}\) (c) 0.67 mm s\(^{-1}\).
formation of intermetallic compounds (IMCs) layers from Al-rich (Fe₄Al₁₃, Fe₂Al₅) or Fe-rich (Fe₃Al) compounds at the Al–Fe joint interface during the FSW process has a detrimental effect on the mechanical performance of dissimilar joints \[4\].

### 3.3. Hardness

The average microhardness of AA6061 T6 and M250 steel is 85 HV and 310 HV, respectively, as shown in figure 11. There are differences in the average hardness of all the AS (Al side) joints. At the TTS of 0.33 mm s⁻¹, the joints show a minimum hardness of 86 HV in the TMAZ. Similarly, 88 HV and 98 HV hardness values are recorded at TTS of 0.5 mm s⁻¹ and 0.67 mm s⁻¹, respectively (Al side). On the other hand, the fabricated joints in the TMAZ of RS exhibit the lowest hardness value of 296 HV at the TTS of 0.33 mm s⁻¹. In the TMAZ, the same fabricated joints have hardness values of 299 HV and 255 HV at TTS of 0.5 mm s⁻¹ and 0.67 mm s⁻¹, respectively (M250 side). The width of TMAZ progressively reduced, and the highest hardness value of the TMAZ was recorded when the TTS increased from 0.33 mm s⁻¹ to 0.67 mm s⁻¹. In this investigation, the Al side’s microhardness’s recorded values at the TTS value of 0.67 mm s⁻¹ are higher than other joints produced at different TTS. The hardness of TMAZ is lower than that of the SZ.

### 3.4. Tensile properties

Figure 12 depicts the stress-strain curves of the joints made with different TTS. The various effect of TTS on the tensile properties of joints is illustrated in figure 13. The transverse tensile properties are derived from the stress-strain curves, like yield strength (YS), ultimate tensile strength (UTS), elongation, and the failure’s location are presented in table 4. The welded joint has a lower tensile strength than the PMs. The joint fabricated with the TTS value of 0.33 mm s⁻¹ has UTS of 224 MPa that is 38% lower than the aluminium alloy PM, and with 0.5 mm s⁻¹ and 0.67 mm s⁻¹ exhibits 257 MPa and 294 MPa, respectively. The estimated joint efficiencies are 94%, 81%, and 72% for the TTS of 0.67 mm s⁻¹, 0.5 mm s⁻¹, and 0.33 mm s⁻¹ respectively. However, the joints fabricated at TTS values of 0.67 mm s⁻¹, 0.5 mm s⁻¹ and 0.33 mm s⁻¹ produce elongation of 9.17%, 9.4%, and, 9.8% respectively.

### 3.5. Fracture surface

The tensile fracture location of the tested specimens is depicted in figure 13. The complete fracture path is well exhibited by the cross-sectional macro photograph of the fractured specimens. Conversely, the sample’s hardness influences the fracture locations \[18\]. The fracture occurs along with the TMAZ. The TMAZ reveals the fractures of all the joints, and it appears along the weld periphery.
In all the joints, there are about two types of fracture patterns present at the macro level. First, the uneven surface is observed directly below the tool shoulder and second flat like fracture surface around the pin’s periphery. The SEM images reveal the fracture surface at higher magnification. The joints fabricated using a TTS value of 0.5 mm s$^{-1}$ and 0.33 mm s$^{-1}$ exhibit flat, featureless surfaces and subtle dimples surfaces. However, it has become very much apparent that the tensile samples undergo a complex mode of failure. The joint fabricated
using a TTS value of 0.67 mm s$^{-1}$ reveals populated dimples along the loading direction and results in a ductile mode of failure.

4. Discussion

The behavior of material flow in SZ and the heat generation during the welding process influences the dissimilar welded joint’s quality. There are three significant heat generation and material flow states: inadequate, adequate, and surplus states, which often occurs in the weld SZ. It is essential to regulate material flow, thermal softening, heat generation, and plasticization of material to achieve defect-free joints. TTS is a predominant parameter of the FSW process that significantly influences material flow and heat generation.

The findings showed that defect-free joints manufactured using TTS varying from 0.33 mm s$^{-1}$ to 0.67 mm s$^{-1}$, and a tunnel defect found in SZ at 0.83 mm s$^{-1}$ and 1 mm s$^{-1}$ TTS respectively, as shown in

Figure 13. Photograph of Fracture surface examination.
The defect at higher TTSs is due to insufficient material flow and heat generation in SZ. However, sufficient heat has generated when TTS is less than 0.67 mm s$^{-1}$. The stirring action of the tool to transport material and heat development is higher at lower TTS. Therefore, it observed that sufficient material flow and heat are obtained only at the lower TTS range. Increasing the TTS from 0.83 mm s$^{-1}$ to 1 mm s$^{-1}$ would lead to adequate to low heat generation. Limited tool rubbing and thermal softening occur only at the minimum stirring time. Hence, the defect formation due to higher TTS is often related to the insufficient heat and material flow in SZ. During the FSW plunging stage, a dwell period was followed to generate a preheat zone at the tool’s leading edge. The preheat zone enabled two distinct functions. First, it is used to plasticize the material to move the tool without tool breaking. Secondly, the preheat zone’s material is expelled to the tool’s rear end during the tool’s forward motion, assisting the defect-free SZ formation. The narrowed preheat zone during the FSW process is formed mainly due to the thermal softening. In these circumstances, inadequate heat generation at higher TTS may further narrow down the preheat region leads to the defective joint [15, 17].

The microstructural features vary accordingly with the changes in TTS. The mechanical properties of the joint depend on the microstructural modification occurring in the various region. As per the Hall-Petch relation, the hardness of the material is inversely proportionally to the grain size. The finer grain size yields higher hardness and vice versa [19]. The TMAZ exhibits lesser hardness in the joint fabricated among the various regions due to coarser grains using TTS of 0.83 mm s$^{-1}$ and 1 mm s$^{-1}$. The excessive amount of grain boundaries is present due to the fine grains in SZ. Grain boundaries are the high energy regions, and it is capable of hindering the dislocation motion. Due to IMCs and steel flakes with and without IMC formation in the SZ, the microhardness on the SZ of the Al side exhibits a zigzag style variation. Due to this reason, the SZ shows a higher hardness value than the TMAZ in all the successful joints. The joint fabricated using TTS of 0.67 mm s$^{-1}$ exhibits higher hardness than the other two joints, attributed to smaller grain size in all the specific zones [20, 21].

As reported earlier, the material strain rate and heat generation increase at higher TTS, and both these variables increase the formation of a thick IMC layer at the joint interface. The increased brittleness and creation of microcracks in the thicker IMC layer contributes to a sudden fall in the joint’s UTS through better bonding performance [22]. The sudden decrease in UTS above a 0.67 mm s$^{-1}$ tool rotational speed can be due to the previously mentioned combined effect on the formation of the IMC layer of higher heat generation and material strain intensity. The insufficient heat generation and material strain rate indicate a very thin or no IMC layer formation at lower TTS and weak bonding at the joint interface. As comparatively higher temperatures occur towards the top of the joint where the tool shoulder rubs and thus better adhesion, the decrease in joint UTS is incremental at lower TTS [23]. The fact that the highest UTS obtained for a joint created with a near-uniform at 0.67 mm s$^{-1}$ and that a thin layer of IMC is indicated at the interface is vital for the weld’s strength.

The joint fabricated using TTS of 0.67 mm s$^{-1}$, leading to higher tensile strength, is attributed to more refined grains in narrowed TMAZ and the process zone. The load will be concentrated more on the weakest region during the tensile loading. The fracture locations are consistent on both the joints presented in figure 13. Therefore, the fracture is occurred at the weak SZ-TMAZ and follows a zigzag trend.

Furthermore, the interface has different grain orientations that resist failing, and subsequently, the smooth fracture surface is not detected. The existence of load concentration is known as strain localization [24]. Due to strain localization, the weakest region alone expands during tensile loading. Thus, a decreased stretched value was observed for the joints related to the PM. When comparing macro and microfracture surfaces, it found that all the welded joints had experienced a combined failure of brittle fracture and ductile fracture [25].

This study exemplifies that too high TTS leads to low heat input ending up in poor joint properties, whereas the inadequate tool stirring results in defect formation. Hence, the proper TTS must be chosen to generate material flow and a balanced state of heat to yield a perfect dissimilar joint. The heat input should also be minimal to obtain a smaller grain size and thinner TMAZ.

5. Conclusion

In this study, the FSW of Maraging steel M250 with AA6061 T6 successfully performed at different TTS. The effect of TTS on mechanical properties and the formation of the IMC layer was studied. The research work was carried out, and the following conclusions are drawn.

- The softened zone consisting of two HAZs and an SZ of the FSWed dissimilar joints had low tensile strength than the PM.
- TTS had a significant influence on tensile properties and fracture location. The obtained joint strength is almost 94% of aluminium alloy PM when TTS is 0.67 mm s$^{-1}$. 
• Sufficient heat generation was obtained when the TTS was kept below 0.67 mm s\(^{-1}\), resulting from the reduced IMC layer formed. The joint efficiency was better at the reduced thickness of the IMC layer.

• When TTS was more than 0.67 mm s\(^{-1}\), it led to the formation of voids resulting in low tensile properties, and also, the fracture location shifted from the weld center to near or between the TMAZ and the weld SZ.

Data availability statement

No new data were created or analyzed in this study.

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