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Review Paper on Friction Stir Welding of Aluminium and Magnesium Alloys

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Abstract

Objective: Friction Stir Welding (FSW) is a relatively new solid state welding technique for similar and dissimilar materials, especially on current interest with aluminum and magnesium alloys. **Methods/Analysis:** The Friction Stir Welding of aluminum alloys with magnesium alloys are reviewed on this paper. The basic principles of FSW are described, followed by process parameters study which affects the weld strength. **Findings:** The microstructure and the likelihood of defects also reviewed. Tensile strength properties attained with different process parameters are discussed. **Conclusion/Application:** It is demonstrated that FSW of aluminum and magnesium alloy is becoming an emerging technology with numerous commercial applications.

Keywords: Aluminum Alloys, Friction-Stir Welding, Magnesium Alloys, Microstructure, Tensile Strength

1. Introduction

In recent times, focus has been on developing fast, efficient processes that are environment friendly to join two dissimilar materials. The spotlight has been turned on Friction Stir Welding as a joining technology capable of providing welds that do not have defects normally associated with fusion welding processes[1–3].

2. Process Parameters

It is well understood that the effect of some important parameters such as rotational speed and welding speed on the weld properties is the major topics for researchers. In all the above cases, FSW parameters are selected by trial and error to fix the major topics for researchers[4].

Lakshminarayanan A. K. et al.[5] conducted study on AA2219 aluminum alloy at spindle rotation of 500–1600 RPM and frictional speed of 0.37–2.25 mm per sec. They found that defect free FSW on AA2219 metals produced under a wide range of rotational speeds and welding speeds.

Yang Yong et al.[6] conducted study on dissimilar metals such as 5052 aluminum alloy and AZ 31 magnesium alloy. They found that sound weld was obtained at rotational speed of 600 RPM with welding speed of 40 mm/min. The microstructure of the stir zone is greatly refined.

Elangovan and Balasubramaniam[7] conducted stud on 2219 aluminum alloy material by FSW process. They have used five different tool pin profiles - straight, cylindrical, threaded cylindrical, triangular and square with three welding speeds. Square pin profiled tool produced defect free Friction Stir Processed (FSP) irrespective of welding speeds. Of the three welding speeds used to fabricate the joints, the joints fabricated at a welding speed of 0.76 mm per seconds showed superior tensile properties, irrespective of tool pin profiles. FSW joints usually consist of four different regions as shown in Figure 2. They are: 1. Unaffected Base Metal, 2. Heat Affected Zone (HAZ), 3. Thermo-Mechanically Affected Zone (TMAZ) and 4. Friction Stir Processed (FSP) zone. The formations of above regions are affected by the material flow behavior under the action of rotating non- consumable tool. However, the material flow behavior is predominantly influenced by the FSW tool profiles, FSW tool dimensions and FSW process parameters[8].

In the FSW process, parameter selection and tool geometry are among the key factors that determine the

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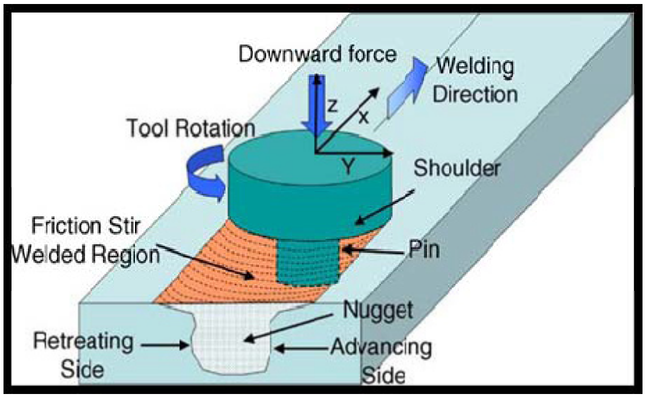


Figure 1. Schematic illustration of Friction Stir Welding[9].

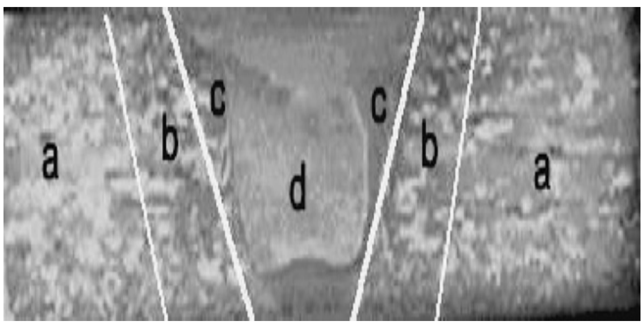


Figure 2. Different regions of FSW: **(a)** Unaffected Zone, **(b)** Heat Affected Zone (HAZ) **(c)** Thermo-Mechanically Affected Zone (TMAZ) and **(d)** Friction Stir Processed (FSP)[7–8].

quality of the fabricated joint. The value of the different parameters such as welding speed, rotational speed, tilt angle and pin geometry could lower the force exerted from the TMAZ section to the tool which improves the quality of the weld and less thermal energy is needed for the process prompting both sheets to reach the plastic state.

Commercial magnesium alloys do not have enough strength to apply for structural materials. However, magnesium alloys are attractive to reduce the weight products. On the other hand, aluminum alloys have been used for products required high strength. Magnesium alloy and aluminum alloy should be used in the proper portion of the part of structure. The joint of these dissimilar metals required. However, dissimilar welding between aluminum alloy and magnesium alloy by conventional fusion welding[10,11] is unable because of the vast volume of $Mg_{17}Al_{12}$ intermetallic compound formation in the fusion zone. The processing temperature during FSW does not reach melting points of the alloys, so the formation of intermetallic compounds in stir zone is limited[12–14]. These intermetallic compounds should be dispersed finely to prevent the brittleness [15,16]. The proper welding condition for dissimilar A5052-H and AZ31B FSW joint were more limited region than that for A5XXX or AZ31B FSW joint[17–24].

Nagasawa et al.[25,28] FSW'ed 6-mm AZ31 plates with a rotational speed of 1750 rpm and a transfer speed of 88 mm/min and found out that the mechanical strength of the weld was comparable to the base material but with only half of the ductility. The highest measured temperature was 460°C, showing a true solid state process.

Park et al.[26] also studied the FSW on 6-mm AZ31 plates at 1220 rpm and 90 mm/min, which showed a much lower yield strength and elongation and a slightly lower ultimate tensile strength of the weld from transverse tensile test compared with the base material. With a micro-texture analysis, they concluded that a heterogeneously distributed (0002) basal plane contributed to the changes in the mechanical properties.

Nakata et al.[27] studied the optimal processing conditions for FSW of 2-mm AZ91D thixomolded sheet. An increase of 38~50% of the tensile strength in the weld could be obtained over base material with rotational speed between 1240 to 1750 rpm and a transfer speed of 50 mm/min. They contributed the increase of strength to the fine recrystallized structure of 2~5 μm grain sizes.

3. Flow Mechanisms and Tool Design

The metal flow and heat generation in the softened material around the tool are fundamental to the friction stir process. Material deformation generates and redistributes heat, producing the temperature field in the weld. But since the material flow stress is temperature and strain rate sensitive, the distribution of heat is itself governed by the deformation and temperature fields. In fact their control lies at the core of almost all aspects of FSW, for example, the optimization of process speeds and machine loading, the avoidance of macroscopic defects, the evolution of the microstructure and the resulting weld properties.

Early work on the mode of material flow around the tool used inserts of a different alloy, which had a different contrast to the normal material when viewed through a microscope, in an effort to determine where material was moved as the tool passed[29,30].

More recently, an alternative theory has been advanced that advocates considerable material movement in certain locations[31]. This theory holds that some material does rotate around the pin, for at least one rotation and it is this material movement that produces the "onion-ring" structure in the stir zone. The researchers used a combination of thin copper strip inserts and a "frozen pin" technique, where the tool is rapidly stopped in place. They suggested that material motion occurs by two processes:

1. Material on the advancing front side of a weld enters into a zone that rotates and advances with the pin. This material was very highly deformed and sloughs off behind the pin to form arc-shaped features when viewed from above (i.e. down the tool axis). It was noted that the copper entered the rotational zone around the pin, where it was broken up into fragments. These fragments were only found in the arc shaped features of material behind the tool.
2. The lighter material came from the retreating front side of the pin and was dragged around to the rear of the tool and filled in the gaps between the arcs of advancing side material. This material did not rotate around the pin and the lower level of deformation resulted in a larger grain size[32].

4. Microstructural Studies

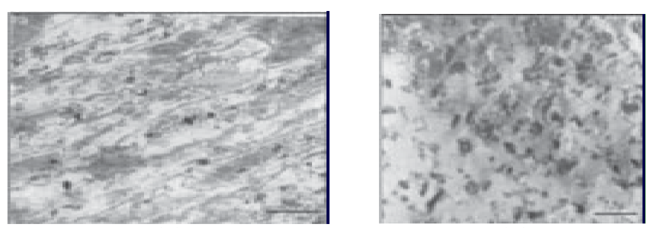
Typical microstructures of the FSWed 7075 Al alloy are shown in Figure 3. Fine-grained microstructure is formed in the stirred zone, as shown in Figure 3(a). It is evident that equiaxed fine grains with average size of about 3 mm are developed homogeneously in the whole area within the nugget zone. A typical TEM microstructure developed under FSW and associated Selected Area Electron Diffraction (SAED) pattern are presented in Figure 3(b). No dislocation substructure is observed in the inside of newly formed fine grains. Most part of grain boundaries developed has high angle misorientations, as demonstrated by SAED pattern. It is also seen in Figure 3(b) that there are many second phase particles along the boundaries and also in grain interiors[33].

Thermo-mechanically affected zone is the transition zone between the base metal and the weld nugget, characterized by a highly deformed structure as shown in Figure 4a. The optical microscopy does not reveal the grains properly. It shows a banded structure. There is no recrystalization in this region. TEM reveals the strengthening precipitates and are shown in Figure 4b. There is no significant change in the size and morphology of coarser precipitates, but their orientation along rolling direction like in parent metal is absent in TMAZ.

The precipitates are quite random. The finer precipitates observed in parent metal are coarsened during welding[34].

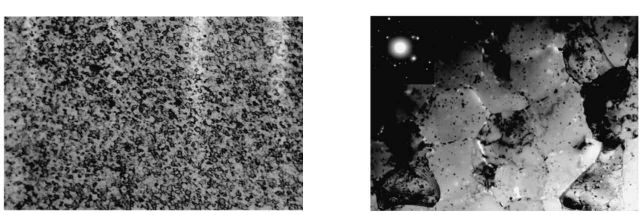
Optical microstructure of half of the cross-section of the FS welded 7075-T6 Al sample is shown in Figure 5, the overall view of the etched weld zone is clearly visible. The weld zone is a nearly V-shaped and widens near the top surface due to the tool geometry and the close contact between the tool shoulder and the upper surface of the weld.

Figure 6(a) shows the SEM micrograph of the weld nugget in which the grains boundaries can be identified and the average grain size is measured to be ~4 μm. In this region, fine equiaxed grain sizes are formed due to recrystallization[35].



(a) (b)

Figure 4. **(a)** Microstructure in TMAZ **(b)** Distribution of precipitates in TMAZ.



(a) (b)

Figure 3. Typical microstructure developed in 7075 Al alloy during FSW. **(a)** Optical and **(b)** TEM micrographs.

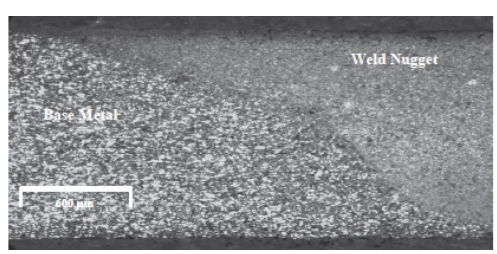
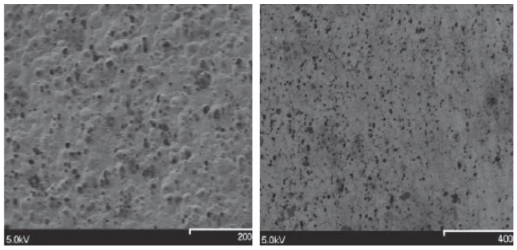


Figure 5. Optical macrograph of an etched 7075–T6 Al sample showing different regions of the weld, 50x.



(a) (b)

Figure 6. (a) SEM micrograph of the weld nugget of 7075-T6 Al, the grain size is ~4μm and (b) SEM micrograph showing the $MgZn_2$ precipitation in the weld nugget.

Although the exact mechanisms of developing this structure are not well understood, dynamic recrystallization has appeared to explain the formation of fine grained equiaxed stir zone microstructures having grain sizes, which ranges from 1 to 10 μm. This behavior may be attributed to the nature of material flow during FSW processing, where the material near the top of the work piece is stirred under the action of the shoulder in addition to the vertical motion occurred mainly due to the threading on the tool pin. In this case, the stirred material from the top is carried down by the threads and deposited in the weld nugget. None of the macroscopic defects typical of fusion welded Al based alloys were observed in the FSW specimens. Since the metal does not melt, no casting structure is formed as in conventional fusion welding and neither does shrinkage occur in the weld zone due to solidification.

Figure 6 (b) shows the precipitates of $MgZn_2$ in the interior section of the weld nugget. It is obvious from this image that the $MgZn_2$ precipitates are uniformly distributed in the weld nugget. During the FSW process, the precipitates have dissolved into the solution and reprecipitated on subsequent cooling. The recrystallization of the weld nugget and the redistribution of the precipitates indicate that the temperature obtained during the process is above the solutionizing temperature but below the melting of the alloy. The larger precipitates dominate the weld nugget because the cooling rates are such that larger precipitates could nucleate and grow but not the finer ones[36].

5. Tensile Testing

The FSW welds cut according to the ASTM specifications for tensile testing are shown in Figure 7. The tensile testing of the welds was done using a UTM machine and the load verses displacement graph has been obtained as shown in Figure 8 and Figure 9.

Figure 7. Tensile specimen.

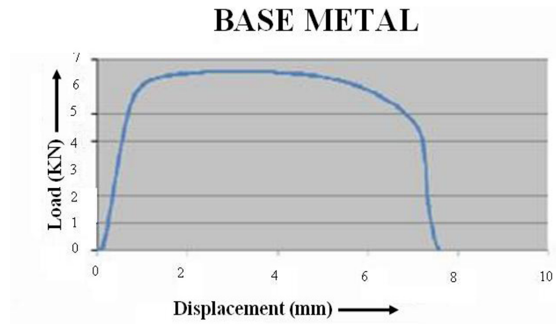


Figure 8. Tensile test result for base metal.

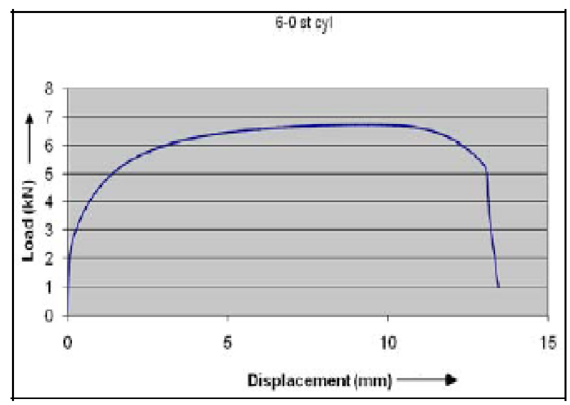


Figure 9. Tensile test result for welded plate.

The tensile testing results show that compared to base metal the tensile property of the weld improved considerably. And also the displacement before failure for welded plate is 13mm as compared to 7.5mm in case of base material which indicates the increase in ductility[37].

The plastic flow is responsible for obtaining the weld with high tensile strength and fewer defects and therefore the tool geometry plays a role in achieving a quality weld. Taguchi's technique is a powerful tool in quality optimization. Taguchi's technique makes use of a special design of Orthogonal Array (OA) to examine the quality characteristics through a minimal number of experiments[38].

Functional parameters involved during the Friction Stir Welding (FSW) process is considered as numerical data and applied it over a Hyper Geometric Function and changes in Gamma values are studied. The aim of welding

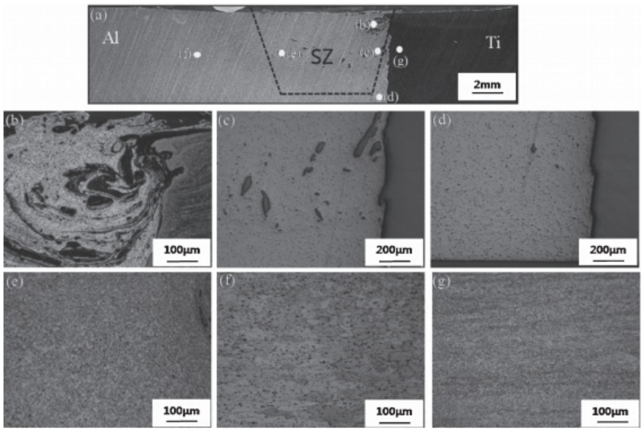


Figure 10. **(a)** Macro image of weld zone, **(b)** Probe root area of interface, **(c)** Middle area of interface, **(d)** Probe tip area of interface, **(e)** SZ of AA6061-T6, **(f)** BM of AA6061-T6, **(g)** BM of Ti-6Al-4V.

needs to be defect free which requires uniform distribution of weld bead. This uniform distribution is dependent on functional parameters viz., welding rotational speed, weld transverse speed and axial load[39].

The Figure 10(a) shows the macro image of weld zone for the AA6061-T6. The metal flow pattern is clearly visible on Figure 10(b). Middle area of the weld interface evaluated by OM is shown in Figure 10(c). Titanium alloy fragments were observed in SZ. The SZ has a composite structure of aluminum alloy refoinced by titanium particles. However, they were not found in the probe tip area of the weld interface Figure 10(d)). This is why the probe did not stir the titanium alloy in direction. Crystal grains of the aluminum alloy in SZ Figure 10(e)) became significantly fine compared with the initial grain size of aluminum alloy base metal Figure 10(f). Figure 10(g) shows titanium alloy base metal around the weld interface[40].

6. Conclusion

The present review has demonstrated the extensive research effort on understanding the effect of process parameters of FSW on aluminium and magnesium alloys. Metal flow modelling may have a role to play here, though capturing this aspect of the thermomechanical behaviour remains a significant challenge. The macro strure reveals the location of weaker zone. From an engineering perspective, there is a need to investigate the occurrence and significance of flaws in Friction Stir Welds using Optical Microscope and Scanning Electron Microscope. In particular, the influence of tool design on flaw occurrence and the development of nondestructive testing techniques. It is clear that like Tauguchi technique, hypergeometry can be used as a design of experiment techniques.

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