Friction Stir Welding and Processing VIII
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FRICTION STIR WELDING OF AZ31B MAGNESIUM ALLOY WITH 6061-T6 ALUMINUM ALLOY: INFLUENCE OF PROCESSING PARAMETERS ON MICROSTRUCTURE AND MECHANICAL PROPERTIES

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Abstract

The success of Friction Stir Welding (FSW) in joining light metal alloys has inspired attempts to further exploit its potential for joining materials which differ in chemical composition, structure, and/or properties. The FSW of relatively soft (e.g., Al/Mg) and hard (e.g., Fe/Ni) combinations of alloys is of particular interest in automotive and aerospace applications. However, joining of dissimilar alloys presents several unique challenges that include the different deformation behaviors, formation of detrimental intermetallic compounds, and differences in physical properties such as thermal conductivity. These factors lead to amplified asymmetry in both heat generation and material flow and consequently lead to the formation of a heterogeneous weld. In this work, a dissimilar metal joint was created between twin roll cast AZ31B magnesium alloy and Al 6061-T6 aluminum alloy plates by FSW. The main aim here is to investigate the effect of key process parameters such as tool rotation speed and welding speed on microstructural evolution and mechanical properties of the resulting heterogeneous joint. A detailed microstructural analysis was carried out to understand the composition of the intermetallic phases generated in the stirred zone and their impact on microhardness and over-all mechanical properties of the weld. Our key finding was that, weld configuration with placing the aluminum alloy plate on the advancing side resulted in a sound, defect free joint compared to the alternate configuration.

Introduction

The use of light metal alloys such as aluminum (Al), magnesium (Mg) and titanium (Ti) alloys in automotive vehicles for light weighting can significantly increase fuel efficiency and cut harmful CO_2 emissions [1, 2]. However, to enable promote the manufacture and integration of parts made from light-weight alternative materials, one key objective is to develop reliable dissimilar material joining technologies. The ability to build parts from a variety of lightweight materials and to join them is a major technological challenge for the transportation industry in its push to increase the use of advanced lightweight materials.

Joining Al alloys to Mg alloys poses one such specific challenge. In this regard, conventional fusion based welding processes such Gas Tungsten Arc Welding (GTAW) [3, 4], Electron Beam Welding (EBW) [4, 5], Laser Beam Welding (LBW) [6], have been applied to join Al alloys to Mg alloys. However, they produce coarse grains, large and continuous intermetallic regions in the weld zone accompanied by a large Heat Affected Zone (HAZ) in the base metals [7]. Also, certain other joining processes involving the use of Zn based filler materials such as brazing [8, 9], diffusion bonding [10, 11], cold metal transfer MIG welding [12, 13] and conventional MIG and TIG (with filler metal) welding [14-16]. However, the formation of different types and continuous layers of intermetallic compounds deteriorates the mechanical properties of the joint. Therefore, it can be argued that the fundamental problem with all dissimilar metal joining techniques of Al alloy to Mg alloy involving solidification see the formation of intermetallic compounds. The lack of control over the size, type and distribution of hard and brittle intermetallics has a detrimental effect on the joint strength.

Solid state welding processes which provide relatively controllable reaction times and heat inputs are found to be promising for dissimilar welding of Mg alloys to and Al alloys and result in a high strength joint [7]. Researchers have considered techniques such as linear friction welding [17], ultrasonic welding [18, 19], resistance spot welding [20] and FSW [21-30] have been studied. In this regard, FSW a solid state joining process that in addition to frictional heat input involves stirring and plastic deformation of the joint region has shown promising initial results. Also, FSW has been studied to join magnesium or aluminum alloys to steels [31, 32] and titanium [33, 34], again with proming results. In this work, we have attempted to study the effect of process parameters on the weld zone microstructure and the formation, morphology, size and distribution of the intermetallic region and its subsequent impact on mechanical properties.

Experimental Procedure

FS welds were performed using a Gantry Friction Stir Welding Machine of type FSW-LM-08, which was designed to weld aluminum alloys with maximum thickness of 10 mm. The tool used for the present study had a 10 mm tool shoulder diameter and a threaded pin with maximum diameter of 3.6 mm and minimum diameter of 2.9 mm. All the welds runs were performed using a tool tilt angle of 3º. The FSW coupons were all 250 x 50 x 3 mm strips sheared from the base material sheets and the edges were cleaned to avoid any prior in-homogeneities in weld. The base material were Al6061-T6 aluminum and AZ31B magnesium, both were obtained from commercial vendors. The nominal chemical composition of the two materials are presented in table I.

Table I: Nominal composition and mechanical properties of Al and Mg alloys.

Alloys	Wt. %	Al	Mg	Si	Cu	Cr	Fe	Zn	Ti	Ca	YS (MPa)	UTS (MPa)
Al6061-T6	Min	95.8	0.8	0.4	0.15	0.04	-	-	-	-	275	350
	Max	98.6	1.2	0.8	0.4	0.35	0.7	0.25	0.15	-		
AZ31B	Min	2.5	0.2	-	-	-	-	0.6	-	-	150	300
	Max	3.5	1	0.1	0.05	-	0.005	1.4	-	0.04		

The samples for microstructure examination of as-received and welded joints were prepared according to the standard metallographic preparation. The FSW plates were cut in the cross-section using TECHCUT 5” precision sectioning machine, then mounted using TechPress 2™ hydraulic-pneumatic automatic mounting press and black phenolic hot mounting resin. The mounted samples were ground and polished utilizing MetPrep 4™ Grinder/Polisher and silicon carbide abrasive paper with grits of 320, 600 and 1200 with rotating the sample 90º between each step. The polishing procedure was performed using Spec-cloth and 1µm diamond polycrystalline solution with alcohol based BlueLube lubricant, followed by 0.04 µm colloidal silica and same lubricant mentioned before. The etching was performed using a standard acetic-picral solution to reveal the microstructure of the magnesium side of the joint. The microstructure was observed using Zeiss AxioVert 40 MAT optical light microscope equipped with an ERc5s camera. Scanning election microscopy was carried to better examine the fine grain structure and intermetallics formed in the stir zone. In addition, EDS analysis was implemented to investigate the chemical composition of the intermetallic. In this preliminary work reported, we only carried out Vicker’s micro-hardness measurements to estimate the relative strength the weld. The microhardness measurements were done in the thickness plane perpendicular to the weld line at a distance of 2 mm from the top of the weld.

Results and Discussion

In this section we present the initial findings of our work. Figure 1 (a-b) present the pictures of two welded coupons. Figure 1 (a) shows a dissimilar weld of Al and Mg performed using tool rotation speed of 1600 rpm and 250 mm/min with placing Mg in the advancing side. While Figure 1 (b) shows the appearance of FS welded plates using 1400 rpm and 500 mm/min welding tool parameters with placing Al in the advancing side. Although, the welding parameters were different for the two cases but it can be seen that al plate configuration has a profound effect on the over-all welding. It was found that when the Al plate is placed in the Advancing Side (AS), a clear uniform defect-free weld zone can be obtained, as shown in Figure 1 (b). This result was further verified by examination of the weld zone under a microscopy.

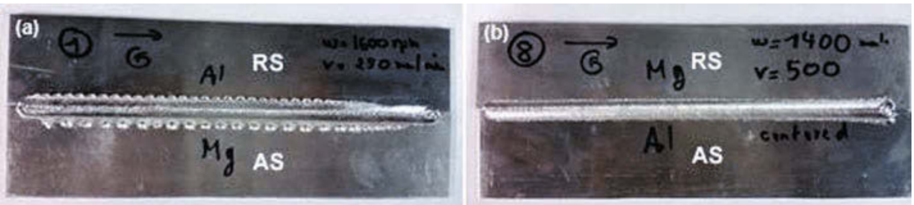

Figure 1. Top view of two welds : (a) Dissimilar FSW of Al and Mg with parameters of 1600 rpm and 250 mm/min, Mg in advancing side; (b): With parameters of 1400 rpm and 500 mm/min, Al in advancing side.

The structure and morphology of the weld was observed under an optical microscope. The weld zone cross-sections perpendicular to the tool traverse direction were observed to distinguish between the two welded materials, Al 6061-T6 and AZ31B. Figure 2 presents a heterogeneous FSW joint of aluminum to magnesium. As already observed in Figure 1, when aluminum was placed in the Retreating Side (RS), a poor quality weld was obtained and many defects such as the voids and excessive tool penetration were readily observed. These finding is well supported by the available literature on dissimilar joining of Al alloys to Mg alloys [21-30].

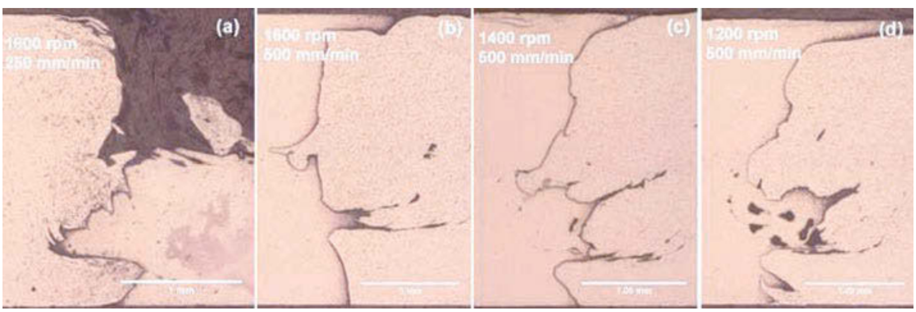

Figure 2. Cross section of weld zone performed using at: (a) 1600 rpm rotational speed and 250 mm/min welding speed (aluminum on the RS). (b-d) Constant welding speed of 500 mm/min and varying rotational speeds to 1600, 1400, 1200 rpm (aluminum on the AS).

Figure 2 (b) through (d) presents an Al/Mg dissimilar FSW weld with aluminum being placed in the advancing side. The influence of the tool rotational speed on the weld zone integrity was studied by keep the welding speed constant at 500 mm/min and reducing the tool rotation speed to 1600 rpm to 1200 rpm. It is observed that there were fewer defects (b, c) as compared to the previous weld (aluminum on RS). However, some internal defects such as worm hole, can be still be observed in the aluminum part, and as the tool rotational speed was decreased to 1200 rpm, again a larger number of voids were observed when comparing to the two previous cases. At this point, it was concluded that tool the rotation speed of 1600 rpm and tool advance speed of 500 mm/min produced the optimum weld.

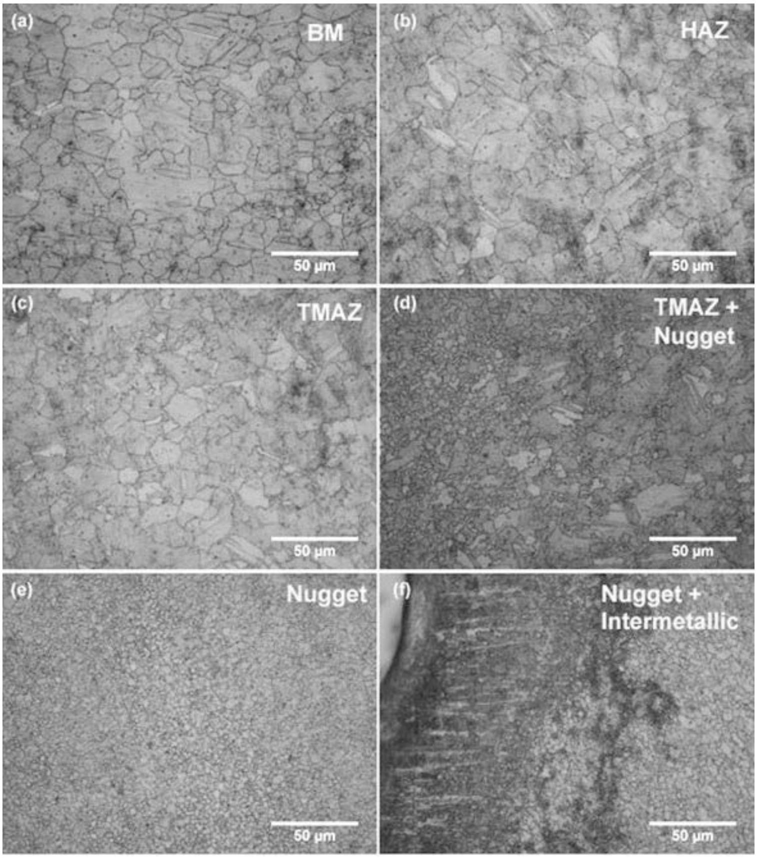

Figure 3. Microstructure of several zones in FS weld of dissimilar Al Mg joint using 1600 rpm and 500 mm/min.

We carried out a detailed microstructure analysis to look at the characteristics of the grain boundaries, grain size and the intermetallic region. The focus of the microstructural evolution in the intial stage of this study was magnesium alloy side of the weld zone. Figure 3 presents different microstructures obtained from several zones in the retreating side of the weld. These zones were identified to be the Base Metal (BM) (Figure 3 (a)), HAZ (Figure 6 (b)) and Thermo-Mechanically Affected Zone (TMAZ) (Figure 3 (c)). The heat affected zone shows larger grains compared to the base metal, while the thermo-mechanically affected zone shown in Figure 3 (d), shows some degree of grain refinement. A very small grain size was observed in the weld nugget as shown in Figure 3 (e). The strong degree of grain refinement (from 20 microns as-received to ~ 1 micron) in Mg rich side of the TMAZ and nugget region was also observed by several other researchers in dissimilar FSW of Al alloy to Mg alloy [21-30]. Figure 3 (f) presents the microstructure of the nugget and the intermetallic region. The microstructure of the intermetallic was not readily resolved with the optical micrographs. Figure 4 presents the SEM micrograph of the dissimilar FSW weld performed using 1600 rpm and 500 mm/min with aluminum placed in the advancing side. Figure 4 (a) shows the interaction between AZ31B magnesium alloy and 6061-T6 aluminum alloy with a void defect in both magnesium side and aluminum side. Figure 4 (b) is a magnified area where the intermetallic of magnesium is interacting with aluminum with the absence of defects in the joint.

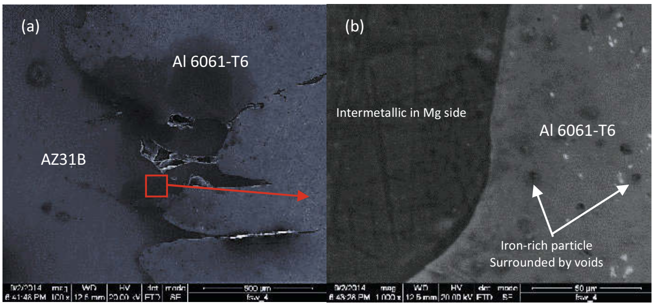

Figure 4. SEM micrograph of intermetallic region and nugget zone in the FSW joint obtained by using 1600 rpm rotational speed and a welding speed of 500 mm/mi, (a) low resolution image shows the over-all morphology of the joint, (b) the transition region between the Al and the Mg intermetallic side of the joint.

Figure 5 presents the SEM observations of dissimilar Al/Mg welded plates performed with 1400 rpm and 500 mm/min with aluminum placed in the advancing side. Figure 5 (a) shows the AZ31B and Al 6061-T6, the dark area is the intermetallic formed in the magnesium side. Figure 5 (b) a magnified area taken from Figure 5 (a) and highlighted with a red rectangle. It also shows an iron-

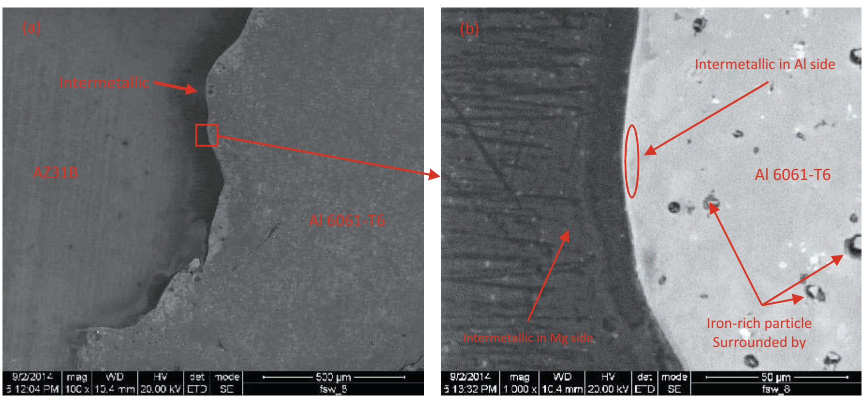

Figure 5. SEM micrographs of FSW sample at 1400 rpm and 500 mm/min. (a) low resolution image shows the over-all morphology of the joint, (b) the transition region between the Al and the Mg intermetallic side of the joint.

rich particle surrounded by voids and micro iron rich phases with the same phenomena in the aluminum side. From these SEM analyses we observe that the voids are initially around the intermetallic phases or iron-rich phases of Al6061-T6. This could be a reason for the presence of the micro-defects in the joint. Also the interaction between Al6061-T6 and AZ31B alloys was defect-free in the most regions. The intermetallic formed in the interface between Al and Mg were reported by McLean et al. [35] and the same observation was reported by Kostka et al. [36] when they studied the microstructure of friction stirred welded AA6040 and AZ31B.

Micro-hardness tests were performed for 4 samples with different welding parameters. It is observed in Figure 6 that the microhardness values in the magnesium part are between 55HV and 65HV. Then under the tool it starts to increase to reach values between 70 and 80 HV. The intermetallic phases showed values between 90 and 110 HV in the center of the weld, these values were results of the brittle nature of the intermetallic formed for to the dynamic recrystallization. The same trend of this increase of the hardness in the middle of the weld was obtained by Somasekharan et al. [37] when they studied the FSW of Az31B-H24 and Al6061-T6, they attributed this trend to the grain size reduction and presence of intermetallics. In the aluminum side and under the tool shoulder, the hardness values are found to be between 70 and 120 HV. Then it reaches 135 HV in the base metal.

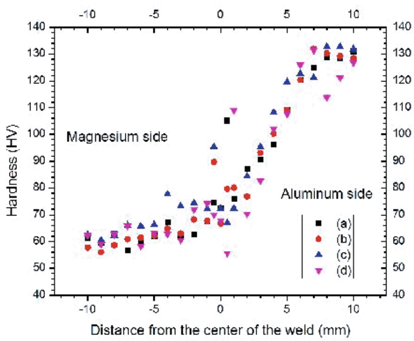

Figure 6. Hardness test obtained in 2 mm from the top of the weld. (a): 1600 rpm, 250 mm/min, Mg (AS); (b): 1600 rpm, 500 mm/min, Al (AS); (c): 1400 rpm, 500 mm/min, Al (AS); (d): 1200 rpm, 500 mm/min, Al (AS).

Conclusions

The twin roll cast AZ31B magnesium and Al6061-T6 aluminum were successfully friction stirred welded using different parameters and material positioning. It was found that placing magnesium (lower YS material) on the advancing side gave poor results with various defects in the weld region. However, performing dissimilar FSW with aluminum (higher YS material) on the advancing side produced better joints. Based on the intial results reported here, the rotational speed of the tool was varied and optimum welding conditions were obtained. It was also conclude that the magnesium rich side of the nugget zone showed evidence of extensive grain refinement and the grain size was reduced to ~ 1 micron. It has been observed that different intermetallic compounds were formed in the stir zone. The nature and morphology of these intermetallic layers were different on the aluminum rich and magnesium rich side of the weld zone. The microhardness results showed significant strengthening in the stirred zone that could be related to grain size reduction. A detailed TEM and EDS analysis and tensile characterization would be carried out in future to fully understand the influence of the intermetallics on mechanical properties of the joint.

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References

1. Pollock, T.M., *Weight Loss with Magnesium Alloys.* Science, 2010. **328**(5981): p. 986-987.
2. Mathaudhu, S.N. and E.A. Nyberg, *MAGNESIUM ALLOYS IN U.S. MILITARY APPLICATIONS: PAST, CURRENT AND FUTURE SOLUTIONS*, in *Magnesium Technology 2010*, S.R. Agnew, et al., Editors. 2010. p. 27-32.
3. Liu, P., et al., *Microstructure characteristics in TIG welded joint of Mg/Al dissimilar materials.* Materials Letters, 2007. **61**(6): p. 1288-1291.
4. Ben-Artzy, A., et al. *Joining of light hybrid constructions made of magnesium and aluminum alloys*. in *TMS Annual Meeting*. 2002.
5. Chi, C.-T., et al., *Aluminum element effect for electron beam welding of similar and dissimilar magnesium–aluminum–zinc alloys.* Scripta Materialia, 2007. **56**(9): p. 733-736.
6. Bannour, S., et al., *The influence of position in overlap joints of Mg and Al alloys on microstructure and hardness of laser welds.* J. Laser Appl., 2013. **25**(3).
7. Liu, L., D. Ren, and F. Liu, *A Review of Dissimilar Welding Techniques for Magnesium Alloys to Aluminum Alloys.* Materials, 2014. **7**(5): p. 3735-3757.
8. Liu, L., J. Tan, and X. Liu, *Reactive brazing of Al alloy to Mg alloy using zinc-based brazing alloy.* Materials Letters, 2007. **61**(11–12): p. 2373-2377.
9. Wang, Z., H. Wang, and L. Liu, *Study on low temperature brazing of magnesium alloy to aluminum alloy using Sn–xZn solders.* Materials & Design, 2012. **39**(0): p. 14-19.
10. Zhao, L.M. and Z.D. Zhang, *Effect of Zn alloy interlayer on interface microstructure and strength of diffusion-bonded Mg–Al joints.* Scripta Materialia, 2008. **58**(4): p. 283-286.
11. Liu, L.M., L.M. Zhao, and R.Z. Xu, *Effect of interlayer composition on the microstructure and strength of diffusion bonded Mg/Al joint.* Materials & Design, 2009. **30**(10): p. 4548-4551.
12. Shang, J., et al., *Microstructure characteristics and mechanical properties of cold metal transfer welding Mg/Al dissimilar metals.* Materials & Design, 2012. **34**(0): p. 559-565.
13. Wang, J., J. Feng, and Y. Wang, *Microstructure of Al–Mg dissimilar weld made by cold metal transfer MIG welding.* Materials Science and Technology, 2008. **24**(7): p. 827-831.
14. Zhang, H.T. and J.Q. Song, *Microstructural evolution of aluminum/magnesium lap joints welded using MIG process with zinc foil as an interlayer.* Materials Letters, 2011. **65**(21–22): p. 3292-3294.
15. Liu, F., D. Ren, and L. Liu, *Effect of Al foils interlayer on microstructures and mechanical properties of Mg–Al butt joints welded by gas tungsten arc welding filling with Zn filler metal.* Materials & Design, 2013. **46**(0): p. 419-425.
16. Liu, F., Z. Zhang, and L. Liu, *Microstructure evolution of Al/Mg butt joints welded by gas tungsten arc with Zn filler metal.* Materials Characterization, 2012. **69**(0): p. 84-89.
17. Bhamji, I., et al., *Linear friction welding of aluminium to magnesium.* Science and Technology of Welding and Joining, 2012. **17**(5): p. 368-374.
18. Panteli, A., et al., *The effect of high strain rate deformation on intermetallic reaction during ultrasonic welding aluminium to magnesium.* Materials Science and Engineering: A, 2012. **556**(0): p. 31-42.
19. Robson, J., A. Panteli, and P.B. Prangnell, *Modelling intermetallic phase formation in dissimilar metal ultrasonic welding of aluminium and magnesium alloys.* Sci. Technol. Weld. Join., 2012. **17**(6): p. 447-453.

20. Hayat, F., *The effects of the welding current on heat input, nugget geometry, and the mechanical and fractural properties of resistance spot welding on Mg/Al dissimilar materials.* Mater. Des., 2011. **32**(4): p. 2476-2484.
21. Mofid, M.A., et al., *Submerged friction-stir welding (SFSW) underwater and under liquid nitrogen: An improved method to join Al alloys to Mg alloys.* Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science, 2012. **43**(13): p. 5106-5114.
22. Morishige, T., et al., *Dissimilar welding of Al and Mg alloys by FSW.* Materials Transactions, 2008. **49**(5): p. 1129-31.
23. Cao, X., C. Garnier, and P. Wanjara. *Tensile strength of friction stir spot welded dissimilar AA5754-to-AZ31B alloys*. in *9th International Conference on Trends in Welding Research, June 4, 2012 - June 8, 2012*. 2013. Chicago, IL, United states: ASM International.
24. Zettler, R., et al. *A study on dissimilar friction stir welds between Al and Mg alloys*. in *7th International Conference on Trends in Welding Research, May 16, 2005 - May 20, 2005*. 2005. Pine Mountain, GA, United states: ASM International.
25. Cabibbo, M., et al., *Microstructural aspects of a fiction stir welded joint of magnesium AZ31 and aluminium 6060 alloys.* Metallurgia Italiana, 2012(10): p. 13-18.
26. Hunt, F., et al. *Friction stir welding of dissimilar magnesium alloys for automotive applications*. in *2007 World Congress, April 16, 2007 - April 19, 2007*. 2007. Detroit, MI, United states: SAE International.
27. Zettler, R., et al., *Dissimilar Al to Mg alloy friction stir welds.* Advanced Engineering Materials, 2006. **8**(5): p. 415-21.
28. Firouzdor, V. and S. Kou, *Al-to-mg friction stir welding: effect of material position, travel speed, and rotation speed.* Metallurgical and Materials Transactions A (Physical Metallurgy and Materials Science), 2010. **41**(11): p. 2914-35.
29. Malarvizhi, S. and V. Balasubramanian, *Influences of tool shoulder diameter to plate thickness ratio (D/T) on stir zone formation and tensile properties of friction stir welded dissimilar joints of AA6061 aluminum–AZ31B magnesium alloys.* Materials & Design, 2012. **40**(0): p. 453-460.
30. Sato, Y.S., et al., *Constitutional liquation during dissimilar friction stir welding of Al and Mg alloys.* Scripta Materialia, 2004. **50**(9): p. 1233-1236.
31. Jana, S., Y. Hovanski, and G.J. Grant, *Friction Stir Lap Welding of Magnesium Alloy to Steel: A Preliminary Investigation.* Metallurgical and Materials Transactions A, 2010. **41**(12): p. 3173-3182.
32. Watanabe, T., H. Takayama, and A. Yanagisawa, *Joining of aluminum alloy to steel by friction stir welding.* Journal of Materials Processing Technology, 2006. **178**(1–3): p. 342-349.
33. Dressler, U., G. Biallas, and U. Alfaro Mercado, *Friction stir welding of titanium alloy TiAl6V4 to aluminium alloy AA2024-T3.* Materials Science and Engineering: A, 2009. **526**(1–2): p. 113-117.
34. Aonuma, M. and K. Nakata, *Dissimilar metal joining of ZK60 magnesium alloy and titanium by friction stir welding.* Materials Science and Engineering: B, 2012. **177**(7): p. 543-548.
35. McLean, A.A., et al., *Friction stir welding of magnesium alloy AZ31B to aluminium alloy 5083.* Science and Technology of Welding & Joining, 2003. **8**(6): p. 462-464.
36. Kostka, A., et al., *Microstructure of friction stir welding of aluminium alloy to magnesium alloy.* Scripta Materialia, 2009. **60**(11): p. 953-956.
37. Somasekharan, A. and L. Murr, *Microstructures in friction-stir welded dissimilar magnesium alloys and magnesium alloys to 6061-T6 aluminum alloy.* Materials Characterization, 2004. **52**(1): p. 49-64.