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Friction Stir Welding of Dissimilar Materials: An Overview

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***Abstract*—**Friction Stir Welding is a solid state welding technique which can be used to produce sound welds between similar and dissimilar materials. Dissimilar welds which include welds between the different series of aluminum alloys, aluminum to magnesium, steel and titanium has been successfully produced by many researchers. This review covers the work conducted in the above mentioned materials and further concludes by showing the need to fully understand the FSW process in order to expand the latter industrially.

***Keywords*—**Aluminum, dissimilar materials, FSW, hardness, magnesium, microstructure, steel, tensile test, titanium.

I. INTRODUCTION

THE Welding Institute (TWI) in the United Kingdom invented Friction Stir Welding (FSW) process as a solid-state joining technique and was initially applied to aluminum alloys [1]. Friction stir welding process uses a non-consumable rotating tool consisting of a pin extending below a shoulder that is forced into the adjacent mating edges of the work pieces as illustrated in Fig. 1. The heat input, forging action and stirring action of the tool induces a plastic flow in the material, forming a solid state weld.

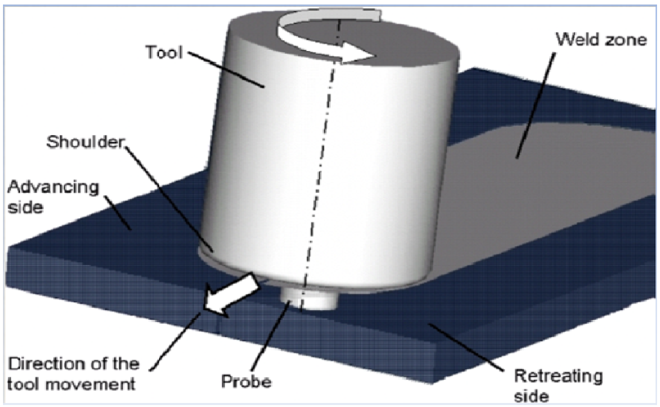

Fig. 1 A schematic illustration of FSW butt-joint [2]

FSW joints usually consist of different microstructural regions as illustrated in Fig. 2 following the terminology used by Mishra *and* Mahoney [3]; this include the unaffected material or parent metal, the Heat-Affected Zone (HAZ), the Thermomechanically Affected Zone (TMAZ) and the weld nugget.

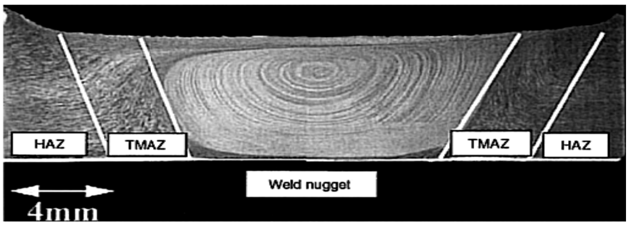

Fig. 2 Illustration of different microstructural regions in the transverse cross section of a friction stir welded material. A, parent metal or unaffected material; B, heat-affected zone; C, thermomechanically affected zone; D, weld nugget [3]

Prior to the development of FSW, conventional fusion welding processes were used to join similar and dissimilar materials. Friction stir welding ofdissimilar materials remains notfully researched. Reviews have been conducted on various aspects of FSW [4-8]. This paper presents a review of the published literature in friction stir welding of dissimilar materials. The review was conducted by focusing on FSW between dissimilar aluminum alloys, aluminum to magnesium, and steel and titanium.

II. FSW MATERIALS COMBINATIONS RESEARCH STUDIES AND CHARACTERIZATION

A. FSW of Dissimilar Aluminum Alloys

Li *and* Shen [9] successfully conducted lap joints of dissimilar AA6063 to AA5052 aluminum alloys using a tool designed from quench hardening $W_9Mo_3Cr_4V$ with some geometric improvements. Furthermore, they placed the two overlap plates of AA5052 on the retreating side which improved the joint integrity of the weld. They demonstrated that improving the degree of mixing of the dissimilar Al alloys and promoting the material plastic deformation in the weld-zone during the FSW contributed to obtaining high-quality lap joints. The influence of the high temperature plastic behavior on friction stir weldability of two aluminum alloys (AA5083-H111/ AA6082-T6) very popular in welding construction was conducted by Leitão*et al* [10].

They found that the AA6082 aluminum alloy displayed good weldability in FSW whereas, the AA5083 alloy, had steady flow behavior at increased temperatures, a very poor weldability was registered under the same welding conditions of the AA6082-T6 alloy. Also, Guo*et al* [11] investigated the microstructure and mechanical properties of AA1100-B4C

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MMC and AA6063 alloy. They found that all the dissimilar welds produced under the welding conditions investigated were stronger than the Al-B4C MMC base materials and demonstrated 100% joint efficiencies (UTS).The material side of the welds or the use of a 0.8 mm offset did not have a significant impact on the tensile properties of the joined assembly even by varying the welding speed. Guo *et al* [11] analyzed the Mg concentration and B4C particle distribution and it indicated a good material mixing and seamless bonding around the interface between the Al-B4C MMC and the AA6063 alloy during FSW.

Koilraj *et al* [12] optimized FSW process with respect to tensile strength of the welds and the optimum settings. Furthermore, the optimum values of the rotational speed, transverse speed, and D/d ratio are 700 rpm, 15 mm/min and 3 respectively. In addition, they concluded that the cylindrical threaded pin tool profile was the best among the other tool profiles considered. Palanivel*et al* [13] examined the influence of tool rotational speed and pin profile on the microstructure and tensile strength of the dissimilar friction stir welded aluminum alloys AA5083-H111 and AA6351-T6. The welds fabricated using straight tool profiles had no defects while the tapered tool profiles caused a tunnel defect at the bottom of the joints under the experimental considered conditions. Furthermore, three different regions namely unmixed region, mechanically mixed region and mixed flow region were observed in the weld zone [13].

Furthermore, Palanivel *et al* [14] joined AA5083-H111 and AA6351-T6 using tool rotational speed of 950 rpm and straight square pin profile which resulted into obtaining the highest tensile strength of 273 MPa. Moreover, the variation in the tensile strength of the dissimilar joints was attributed to material flow behaviour, loss of cold work in the HAZ of AA5083, dissolution and over aging of precipitates of AA6351 and formation of macroscopic defects in the weld zone. Da Silva *et al* [15] investigated the mechanical properties and microstructural features as well as the material flow characteristics in dissimilar 2024-T3 and 7075-T6 FSW joints. The welds were produced at fixed feed rate (254 mm/min) varying the rotation speed in three levels (400, 1000 and 2000 rpm).Da Silva *et al* [15] clearly stated that, typical microstructural features of FSW welds such as SZ, TMAZ and HAZ regions were seen. A sharp transition from the HAZ/TMAZ to the SZ has been observed in the advancing side; while in the retreating side, such transition is more gradual. They found that the minimum hardness value of naturally aged samples in the HAZ at the retreating side was about 88% of 2024-T3 base material. Furthermore, 96% of efficiency in terms of tensile strength was achieved using 1000 rpm rotational speed. Fracture of the weld specimens occurred in the HAZ at the retreating side (2024-T3).

Aval *et al* [16] investigated the microstructures and mechanical propertiesin similar and dissimilar friction stir welding of AA5086-O andAA6061-T6 using thermo-mechanical modeland experimental observations. They concluded that the hardness in AA5086 side mainly depends on recrystallization and generation of fine grains in the weld nugget whereas hardness in the AA6061 side varies with the size, volume fraction and distribution of precipitates in the weld line and adjacent heat affected zone as well as the aging period after welding. Aval *et al* [16] further observed grain refinement in the stirred zone for all their samples; however, the finer grain size distribution is achieved within the AA6061 side where higher strain rates are produced. Shen *et al* [17] in their investigation on microstructures and electrochemical behaviors of the friction stir welding dissimilar welds observed that the microstructure of the FSW weld consist of finer grains in comparison to that of the parent material. Furthermore, intense plastic deformation and frictional heating during welding resulted in the generation of a dynamically recrystallized fine grained microstructure within the stirred zone. Tran *et al* [18] investigated the behavior of friction spot welding between AA 5754-O and AA 7075-T6.They showed that, under cyclic loading conditions, the micrographs show that the 5754/7075 and 7075/5754 welds in cross-tension specimens mainly failed from the fatigue crack along the interfacial surface and from the fracture surface through the upper sheet material[18].Jun *et al* [19] investigated residual strains in dissimilar friction welds. The research was conducted using the Eigen strain Reconstruction Method in FSW between AA5083 and AA6082-T3.They further observed that full-field residual stress–strain distributions can be reconstructed relatively easily based on limited experimental data sets using transparent and straight forward FE modeling framework. Another study was conducted by Ghosh *et al* [20], they joined A356 and 6061 aluminum alloys using FSW under different tool rotation and traversing speeds. They found that the interface microstructure within the weld nugget is dominated by the retreating side alloy as the signature of Si rich particle distribution and it was evident for all the samples produced. They further observed that welds fabricated at the lowest tool rotational and traversing speed exhibited superior mechanical properties when compared to the remaining welds produced. Sundaram *et al* [21] friction stir welded AA2024-T6 and AA5083-H321 using five different pin profiles developed successfully and suitable for the dissimilar FS welding of aluminum alloys. They further observed that increasing the tool rotational speed or welding speed led to the increase in the tensile strength; and it reaches a maximum value and then decreases. Additionally, the increase in the tool axial force led to the increase in the tensile strength of the dissimilar FS welded joints. The tensile strength decreases after it attains a maximum value.

Muruganandam *et al* [22] in FS Welding of dissimilar 2024 and 7075 aluminum alloys, investigated the microstructures, the results revealed that the process led to recrystallized grain structure and precipitates distribution. Moreira *et al* [23] produced friction stir butt welds of AA6082-T6 with AA6061-T6. The welds exhibited intermediate properties and the tensile tests failures occurred near the weld edge line where a minimum value of hardness was observed. Furthermore, microstructural changes induced by the friction stir welding process were clearly identified. Leitao *et al* [24] used AA5182- H111 and AA6016-T4 sheet samples and joined them using FSW. Welds between both alloys exhibited a hardness variation consistent with the microstructure evolution across the TMAZ and no significant decrease in the hardness was observed for the welds and its strength efficiency is about 90%. Still, its ductility seriously decreases relative to the base materials due to the heterogeneous characteristics of these welds. Cavaliere *et al* [25] studied the mechanical and microstructural behaviour of FSW between AA6082 and AA2024. They noticed that the vertical force increased as the travel speed for all the produced joints increases. They also achieved the best tensile and fatigue properties for the joints with the AA6082 on the advancing side and welded with an advancing speed of 115 mm/min. Leitão *et al* [26] joined AA 5182-H111 and AA 6016-T4 using friction stir welding process. They found in the dissimilar welds the presence of small defects at the weld root of the dissimilar welds induced rupture of some of the blanks during the formability tests.

Hatamleh and DeWald [27] joined AA 2195 and AA 7075 and investigated the peening effect on the residual stresses of the produced welds. Results showed that the surface residual stresses resulting from shot peening on both AA 2195 and AA 7075 were higher compared to the laser peening due to the high amount of cold work exhibited on the surface from shot peening. Furthermore, high values of tensile stresses were noticed in the mid-thickness on the laser peened samples.

Recent studies on friction stir welding of dissimilar aluminum and its alloys have been reviewed and a comprehensive summary of the results have been presented.

B. FSW between Aluminum and Magnesium Alloys

Mofid *et al* [28] studied the effect of water cooling during friction stir welding of AA 5083 and AZ31C. They observed that the formation of intermetallic compounds in the stir zone of dissimilar welds significantly affects the mechanical properties of the welds. They suggested the use of submerged friction stir welding under water which resulted in lower peak temperature and because of lower heat input; the intermetallic compounds formation was limited. This was motivated compared to the air welded specimen which had a relatively larger volume fraction of intermetallic compound, higher peak temperature in stir zone and significantly higher hardness in the weld centre [28].Malarvizhi and Balasubramanian [29] also investigated the influences of tool shoulder diameter to pale thickness ration on stir zone formation and tensile properties of FS welded AA6061 and AZ31B. It was found that the joints produced using a shoulder diameter of 21 mm (3.5 times the plate thickness) exhibited superior tensile properties compared to its counterparts. Furthermore the complex intercalated microstructures in the weld zone, with swirls and vortices were indicative of the flow pattern of the dissimilar metals. Simoncini and Forcellese [30] investigated the effect of friction stir welding parameters and tool configuration on micro and macro mechanical properties of similar and dissimilar welds using AA5754 and AZ31 thin sheets. They used two different tool configurations with and without pin. Results showed that the pinless tool leads to the obtaining of higher values of the ultimate tensile strength and ductility as compared to the welds made with tool pin. The microstructure of the cross-section showed that the bonded interface is clearly evident. Venkateswaran *and* Reynolds [31] performed FSW on AA 6063-T5 and AZ31B-H24 and analyzed the factors affecting the resulting weld properties. The nugget grain size on both the Al and Mg sides monotonically increased as the tool rotational speed increases. Furthermore, the transverse tensile test results are correlated with several interface features including actual interface length, extent of interpenetration between the aluminum and magnesium base metals, maximum intermetallic layer thickness, and area fraction of micro-void coalescence on the tensile fracture surfaces [31].Chowdhury*et al* [32] investigated the lap shear strength and the fatigue life of friction stir spot welded AZ31 and AA 5754 alloys. Results showed that the Al/Mg dissimilar welds were characterized by the formation of a distinctive interfacial layer consisting of $Al_{12}Mg_{17}$ and Al_3Mg_2 intermetallic compounds. In the Al/Mg dissimilar weld, a characteristic interfacial layer consisting of intermetallic compounds $Al_{12}Mg_{17}$ and Al_3Mg_2 was observed. Furthermore both Mg/Mg and Al/Al similar welds had significantly higher lap shear strength, failure energy and fatigue life than the Al/Mg dissimilar weld. Sharifitabarand Nami [33] investigated the microstructures and hardness profiles across the interface of friction stir welded joints between monolithic AA 2024-T4 and Al/Mg_2Si metal matrix cast composite (MMC). The results showed that there was a complicated pattern of materials flow in the stir zone especially in sample welded in two passes. Furthermore, in the sample welded using one pass, it was found that the hardness increased from the base metal to the stir zone on the MMC side. Nevertheless, hardness variation in the sample welded in two passes was complicated and there was alternative decrease and increase in hardness value at the joint interface.Yong *et al* [34] investigated FSW between AA 5052 and AZ31 Mg alloy; they produced sound welds at rotational speed of 600 rpm and welding speed of 40 mm/min. The microstructure of the base metal was replaced by equiaxed and fine grains in the stir zone. Furthermore, at the top of the stir zone, 5052 and AZ31 alloys were simply bonded, while onion ring structure which consisted of aluminum bands and magnesium bands was formed at the bottom of the stir zone. In addition, they found that microhardness profiles presented uneven distributions and the maximum value of microhardness in the stir zone was twice higher than that of the base materials [34].Liu *et al* [35] characterized the galvanic corrosion of a dissimilar friction stir welded 2024-T3 Al/AZ31B-H24 Mg joint prepared using a water-based and a non-water-based polishing solution. It was shown that the water-based polishing solution induced more easily the galvanic corrosion attack than the non-water-based polishing solution during the polishing process. Furthermore, they attributed the low microhardness value in the corroded region to the formation of the porous magnesium hydroxide layer with microcracks. Kostka *et al* [36] characterized the microstructure of the interface between AA6040 and AZ31 joined by friction stir welding. Results showed that the intermetallic compound layer has a thickness of about 1 μm and consists mainly of fine-grained $Al_{12}Mg_{17}$ phase.

Review on FSW between aluminum and magnesium alloys has been presented, however all authors reported the formation of intermetallic compounds which are detrimental to the joint integrities. There is therefore a need for more research to reduce the formed intermetallics in the welds as this will offer this dissimilar joints opportunities for industrial applications.

C. FSW between Aluminum Alloys and Steel

AA 6111-T4 and DC04 low carbon steel sheets has been friction stir welded by Chen *et al* [37]. They successfully produced high quality friction spot welds between thin Al and steel automotive sheet within a weld time of one second which is the target time desired by industry. Ogura *et al* [38] used AA3003/SUS304 and friction stir welded them in lap joints. The results showed that the strength in the centre region and on the advancing side was larger than that at the retreating side. Coelho *et al* [39] investigated the mechanical properties and their relation to microstructure of AA6181-T4 and DP600 and HC260LA HSS plates by FSW. Results showed that across all the weld regions in the Al alloy side (BM-HAZ-TMAZ-SZ), strong differences in the grain size distribution and shape occurred. Bang *et al* [40] used Hybrid FSW (HFSW) welding to join Al6061-T6 aluminum alloy and STS304 stainless steel. Their results showed that the maximum tensile strengths obtained at the weld were 93% of the aluminum alloy base metal for HFSW and 78% for FSW. Furthermore, fracture patterns of the crack propagation of HFS welds exhibits entirely ductile fracture mode showing dimples at the fracture surface and locally brittle fracture mode with cleavage facet which are hardly accompanied by plastic deformation [40]. Mashiko *et al* [41] investigated joint interface of friction stir welding between SUS304 and A6063 using HTS-SQUID gradiometer. Large voids were observed on the joint interface by the conditions with excess heating. Furthermore, the hardness test on the SUS boards near the interfaces, the SUS jointed with 200 mm/min, which caused excess heating, was about half softer than the matrix [41].Tanaka *et al* [42] FS welded mild steel to A7075-T6 and investigated the joint strength. They found that the joint strength increased with reduction in the thickness of the intermetallic compound at the weld interface. Uematsu *et al* [43] welded A6061 and low carbon steel sheets, SPCC by a friction stir spot welding (FSSW). Results showed that high tensile-shear strength of the dissimilar welds was achieved by a newly designed scroll grooved tool without probe. It is challenging to weld Aluminum and its alloys to steel using conventional welding techniques due to the differences in their properties but the studies reviewed above showed that Al and steel can be successfully joined using the FSW process.

D. FSW between Aluminum and Titanium Alloys

Yu-hua *et al* [44] friction stir welded TC1 Ti alloy and LF6 Al alloy plates. They obtained an excellent surface appearance; furthermore the interface macrograph of the lap joint cross sections at different parameters significantly changed. They further noticed that at the welding speed of 60 mm/min and the tool rotation rate of 1500 rpm, the interfacial zone of the lap joint can be divided into three kinds of layers.When the welding speed increases to 150 mm/min, groove-like crack occurs on the interface. Yu-hua *et al* [44] showed that the microhardness of the lap joint presents an uneven distribution; the maximum value of hardness reaches HV 502 in the middle of the stir zone. Wei *et al* [45] welded AA 1060 sheets and Ti–6Al–4V sheets using FSW lap process by employing a cutting pin of rotary burr tool. They showed that there are many titanium scrapings distributed in the aluminum near the interface. In addition, a swirl-like structure with lighter and darker parts was observed in the SEM micrograph of the interface region. Aonuma and Nakata [46] studied the effect of calcium on intermetallic compound layer between Mg–Al alloy and titanium. They found that calcium added in Mg–Al alloy reacted with aluminum to make Al_2Ca compound and decreased the solid-solution aluminum in the matrix of Mg–Al–Ca alloy. Furthermore, this suppressed the formation of Ti–Al intermetallic compound layer at the joint interface.Aonuma *and* Nakata [46] showed that the suppression of the Ti–Al intermetallic compound layer at the joint interface resulted in the higher tensile strength of the dissimilar joint with titanium plate in comparison with Mg–Al alloy containing same aluminum contained. Chen and Nakata [47] friction stir welded ADC12 cast aluminum alloy to pure titanium sheet. They observed the formation of a transient phase ($TiAl_{3)}$ at the joining interface by Al–Ti diffusion reaction. Furthermore, Chen and Nakata [47] observed that the formation of $TiAl_3$ is strongly dependant on welding speeds (heat inputs) during FSW and therefore affects the mechanical properties of joints. Dressler *et al* [48] investigated the feasibility of friction stir welding between TiAl6V4 and AA2024-T3 and the properties of produced joints. Furthermore, Dressler *et al* [48] shifted the tool pin centre towards the aluminum plates and observed that the resulting microstructure is characteristic of a conventional friction stir weld. Friction Stir Welding Titanium to aluminum alloys might have many applications in aerospace and industries; therefore the development of this technique is of major importance.

III. CONCLUSION

In conclusion, an overview of friction stir welding of dissimilar materials focusing on aluminum to other materials has been conducted. The latter focuses on dissimilar aluminum alloys, aluminum to magnesium, aluminum to steel and titanium. Furthermore, this paper review showed that there is a significant progress in FSW of dissimilar materials. Most of the cited research studies are more focused on understanding the microstructure and physical properties of various welds. FSW technology need to be more developed to enable the technique to be employed industrially. The full understanding of the dissimilar FSW process is needed to accommodate the huge demand in the industries including manufacturing and the aerospace industry. Furthermore, the improvement of current weld quality and properties using the FSW process needs to be looked into.

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REFERENCES

[1] W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Temple-Smith, C.J. Dawes, “Friction stir Butt Welding”. International Patent No. PCT/GB92/02203, 1991, GB patent application No. 9125978.8.

[2] A. Scialpi, M. De Giorgi, L.A.C. De Filippis, R. Nobile, F.W. Panella, “Mechanical analysis of ultra-thin friction stir welding joined sheets with dissimilar and similar materials”, Materials and Design 29 (2008), pp. 928–936.

[3] Rajiv S. Mishra and Murray W. Mahoney, “Friction Stir Welding and Processing”, 2007, ASM international, the materials information society.

[4] T. DebRoy and H. K. D. H. Bhadeshia, “Friction stir welding of dissimilar alloys – a Perspective”, Science and Technology of Welding and Joining 2010, Vol 15 No 4, pp. 266- 270.

[5] R. Rai, A. De, H. K. D. H. Bhadeshia and T. DebRoy, “Review: friction stir welding tools”, Science and Technology of Welding and Joining, 2011, Vol 16 No 4, pp. 325- 342.

[6] M. Sivashanmugam, S. Ravikumar, T. Kumar, V. Seshagiri Rao, D. Muruganandam, “A Review on Friction Stir Welding for Aluminum Alloys”, 978-1-4244-9082-0/10/$26.00 ©2010 IEEE, pp. 216 – 221.

[7] Z.Y. MA “Friction Stir Processing Technology: A Review” Metallurgical and Materials Transactions A, 2008, Vol. 39A, pp. 642 – 658.

[8] V. Soundararajan, M. Valant and R. Kovacevic, “An Overview of R&D Work in FrictionStir Welding at SMU”Association of Metallurgical Engineers of Serbia (AMES), pp. 276 – 295.

[9] Bo Li, Yifu Shen, “A feasibility research on friction stir welding of a new-typed lap–butt joint of dissimilar Al alloys” Materials and Design 34 (2012) , pp. 725–731.

[10] C. Leitão, R. Louro, D.M. Rodrigues, “ Analysis of high temperature plastic behaviour and its relation with weldability in friction stir welding for aluminum alloys AA5083-H111 and AA6082-T6 Materials and Design 37 (2012), pp. 402–409.

[11] J. Guo, P. Gougeon, X.-G. Chen, “Microstructure evolution and mechanical properties of dissimilar friction stir welded joints between AA1100-B4C MMC and AA6063 alloy”, Materials Science and Engineering A 553 (2012) 149– 156.

[12] M. Koilraj, V. Sundareswaran, S. Vijayan, S.R. Koteswara Rao, “Friction stir welding of dissimilar aluminum alloys AA2219 to AA5083 – Optimization of process parameters using Taguchi technique” Materials and Design 42 (2012), pp. 1–7.

[13] R. Palanivel, P. Koshy Mathews, N. Murugan, I. Dinaharan, “Effect of tool rotational speed and pin profile on microstructure and tensile strength of dissimilar friction stir welded AA5083-H111 and AA6351-T6 aluminum alloys”, Materials and Design 40 (2012) , pp. 7–16.

[14] R. PalaniveI, P. Koshy Mathews, “Mechanical and microstructural behaviour of friction stir welded dissimilar aluminum alloy”, IEEE-International Conference On Advances In Engineering, Science And Management (ICAESM -2012) March 30, 31, 2012, pp. 7- 11.

[15] A.A.M. da Silva, E. Arruti, G. Janeiro, E. Aldanondo, P. Alvarez, A. Echeverria, “Material flow and mechanical *behaviour* of dissimilar AA2024-T3 and AA7075-T6 aluminum alloys friction stir welds”, Materials and Design 32 (2011) , pp. 2021–2027.

[16] H. Jamshidi Aval, S. Serajzadeh, A.H. Kokabi, “Evolution of microstructures and mechanical properties in similar and dissimilar friction stir welding of AA5086 and AA6061”, Materials Science and Engineering A 528 (2011), pp. 8071– 80853.

[17] Changbin Shen, Jiayan Zhang, Jiping Ge, “Microstructures and electrochemical behaviors of the friction stir welding dissimilar weld”, Journal of Environmental Sciences, 2011, 23(Supplement) S32–S35.

[18] V.-X. Tran, J. Pan, T. Pan, “Fatigue behavior of spot friction welds in lap-shear and cross-tension specimens of dissimilar aluminum sheets”, International Journal of Fatigue 32 (2010), pp. 1022–1041.

[19] T-S. Jun, K. Dragnevski, A.M. Korsunsky, “Microstructure, residual strain, and eigenstrain analysis of dissimilar friction stir welds”, Materials and Design 31 (2010) , pp. S121–S125.

[20] M. Ghosh, K. Kumar, S.V. Kailas, A.K. Ray, “Optimization of friction stir welding parameters for dissimilar aluminum alloys” Materials and Design 31 (2010) , pp. 3033–3037.

[21] N. Shanmuga Sundaram, N. Murugan, “Tensile behavior of dissimilar friction stir welded joints of aluminum alloys” Materials and Design 31 (2010) , pp. 4184–4193.

[22] D. Muruganandam, S. Ravikumar, Sushil Lal Das “Mechanical and Micro Structural Behavior of 2024–7075 Aluminum Alloy Plates joined by Friction Stir Welding”, 978-1-4244-9082-0/10/$26.00 ©2010 IEEE , pp. 247- 251.

[23] P.M.G.P. Moreira, T. Santos, S.M.O. Tavares, V. Richter-Trummer, P. Vilaça, P.M.S.T. de Castro, “Mechanical and metallurgical characterization of friction stir welding joints of AA6061-T6 with AA6082-T6” Materials and Design 30 (2009), pp. 180–187.

[24] C. Leitao, R.M. Leal, D.M. Rodrigues , A. Loureiro, P. Vilaca, “Mechanical behaviour of similar and dissimilar AA5182-H111 and AA6016-T4 thin friction stir welds” Materials and Design 30 (2009) , pp. 101–108.

[25] P. Cavaliere, A. De Santis, F. Panella, A. Squillace, “Effect of welding parameters on mechanical and microstructural properties of dissimilar AA6082–AA2024 joints produced by friction stir welding” Materials and Design 30 (2009), pp. 609–616.

[26] C. Leitão, B. Emílio, B.M. Chaparro, D.M. Rodrigues, “Formability of similar and dissimilar friction stir welded AA 5182-H111 and AA 6016-T4 tailored blanks” Materials and Design 30 (2009) , pp. 3235–3242.

[27] Omar Hatamleh, Adrian DeWald, “An investigation of the peening effects on the residual stresses in friction stir welded 2195 and 7075 aluminum alloy joints”, Journal of Materials Processing Technology 209 (2009), pp. 4822–4829.

[28] M.A. Mofid, A. Abdollah-zadeh, F. Malek Ghaini, “The effect of water cooling during dissimilar friction stir welding of Al alloy to Mg alloy” , Materials and Design 36 (2012), pp. 161–167.

[29] S. Malarvizhi , 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 and Design 40 (2012) , pp. 453–460.

[30] M. Simoncini, A. Forcellese, Effect of the welding parameters and tool configuration on micro- and macro-mechanical properties of similar and dissimilar FSWed joints in AA5754 and AZ31 thin sheets, Materials and Design 41 (2012), pp. 50–60.

[31] P. Venkateswaran, A.P. Reynolds, “Factors affecting the properties of Friction Stir Welds between aluminum and magnesium alloys” Materials Science and Engineering A 545 (2012), pp.26– 37.

[32] S.H. Chowdhury, D.L.Chen, S.D.Bhole, X.Cao, P.Wanjara, “Lap shear strength and fatigue life of friction stir spot welded AZ31 magnesium and 5754 aluminum alloys”, Materials Science & Engineering A 556 (2012) , pp. 500–509.

[33] M. Sharifitabar, H. Nami, “Microstructures of dissimilar friction stir welded joints between 2024-T4 aluminum alloy and Al/Mg2Si metal matrix cast composite , Composites: Part B 42 (2011), pp. 2004–2012.

[34] YAN Yong, ZHANG Da-tong, QIU Cheng, ZHANG Wen, “Dissimilar friction stir welding between 5052 aluminum alloy and AZ31 magnesium alloy”, Trans. Nonferrous Met. Soc. China 20 (2010), pp. s619−s623.

[35] C. Liu, D.L. Chen, S. Bhole, X. Cao, M. Jahazi, “Polishing-assisted galvanic corrosion in the dissimilar friction stir welded joint of AZ31 magnesium alloy to 2024 aluminum alloy” , Materials Characterization 60 (2009) , pp. 3 7 0 – 3 7 6.

[36] A. Kostka, R.S. Coelho, J. dos Santos, A.R. Pyzalla, “Microstructure of friction stir welding of aluminum alloy to magnesium alloy”, Scripta Materialia 60 (2009), pp. 953–956.

[37] Y.C. Chen, A. Gholinia, P.B. Prangnell, “Interface structure and bonding in abrasion circle friction stir spot welding: A novel approach for rapid welding aluminum alloy to steel automotive sheet” Materials Chemistry and Physics 134 (2012), pp. 459– 463.

[38] Tomo Ogura,Yuichi Saito, Taichi Nishida, Hidehito Nishida, Takumi Yoshida, Noriko Omichi, Mitsuo Fujimoto, Akio Hirose, “Partitioning evaluation of mechanical properties and the interfacial microstructure in a friction stir welded aluminum alloy/stainless steel lap joint”, Scripta Materialia 66 (2012) , pp. 531–534.

[39] R.S. Coelho, A. Kostka, J.F. dos Santos, A. Kaysser-Pyzalla , “Friction-stir dissimilar welding of aluminum alloy to high strength steels: Mechanical properties and their relation to microstructure”, Materials Science & Engineering A 556 (2012) , pp. 175–183.

[40] HanSur Bang, HeeSeon Bang, GeunHong Jeon, IkHyun Oh, ChanSeung Ro, "Gas tungsten arc welding assisted hybrid friction stir welding of dissimilar materials Al6061-T6 aluminum alloy and STS304 stainless steel" Materials and Design 37 (2012), pp. 48–55.

[41] Y. Mashiko, Y. Hatsukade, T. Yasui, H. Takenaka, Y. Todaka, M. Fukumoto, S. Tanaka,"Evaluation of joint interface of friction stir welding between dissimilar metals using HTS-SQUID gradiometer", Physica C 470 (2010), pp. 1524–1528.

[42] Tsutomu Tanaka, Taiki Morishige and Tomotake Hirata, "Comprehensive analysis of joint strength for dissimilar friction stir welds of mild steel to aluminum alloys" Scripta Materialia 61 (2009), pp. 756–759.

[43] Yoshihiko Uematsu, Keiro Tokaji, Yasunari Tozaki, Yasuhito. Nakashima, "Fatigue behaviour of dissimilar friction stir spot weld between A6061 and SPCC welded by a scrolled groove shoulder tool" , Procedia Engineering 2 (2010), pp. 193–201.

[44] CHEN Yu-hua, NI Quan, KE Li-ming, "Interface characteristic of friction stir welding lap joints of Ti/Al dissimilar alloys", Trans. Nonferrous Met. Soc. China 22(2012), pp. 299-304.

[45] Yanni Wei, Jinglong Li, Jiangtao Xiong, Fu Huang, Fusheng Zhang, Syed Hamid Raza Joining aluminum to titanium alloy by friction stir lap welding with cutting pin" , Materials Characterization 71, (2012), pp. 1-5.

[46] Masayuki Aonuma, Kazuhiro Nakata, "Effect of calcium on intermetallic compound layer at interface of calcium added magnesium–aluminum alloy and titanium joint by friction stir welding, Materials Science and Engineering B 173 (2010), pp. 135–138.

[47] Y.C. Chen, K. Nakata, "Microstructural characterization and mechanical properties in friction stir welding of aluminum and titanium dissimilar alloys", Materials and Design 30 (2009), pp. 469–474.

[48] Ulrike Dressler, Gerhard Biallas, Ulises Alfaro Mercado, "Friction stir welding of titanium alloy TiAl6V4 to aluminum alloy AA2024-T3" , Materials Science and Engineering A 526 (2009) , pp. 113–117.