Stephan Thangaiah I S
Professor
VIT Business School
Vellore Institute of Technology
Tamilnadu
India

Sevvel P
Professor
Department of Mechanical Engineering
S.A. Engineering College
Tamilnadu
India

Satheesh C
Assistant Professor
Department of Mechanical Engineering
Madha Institute of Engineering & Technology
India

Mahadevan S
Professor
Department of Mechanical Engineering
S.A. Engineering College
Tamilnadu
India

Experimental Study on the Role of Tool Geometry in Determining the Strength & Soundness of Wrought Az80a Mg Alloy Joints During Fsw Process

An investigation was conducted to find out the influencing role of the geometry of the FSW tool on the tensile strength, corrosion resistance, wear rate of the wrought AZ80A Mg alloy joints during the FSW process. FSW tools with two uniquely different geometries, namely stepped cylindrical shoulder tool and stepless cylindrical shoulder tool were employed at different combinations of speeds of rotation and traversing speed. Comprehensive observations & investigations were also carried out regarding the tensile strength, wear losses & corrosion resistance of the fabricated joints. The joints fabricated using stepped cylindrical shoulder tool exhibited appreciable tensile strength values at combinations of higher traversing feeds and low values of rotational speeds of the FSW tool. At the same time, *the joints possessing fine sized refined grains in their nugget zone have been found to exhibit higher wear losses.*

Keywords*: Friction Stir Welding, AZ80A Mg alloy, Tool Geometry, Tensile Strength, Wear losses, Corrosion resistance, Traversing speed, Tool rotational speed.*

1. INTRODUCTION

Today's current demand & challenge related with automobile manufacturing units aims for enhancing the fuel economy along with reduction of emission levels of greenhouse gases, and this can be eventually obtained by reducing the weight of the automobile [1–4]. Redu–cing the weight of the automobiles without any compromise in reliability & safety is a quite bit challenging task, which can be obtained with the help of designing suitable innovative structures & by employing light weight metals for manufacturing various auto–mobile components [5,6]. Various alloys of magnesium have attracted many automobile manufacturing engi–neers & researchers working in the domain of fabricating light weight transportation units, as they belong to the category of light weight metals [7–10]. Further, features of alloys of magnesium, namely high stiffness, reasonable specific strength, ability to conduct heat in a faster rate, easy castability & machinability, tremendous electro magnetic interference damping and shielding capability etc also have made them to be one of the most inevitable material for use in present automobile manufacturing sectors [11–14] .

At the same time, the tribological properties and formability features of the majority of the Mg alloys are not meritorious. Another factor which plays a dominant role in hindering a wide usage of Mg alloys, is their poor formability at room temperature, resulting from their hexagonal close-packed (HCP) crystal. Hence, a large scale usage of Mg alloys entails the choice for suitable joining methodology to fabricate high quality, sound joints with predominant mechanical properties [15–19]. Friction stir welding (FSW), an energy efficient & eco friendly solid state joining method, with the ability for fabricating joints without melting the base materials, has gained the attraction of various experimental researchers working with the objective of joining light weight metals [20–22]. FSW have been proven to possess various merits over the conventional fusion joining process like completely eliminating the inherent defects due to casting and refining the structure of grains in a adequate manner, thereby increasing the strength of the fabricated joints, their corrosion resistance properties, formability, ductility etc [23–27].

2. LITERATURE REVIEW

Unlike majority of the metals like steel, aluminium, copper etc, which are cubic latticed, Mg alloys are hexagonal latticed and complications may arise due to their hcp (hexagonal close packed) structure, especially w.r.t plastic deformation[28–34]. As a result, in majority of the applications, magnesium as cast alloy is commonly preferred. But, the present demand for enhanced fuel economy & weight reduction in automobile manufacturing sector compels the extensive need for employing wrought magnesium alloys like AZ80A, in fabrication of various advanced automobile components & parts, intermediate compressors, cano–pies, auxiliary gearboxes, castings for gearboxes, generators, engine components and engine blocks for extra rapid performance race vehicles [35–41]. As a result, special care & consideration should be given, while choosing a appropriate process for joining com–ponents composed of AZ80A Mg alloy. Few & unlimited experimental

Received: April 2018, Accepted: June 2018
Correspondence to: Prof. P. Sevvel, Department of Mechanical Engineering, S.A. Engineering College, Chennai – 600 077, Tamilnadu, India
E-mail: drsevvel@saec.ac.in
doi:10.5937/fmet1804612T

works and investigations have been done on joining of wrought Mg alloys (like AZ31, AZ61, ZK60, AM60 etc) using the FSW process [42–51].

For example, Masayuki Aonuma et al. [42] carried out an experimental work to understand the role of the alloying elements during joining of ZK60 Mg alloy with Ti metal using FSW process. Joints were obtained successfully and a thin Zr and Zn layer thickness – 1mm) was generated at the interface of the joint surfaces, which leads to a fracture at the joint interface during tensile test and revealed the fact that, the alloying elements have appreciable beneficary effect in improving the strength of the dissimilar FSW joints. Even though, microstructures of wrought & cast Mg alloys can be naturally, unquestionably refined after FSW, the strength of the joint was often to decrease due to dissolution of precipitates and redistribution of textures. Zhe et al. [46] experimentally proved that the strength of the ZK60 Mg alloys fabricated using FSW process can be improved through adoption of aging treatment and post-weld compression. It was found during the investigation that the post-weld compression has increased the precipitates number in the fabricated ZK60 Mg alloy joints during the consequent aging. Another researcher Dhanapal et al [49] investigated the corrosion performance of the wrought AZ61A Mg alloy joints fabricated using the technique of FSW. The corrosion performance of the fabricated joints was validated by immersing the joints in solutions of NaCl with different values of pH, different concentrations of chloride ion & at various time intervals of immersion. The investigation helped us to understand that there is a notable improvement in the resistance towards to corrosion of the AZ61A joints w.r.t alkaline solutions when compared to that of the neutral and acidic solutions. Further, it was observed that the β-phase distribution places a significant role in influencing the corrosion performance.

Kim et al. [51] carried out an experimental work on understanding the microtexture evolution, in the SZ (stir zone) of the fabricated AZ31 Mg alloy joints through advanced techniques namely polycrystal modeling and microtexture analysis. It was revealed by the employment of the analysis using the EBSD (electron back scatter diffraction) that, the process of FSW has induced to a greater extent, the formation of strong fibered textures in the SZ and this development of fibered textures were dependent on the moving track of the material point w.r.t the pin of the rotating of the FSW tool.

Relatively poor ductility and formability is inevitable in AZ80A Mg alloy joints fabricated using conventional fusion joining techniques, and the existence of hcp structure with systems of slip at temperature of ambience, is one of the major reasons for this poor ductility, which hinders the successful fabrication of sound quality AZ80A Mg alloy joints. In this experimental research work, an investigational attempt was made to understand in detail, the important role of the FSW tool design & its geometry in influencing the tensile strength, losses due to wear, rate of corrosion of the AZ80A joints during their fabrication at optimized values of FSW process parameters namely traversing speed of the FSW tool and speeds of rotation of the FSW tool, with others parameters (including axial force, depth of penetration by the pin profile of the FSW tools into the joint surface etc) being constant.

3. METHODOLOGY OF INVESTIGATION

3.1 Machine and Parent Material

Flat 5mm thickness wrought AZ80A Mg alloy plates of 125 mm length and 55mm width composed of 7.82% aluminium, 0.31% manganese, 0.69% zinc, 0.051% of copper, 0.049% of iron, o.11% of silicon, 0.052% of nickel and balance being magnesium [52, 53] is used as the metal of base of investigation.

The entire experimental process of joining flat plates of wrought AZ80A Mg alloy using the technique of FSW was done using a self ingeniously fabricated & developed FSW machine (semi automatic in nature). A maximum spindle speed of 1500 rpm can be achieved in the above mentioned FSW machine and this FSW machine houses a 5kW power spindle motor, which can provide a maximum of 3 ton axial force from the upward direction. This FSW machine houses an adjustable fixture which has provision for holding individual flat work plates with a maximum length of 200 mm and width of 75mm. A photographic illustration of the wrought AZ80A Mg alloy flat plates being firmly held in their respective position in the FSW machine's fixture (before friction stir welding is being carried out on those plates) can be seen in the Figure 1.

Figure 1. Photograph of the wrought AZ80A Mg alloy flat plates being firmly held in their respective position in the specially designed fixture of the FSW machine

3.2 Material & Geometry of the FSW tool

Usually, the tool for carrying out an FSW is selected depending upon the materials to be joined together and fabricating a FSW tool with appropriate, suitable material plays a significant role in successfully fabricating the FSW joints, at different preferred levels & values of FSW process parameters [54–56]. HSS (high speed steel) of grade M35 was chosen as the raw material for the FSW tool in this experimental investigation. The hardness of the above mentioned HSS FSW tool was around 61 – 62 HRC.

Designing an FSW tool with suitable geometry includes the design of the tool shoulder as well as the design of the tool pin profile. The FSW tool shoulder executes the function of preventing the plasticized metal from escaping the surface of the workpiece, being welded. It also plays a vital role in generating the required amount of frictional heat in ideal volumes during the joining process [57–59]. Likewise, the careful consideration & care must be taken while desig–ning the FSW tool pin profile, as it regulates the uniform flow of the plasticized material along the entire NZ (nugget zone), during the friction stir welding process [60, 61].

In this experimental investigation, two FSW tools (made up of M35 grade HSS material) designed with two different shoulder profiles, namely stepped cylindrical shoulder tool and stepless cylindrical shoulder tool are employed for the purpose of fabricating joints between two flat plates of wrought AZ80A Mg alloy. The photographic of the stepless cylindrical shoulder tool is shown in the Figure 2 (a). This tool was designed and fabricated in such a way that this tool has a shoulder diameter of 30 mm and a tapered pin profile. The major pin diameter of this FSW tool is 7 mm and it tapers down to 4 mm along a total pin length of 4.75 mm.

Figure 2. Photographs of the different designs of the FSW tools employed in this investigation (a) stepless cylindrical shoulder tool shoulder and (b) stepped tool shoulder

Similarly, the FSW tool with stepped cylindrical shoulders is designed in such a way that, it has a 20mm outside tool shoulder diameter and the inner diameter of the tool shoulder is 15 mm, as seen in the Figure 2 (b). The geometry of this tool pin profile is exactly as that of the stepless cylindrical shoulder tool, i.e., with the tapered shaped pin as its pin profile.

3.3 Parameters of the FSW process

The experimental investigations were conducted using the concept of the 2 factors with 3 levels full factorial de–sign with two types of replicants for both the types of the FSW tools, i.e., for the stepless cylindrical shoulder tool & for the stepped cylindrical shoulder tool. The different values of the speeds of rotation of the FSW tool and the traversing speed of the FSW tool employed in this experimental work are clearly described in the Table 1.

Table 1. Details of the FSW process parameters and their corresponding values employed during this investigation

S. No.	Speed of rotation of the FSW tool (rpm)	Traversing speed of the FSW tool (mm/min)
1	500	0.5
2	750	1.5
3	1000	3.0

The other FSW process parameters namely axial force, depth of penetration of the FSW tool pin profile etc are kept as constant values throughout the entire experimental work. An axial force of 3kN was maintained throughout the entire joining process and the total depth of penetration of the pin profile of both the FSW tools were about 4.75mm for the entire set of the experiments. Different stages of fabrication of flat wrought AZ80A Mg alloy plates into sound quality joints by employing the stepped cylindrical shoulder FSW tool with tapered pin profile are illustrated in a detailed manner in the Figure 3. It can be observed that, after placing the flat plates firmly in the specially designed fixture, the rotating FSW tool was slowly made to penetrate into the joint surface of the two flat AZ80A Mg alloy flat plates. Once the pin profile has made its full penetration depth of 4.75mm, the shoulder surface of the stepped FSW tool touches the joint surface, then the automatic traversing mechanism of the FSW machine is engaged in full fledged manner, which permits the FSW tool to make its further travel with the preset speed of rotation and traversing speed for the remaining entire length of the workpiece surface as seen in the Figure 3.

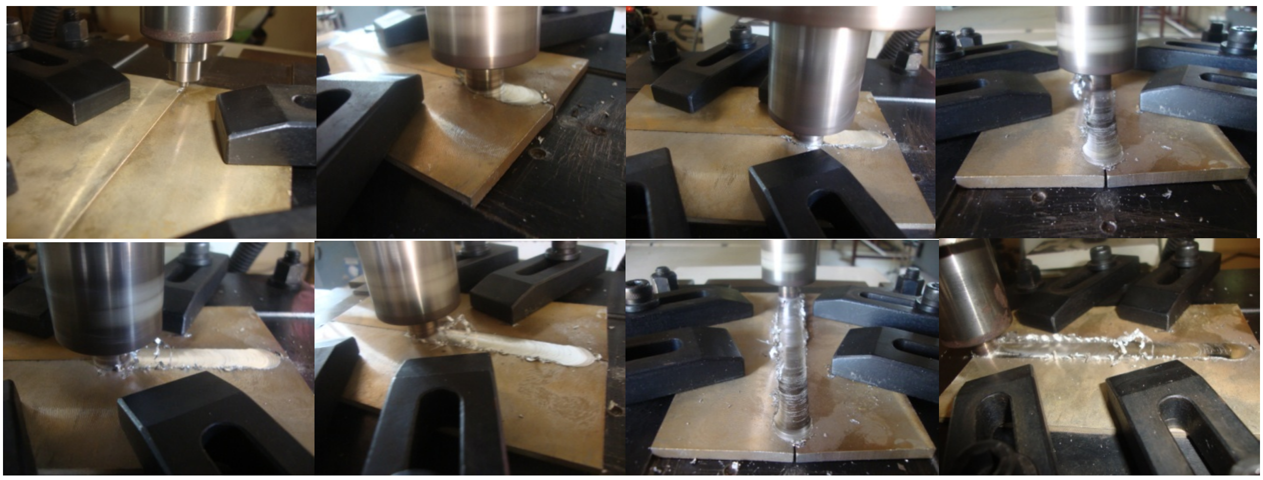

Figure 3. Different stages of fabrication of flat wrought AZ80A Mg alloy plates into sound quality joints by employing the stepped cylindrical shoulder FSW tool with tapered pin profile

4. EXPERIMENTAL RESULTS, OBSERVATTIONS & INVESTIGATIONS

4.1 Morphology of the joint surface

The photographs of the joints fabricated using the two different types of the FSW tool geometries namely, the stepless cylindrical shoulder tool and the stepped cylin–drical shoulder tool at above mentioned combinations of speeds of rotation of the tool and traversing speed of the FSW tool are shown in the Figure 4 (a) and (b).

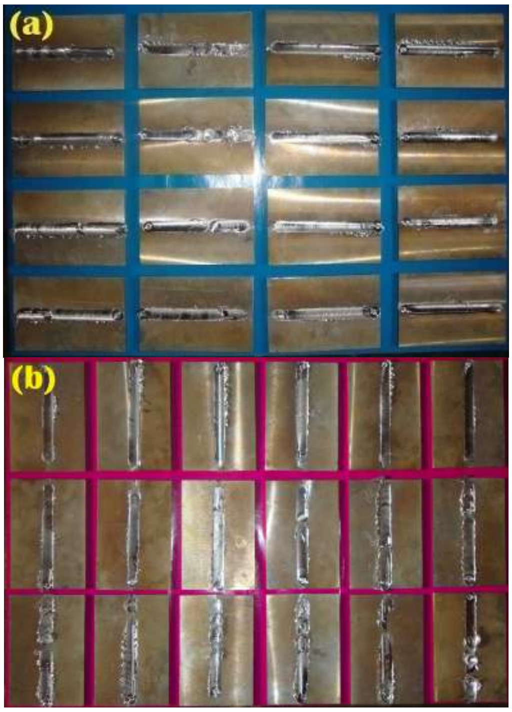

Figure 4. Photographs of a part of the joints fabricated during this investigation under combination of various process parameters using (a) Stepless cylindrical shoulder tool and (b) Stepped cylindrical shoulder tool

4.2 Tensile strength of the fabricated joints

The combined effect & influence of the two different process parameters of the FSW technique on the tensile strength of the wrought AZ80A Mg alloy joints fabri–cated using the stepless cylindrical shoulder tool and the stepped cylindrical shoulder tool are graphically illustrated in the Figures 5 & 6.

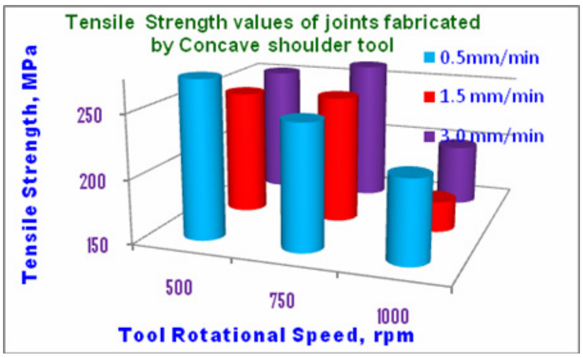

Figure 5. Graphical illustration of the tensile strength of the wrought AZ80A Mg alloy joints fabricated using stepless cylindrical shoulder tool at different combinations of traversing speed and rotational speeds of the FSW tool

From the Figure 5, it can be observed clearly that, for the traversing speed of 0.5 mm/min, the strength of the fabricated joints seems to decrease when the speeds of rotation of the FSW tool is increased. For the 1.5 mm/min value of tool traversing speed, there is no significant change in the tensile strength of the joints, when the speed is increased from 500 rpm to 750 rpm. But, further increase in the speed of the FSW tool (to 1000 rpm) decreases the tensile strength of the fabricated joints in a drastic manner. In the case of the 3 mm/min traversing speed, the joint strength increases when the speed is raised form 500 rpm to 750 rpm, but decreases with further increase (1000 rpm) in the rotational speeds of the FSW tool.

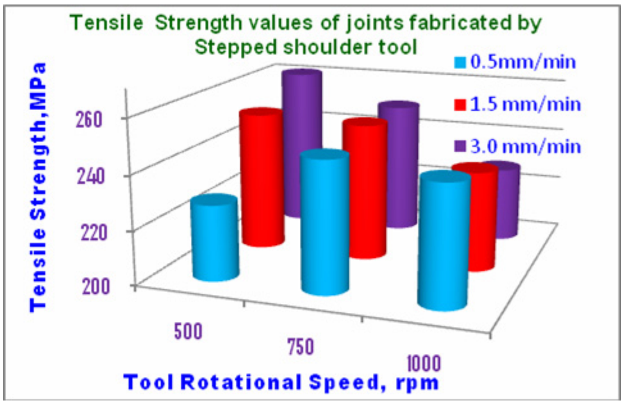

Figure 6. Graphical illustration of the tensile strength of the wrought AZ80A Mg alloy joints fabricated using stepped cylindrical shoulder tool at different combinations of traversing speed and rotational speeds of the FSW tool

At a 500 rpm FSW tool rotational speed, the tensile strength of the fabricated AZ80A Mg alloy joints are found to decrease at 1.5mm/min & then again increases with increase in the traversing speed (i.e., at 3.0 mm/min). At the same time, the joints produced at combination of 0.5 mm/min and 500 rpm exhibits the highest tensile strength values when compared with that of the other two combinations. At a 750 rpm FSW tool rotational speed, the tensile strength of the fabricated AZ80A Mg alloy joints are found to continuously increase with the increase in the traversing speeds and the lowest tensile strength for this set is exhibited by the 750 rpm – 0.5 mm/min combination. For 1000 rpm FSW tool rotational speed, the tensile strength of the joints are found to decrease with the increase in the traversing speed (1.5 mm/min), but further increase in the traversing speed (3.0 mm/min) increases the tensile strength of the fabricated joints. And the combination of 1000 rpm – 0.5 mm.min exhibits the highest values if the tensile strength, when compared with that of other two 1000 rpm & feed rate combinations.

4.3 Analysis of the optical micrographs of the fabricated joints

The above observations, adds weightage to the fact that the strain hardening effects are common phenomenon encountered at low speeds of rotation of the FSW tool, due to the generation of dislocations in grain structures, leading to the piling up of the slipped planes [62–64]. The optical micrograph image of the AZ80A Mg alloy joint fabricated at a combination of traversing speed of 0.5 mm.min and speed of rotation of the FSW tool of 500 rpm is illustrated in the Figure 7(a). The twinned grains presence is clearly visible in this optical micrographical image. But at the same time, it can be seen that this effect of grain twinning is considerably reduced in the case of the joints fabricated at a FSW process parameter combination of 0.5 mm/min and 1000 rpm, as seen in the Figure 7 (b).

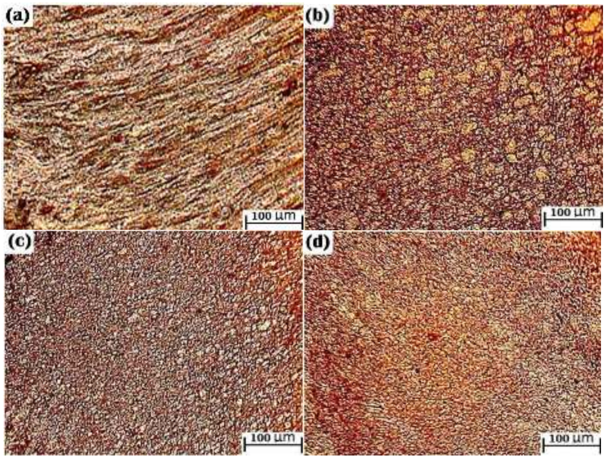

Figure 7. Optical micrographical images of the AZ80A Mg alloy joints fabricated using the stepless cylindrical shoulder tool at a process parameter combination of (a) 0.5 mm/min – 500 rpm; (b) 0.5 mm/min – 1000 rpm and using the stepped cylindrical shoulder tool at a process parameter combination of (c) 3.0 mm/min – 500 rpm (with less than 8 μm grain sizes) and (d) 3.0 mm /min – 1000 rpm (with less than 5 μm grain sizes)

The readings & observations illustrated in the Figure 6 describes us that, the stepped cylindrical shoulder tool has produced sound quality joints with appreciable tensile strength values at combinations of higher traversing feeds and low values of rotational speeds of the FSW tool. It can be seen that, the tensile strength of the AZ80A Mg alloy joints fabricated using the stepped cylindrical shoulder tool increases with the simultaneous raise in the values of the traversing speed along with the combination of low rotational speeds. On the other hand, at 1000 rpm (i.e., at larger FSW tool rotational speeds), the tensile strength of the AZ80A Mg alloy joints fabricated using the stepped cylindrical shoulder tool seems to decrease with simultaneous increase in the traversing speed.

These observations are due to the fact that, at low values of speeds of rotation of the FSW tool, the amount of heat produced due to the frictional heat would not be sufficient enough to create uniform flow of the materials and during faster traversing speeds (i.e., at higher rates of feed), the time period required for grain deformation is not enough [65–67]. On the contrary, at larger values of speeds of rotation of the FSW tool, increase in rates of feed, will lead to the fine refinement of grains in the nugget zone. This is due to the fact that, higher tool rotational speeds generates the ideal amount of frictional heat leading to uniform flow of metals and will eventually result in rapid & uniform solidification of the grains in the nugget zone at higher traversing feeds , which is evidently illustrated in the Figure 7 (c) and (d).

It can be understood that, the size of the grains in the nugget zone have played a vital role in determining the strength of the AZ80A joints fabricated using the stepped cylindrical shoulder tool. The internment time taken for the plasticized stirred material created by the stirring action of the stepped cylindrical shoulder seems to have influenced the softening rate of the plasticized material, in the nugget zone. This rate of softening followed by eventual cooling has led to the recrystallization process and formation of fine refined grains in the nugget zone. This internment time period is very much less with that of the stirring action created by the stepless cylindrical shoulder tool, due to the reason that, the stepped cylindrical shoulder has performed the function of preventing the plasticized material, being getting escaped from the joint surface area and the stepless cylindrical shoulder tool, due to its design geometry cannot perform this function in a required manner. This is one of the most important reason for formation of fine refined grains in the nugget zone of the AZ80A Mg alloy joints fabricated using the stepped cylindrical shoulder tool.

4.4 Losses due to wear

The combined effect & influence of the two different process parameters of the FSW technique on the wear losses of the wrought AZ80A Mg alloy joints fabricated using the stepless cylindrical shoulder tool and the stepped cylindrical shoulder tool are graphically illustrated in the Figure 8 & 9.

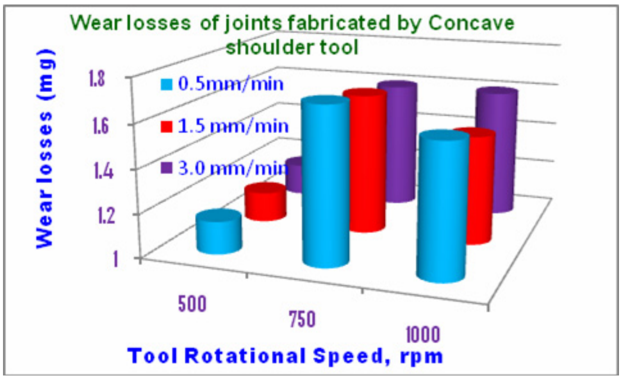

Figure 8. Graphical illustration of the wear losses of the wrought AZ80A Mg alloy joints fabricated using stepless cylindrical shoulder tool at different combinations of traversing speed and rotational speeds of the FSW tool

From the Figure 8, it can be seen that the losses due to wear were found to be obtained at higher values of the tensile strength. This can be understood clearly by comparing the Figure 5 and 8. It can be found that, at smaller speeds of rotation of the FSW tool (i.e., 500 rpm), larger tensile strength values were obtained. Likewise, losses due to wear were also found to be minimum at this FSW tool rotational speed (500 rpm). The losses due to wear were found to increase with increase in speeds of rotation of the FSW tool (i.e., from 500 rpm to 750 rpm and 1000 rpm).

From the Figure 9, it is evident that the traversing speed (i.e., rate of feed) is found to dominate the losses due to wear on the AZ80A Mg alloy joints fabricated using the stepped cylindrical shoulder tool. At 500 rpm, i.e., at smaller values of the speeds of rotation of the FSW tool, larger values of the traversing speed (3.0 mm/min) have yielded the minimum losses due to wear and smaller values of the traversing speed (0.5 mm/min) have yielded the maximum losses due to wear.

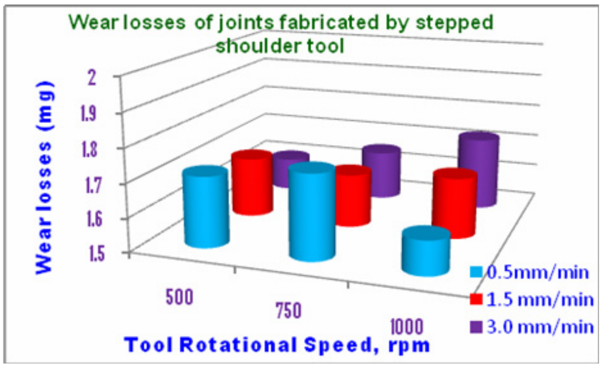

Figure 9. Graphical illustration of the wear losses of the wrought AZ80A Mg alloy joints fabricated using stepped cylindrical shoulder tool at different combinations of traversing speed and rotational speeds of the FSW tool

At the same time, this impact is completely inverse in the case of higher values of the speeds of rotation of the FSW tool (i.3., at 1000 rpm). At this 1000 rpm, the smaller traversing speed values (0.5 mm/min) have yielded the minimum losses due to wear and higher traversing speed values (3.0 mm/min) have yielded the maximum losses due to wear.

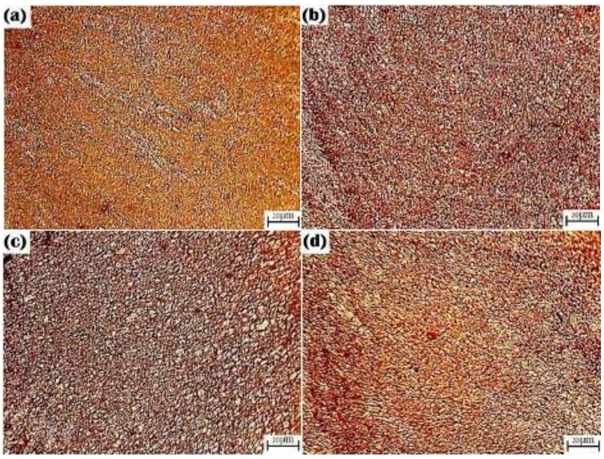

Figure 10. Optical micrograph images of the wrought AZ80A Mg alloy joints fabricated using stepped cylindrical shoulder tool at different combinations of (a) 0.5 mm/min – 500 rpm; (b) 1.5 mm/min – 500 rpm; (c) 0.5 mm/min – 1000 rpm and (b) 1.5 mm/min – 1000 rpm

This phenomenon can be understood clearly by analysing the nugget zones of the wrought AZ80A Mg alloy joints fabricated at different combinations of speeds of rotation of the tool and traversing speed using two different tool geometries, namely, stepless cylindrical shoulder tool and stepped cylindrical shoulder tool. The joints possessing fine sized refined grains in their nugget zone have been found to exhibit higher losses due to wear when compared to that of the joints having large sized grains in their nugget zone. The reason for this is very much identical to that of the reasons discussed for the tensile strength values. Figure 10 shows in detail, the optical micrograph images of the nugget zone of the joints fabricated using stepped cylindrical shoulder tool at different combinations of the speeds of rotation of the tool and traversing speed, which are advocating this observation. Yet, the losses due to wear is found to be more for the AZ80A Mg alloy joints fabricated by the stepped cylindrical shoulder tool when compared with that of the joints generated using the stepless cylindrical shoulder tool.

4.5 Rate of Corrosion

The rates of corrosion of the wrought AZ80A Mg alloy joints fabricated at different combinations of speeds of rotation of the tool and traversing speed using two different tool geometries, namely, stepless cylindrical shoulder tool and stepped cylindrical shoulder tool are graphically illustrated in the Figure 11 and 12 respectively.

In majority of the AZ80A Mg alloy joints fabricated using FSW process, the rate of corrosion is found to be larger, when compared with that of the parent metal. The major reason for the decline in the resistance towards of the fabricated AZ80A Mg alloy joints is the refinement of the grains, which have taken place in the nugget zone, as a result of FSW process. It is a well known fact that, the grain boundaries have an unstable type of configuration when compared to that of their respective lattice structure.

Moreover, the chemical reactivitiy of these grain boundaries is very much higher and they are regions of higher energy [68, 69]. As a result, these grain boundaries are the common spots susceptible to the reactions of corrosion, when compared to that of the individual faces of grain.

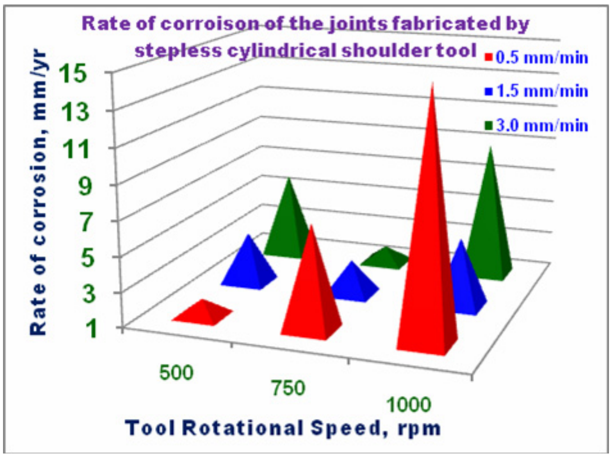

Figure 11. Graphical illustration of the rate of corrosion of the wrought AZ80A Mg alloy joints fabricated using stepless cylindrical shoulder tool at different combinations of traversing speed and rotational speeds of the FSW tool

Similarly, during the etching of a pure metal, the grain boundaries are very much invulnerable to the attack related to corrosion, when compared with that of the individual grains [70].

This low resistance of the grain boundaries to the corrosion attack is mainly due to the weaker binding of the atoms, making them more dissolvable in nature, than the atoms present in the interior surface of the individual grains. Boundaries of twin nature, emanating dislocations, boundaries of subgrains etc are examples of regions having very poor resistance to corrosion attacks [71, 72]. In other words, it can be understood that, if there is generation of fine refined grain boundaries & structures in the nugget zone of the joints fabricated using the FSW process, the joints would be prone to the corrosion attacks very easily, when compared to that of the base metal. By comparing the datas illustrated in the Figure 11 & 12, we can observe that, the AZ80A Mg alloy joints fabricated using a stepped cylindrical shoulder tool exhibits higher rates of corrosion when compared to that of the AZ80A Mg alloy joints fabricated using a stepless cylindrical shoulder tool.

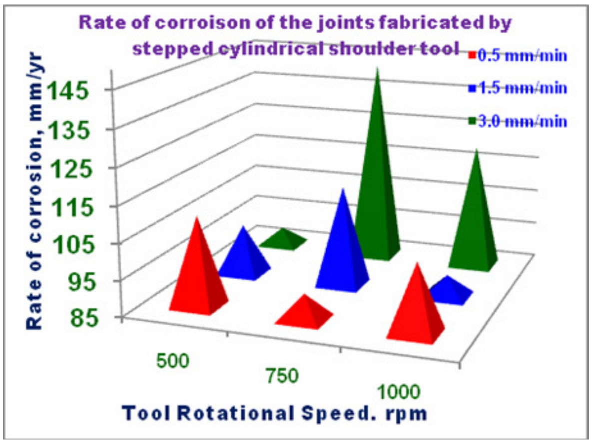

Figure 12. Graphical illustration of the rate of corrosion of the wrought AZ80A Mg alloy joints fabricated using stepped cylindrical shoulder tool at different combinations of traversing speed and rotational speeds of the FSW tool

5. CONCLUSION

In this experimental work, a detailed investigation was carried out to understand the role of the geometry of the FSW tool in determining the tensile strength, losses due to wear, rates of corrosion of the fabricated AZ80A Mg alloy joints, by employing two different FSW tool geometries namely stepless cylindrical shoulder tool and stepped cylindrical shoulder tool, under different combinations of FSW process parameters, namely speeds of rotation of the tool and traversing speed. The recorded observations, experimental results generated in the present investigation allow us to derive the below mentioned conclusions:

- Stepped cylindrical shoulder tool has produced sound quality joints with appreciable tensile strength values at combinations of higher traversing feeds and low values of rotational speeds of the FSW tool.
- The size of the grains in the nugget zone and the for–mation of the fine refined grain structures have played a vital role in determining the strength of the AZ80A joints fabricated using the stepped cylindrical shoul–der tool.
- The joints possessing fine sized refined grains in their nugget zone have been found to exhibit higher losses due to wear when compared to that of the joints having large sized grains in their nugget zone
- The losses due to wear are found to be more for the AZ80A Mg alloy joints fabricated by the stepped cylindrical shoulder tool when compared with that of the joints generated using the stepless cylindrical shoulder tool
- In majority of the AZ80A Mg alloy joints fabricated using FSW process, irrespective of the employed different tool geometry, the rate of corrosion is found to be larger, when compared with that of the parent metal.
- AZ80A Mg alloy joints fabricated using a stepped cylindrical shoulder tool exhibits higher rates of corrosion when compared to that of the AZ80A Mg alloy joints fabricated using a stepless cylindrical shoulder tool

ACKNOWLEDGEMENT

The authors gratefully thank the Management and Mechanical Engg Dept., S.A Engineering College, Chennai, India for providing the welding equipment facilities. The authors wish to express thanks to All India Council for Technical Education (AICTE) Govt. of INDIA, funded project (Grant No. 8023/RID /RPS/037/2011-12) for sponsoring FSW machine.

REFERENCES

[1] Ren, S.R., Ma, Z.Y. and Chen, L.Q.: Effect of welding parameters on tensile properties and fracture behavior of friction stir welded Al–Mg–Si alloy. Scripta Mater, Vol. 56, pp. 69–72, 2007.

[2] Baris Ishak Sipcikoglu, Burcu Yigit, Hüseyin Oflaz, Zeynep Parlar, Vedat Temiz: The Investigation of Friction and Wear Characteristic of Cast Iron against Manganese Phosphate Coated and Austempered Compressor Crankshaft. Vol.43, pp. 186 – 190, 2015.

[3] Sevvel, P. and Jaiganesh, V.: Impact of process parameters during friction stir welding of AZ80A Mg alloy, Science and Technology of Welding and Joining, Vol. 21 (2), pp. 83–90, 2016

[4] Jaiganesh, V., Yokesh Kumar, B., Sevvel, P. and Balaji, A.J.: Optimization of process parameters on commercial mild steel using taguchi technique", International Journal of Engineering & Technology, Vol. 7, pp. 138–142, 2018.

[5] Peel, M., Steuwer, A., Preuss, M. and Withers, P.J.: Microstructure, mechanical properties and residual stresses as a function of welding speed in aluminium AA5083 friction stir welds. Acta Mater, Vol. 51, pp. 4791 – 4801, 2003

[6] Stephan Thangaiah, I.S., Sevvel, P., Satheesh, C. and Jaiganesh, V.: Investigation on the Impingement of Parameters of FSW Process on the Microstructural Evolution & Mechanical Properties of AZ80A Mg Alloy Joints, FME Transactions, Vol.46 (1), pp. 23–32, 2018.

[7] Zeng, R., Dietzel, W., Zettler, R., Chen, J. and Kainer, K.U.: Microstructure evolution and tensile properties of friction-stir-welded AM50 magnesium alloy, Transactions of Nonferrous Metals Society of China, Vol. 18, pp. S76 – S80, 2008.

[8] Sevvel, P., Jaiganesh, V.: Investigation on evolu–tion of microstructures and characterization during

FSW of AZ80A Mg alloy, Archives of Metallurgy and Materials, Vol. 62 (3), pp. 1779–1785, 2017

[9] Akinlabi, E.T., Els-Botes, A. and Lombard, H.: Effect of tool displacement on defect formation in friction stir welding of aluminium and copper, Proceedings of the 8th International Friction Stir Welding Symposium, Hamburg, Germany, pp 76 – 78, 2010.

[10] Sevvel, P. and Jaiganesh, V.: Influence of the arrangement of materials and microstructural analysis during FSW of AZ80A & AZ91C Mg alloys, Archives of Metallurgy and Materials, Vol. 62 (3), pp. 1795–1801, 2017.

[11] Stephan Thangaiah, I.S., Sevvel, P., Manova Raja Singh, S., Venkataraman, S.R. and Satheesh, C.: Design and Investigational Flow Simulation of Power Generation Using Shrouded Wind Turbine, Journal of Advanced Research in Dynamical & Control Systems, Vol. 9 (8), pp. 117–124, 2017.

[12] Mukai, T., Yamanoi, M., Watanabe, H., Ishikawa, K. and Higashi, K.: Effect of grain refinement on tensile ductility in ZK60 magnesium alloy under dynamic loading, Mater Trans, Vol. 42, pp. 1177–1181, 2001.

[13] Naseer Ahmad, Shahid Kamal, Zulfiqar Ali Raza, Tanveer Hussain, and Faiza Anwar: Multi-response optimization in the development of oleo-hydrophobic cotton fabric using Taguchi based grey relational analysis, Applied Surface Science, Vol. 367 (30), pp. 370–381, 2016.

[14] Sevvel, P. and Jaiganesh, V.: A detailed investigation on the role of different Tool Geometry in Friction Stir Welding of various Metals & their Alloys, Proceedings of the International Colloquium on Materials, Manufacturing & Metrology–ICMMM, IIT Madras, pp. 8–9, 2014.

[15] Jaiganesh, V. and Sevvel, P.: Effect of Process Parameters in the Microstructural Characteristics and Mechanical Properties of AZ80A Mg Alloy during Friction Stir Welding, Transactions of the Indian Institute of Metals, Vol. 68, pp. 99–104, 2015.

[16] Choi, D.H., Ahn, B.W., Kim, S.K., Yeon, Y.M., Kim, Y.J. and Park, S.K.: Microstructure evaluation of friction stir welded AZ91 with CaO Mg alloy, Material Transactions, Vol. 52, pp. 802–805, 2011.

[17] Sevvel, P. and Jaiganesh, V.: Experimental Investigation on the impact of the Tool Material & geometry in joining of Al 63400 Alloy using Friction Stir Welding Process, Applied Mechanics and Materials, Vol. 592-594, pp. 312–315, 2014

[18] Aleksandar Todi. C., Dejan Cikara, Tomislav Todic, Branko Pejovic, Ivica Camagic and Vukoje Vukojevic: The Influence of the Vanadium Content on the Toughness and Hardness of Wear resistant High-alloyed Cr-Mo Steel. Vol.45, pp. 130 – 134, 2017.

[19] Jaiganesh, V., Satheesh, C., Manova Raja Singh, S., Sevvel, P. and Balaji, A.J.: Optimization ofProcess Parameters on Commercial Mild Steel Using Regression and Principal Component Analysis", International Journal of Pure and Applied Mathematics, Vol. 117, pp. 741–758, 2017)

[20] Nandan, R., DebRoy, T. and Bhadeshia, H.K.D.H.: Recent trends in friction stir welding process, weldment structure and properties, Prog. Mater. Sci., Vol. 53, pp. 980–1023, 2003.

[21] Prakash Kumar Sahu, Sukhomay Pal: Multi-response optimization of process parameters in friction stir welded AM20 magnesium alloy by Taguchi grey relational analysis, Journal of Magnesium and Alloys, Vol. 3 (1), pp. 36–46, 2015.

[22] Sevvel, P. and Jaiganesh, V.: Effect of Tool Shoulder Diameter to Plate Thickness Ratio on Mechanical Properties and Nugget Zone Characteristics During FSW of Dissimilar Mg Alloys, Transactions of the Indian Institute of Metals, Vol. 68 (S1), pp. 41–46, 2015.

[23] Stephan Thangaiah, I.S., Sevvel, P., Jaiganesh, V. and Satheesh, C.: Experimental Review on Joining of High Strength Alloys under the Influence of Tool Material&Geometry Using FSW Process, Journal of Advanced Research in Dynamical & Control Systems, Vol. 9 (5), pp. 82–90, 2017.

[24] Cao, X. and Jahazi, M.: Effect of tool rotational speed and probe length on lap joint quality of a friction stir welded magnesium alloy, Mater Des, Vol. 32, pp. 1 – 11, 2011.

[25] Nelabhotla, D.M., Jayaraman, T.V., Asghara, K and Das. D.: The optimization of chemical mechanical planarization process-parameters of c-plane gallium-nitride using Taguchi method and grey relational analysis, Materials & Design, Vol. 104 (15), pp. 392–403, 2016.

[26] Sevvel, P. and Jaiganesh, V.: An detailed examination on the future prospects of friction stir welding – a green technology, Proceedings of Second International Conference on Advances in Industrial Engineering Applications – ICAIEA, Anna University, India, pp. 275–280, 2014.

[27] Stephan Thangaiah, I.S., Sevvel, P., Satheesh, C., Manova Raja Singh, S. and Jaiganesh, V.: "Numerical and Statistical Analysis for Betterment of Mechanical Properties During FSW of AZ31B Mg Alloys", International Journal of Pure and Applied Mathematics, Vol. 117 (7), pp. 359–369, 2017.

[28] Wen, W., Kuaishe, W., Qiang, G. and Nan, W.: Effect of Friction Stir Processing on Microstructure and Mechanical Properties of Cast AZ31 Mg Alloy, Rare Met. Mater. Eng., Vol. 41, pp.1522–1526, 2012.

[29] Chowdhury, S.M., Chen, D.L., Bhole, S.D. and Cao, X.: Effect of pin tool thread orientation on fatigue strength of friction stir welded AZ31B-H24 Mg butt joints, Procedia Eng., Vol. 2, pp. 825–833, 2010.

[30] Sevvel, P., Stephan Thangaiah, I.S., Mars Mukesh, S. and Mohammed Anif, G.: Laboratory Scale

Testing of Thermoelectric Regenerative Braking System, International Journal of Vehicle Structures & Systems, Vol. 7(4), 157–160, 2015.

[31] Jaiganesh, V., Sevvel, P. & NagarajanP.K.: Impact of Tool Pin Geometry and Optimized Process Parameters on Mechanical Properties of Friction Stir Welded AZ80A Mg Alloy, Materials Science Forum, Vol. 866, pp. 151-155, 2016.

[32] Commin, L., Dumont, M., Masse, J.E. and Barrallier, L.: Friction stir welding of AZ31 magnesium alloy rolled sheets: Influence of processing parameters, Acta Mater, Vol. 57, pp. 326–334, 2009.

[33] Padmanaban, G. and Balasubramanian, V.: An experimental investigation on friction stir welding of AZ31B magnesium alloy, International Journal of Advanced Manufacturing Technology, Vol. 49, pp. 111–121, 2010.

[34] Sevvel, P. and Jaiganesh, V.: Effect of Tool Shoulder Diameter to Plate Thickness Ratio on Mechanical Properties and Nugget Zone Characteristics During FSW of Dissimilar Mg Alloys, Transactions of the Indian Institute of Metals, Vol. 68 (S1), pp. 41–46, 2015.

[35] Hattingh, D. G., Blignault, C., Van Niekerk, T. I. and James, M. N.: Characterization of the influences of FSW tool geometry on welding forces and weld tensile strength using an instrumented tool, Journal of Materials Processing Technology, Vol. 203 (1–3), pp. 46–57, 2008.

[36] Jaiganesh, V., Srinivasan, D. and Sevvel, P.: Optimization of process parameters on friction stir weldingof 2014 aluminum alloy plates", International Journal of Engineering & Technology,Vol. 7, pp. 09–11, 2018.

[37] Sevvel, P., Sunil Solomon, R., Mahadevan, S. and Shahul Hamid Khan: Optimization of Process Parameters and Evaluation of Response Characteristics in EDM Using Taguchi and ANOVA Method – A Review, Journal of Advanced Research in Dynamical & Control Systems, Vol. 9 (5), pp. 91–100, 2017

[38] Surendran, R., Manibharathi, N. and Kumaravel, A.: Wear Properties Enhancement of Aluminium Alloy with Addition of Nano Alumina. FME Transactions. Vol.45, pp.83 – 88, 2017.

[39] Yu, S., Chen, X., Huang, Z. and Liu, Y.: Microstructure and mechanical properties of friction stir welding of AZ31B Mg alloy added with cerium, Journal of Rare Earths, Vol. 28, pp. 316–320, 2010.

[40] Sevvel, P. and Jaiganesh, V.: Impact of Tool Profile on Mechanical Properties of AZ31B Mg Alloy during FSW Using Optimized Parameters, FME Transactions, Vol. 44(1), pp. 43–49, 2016.

[41] Stephan Thangaiah, I.S. and Sevvel, P.: Conceptual Design of Innovative Eco-Friendly Windmill, Applied Mechanics and Materials, Vol. 852, pp. 531–538, 2016.

[42] Masayuki A., Nakata K.: Dissimilar metal joining of ZK60 magnesium alloy and titanium by friction stir welding, Materials Science and Engineering: B, Vol. 177, pp. 543–548, 2012

[43] Sevvel, P. and Jaiganesh, V.: Characterization of mechanical properties and microstructural analysis of friction stir welded AZ31B Mg alloy thorough optimized process parameters, Procedia Engineering, Vol. 97, pp. 741–751, 2015.

[44] Y. Templeman, G. Ben Hamu, L. Meshi: Friction stir welded AM50 and AZ31 Mg alloys: Microstructural evolution and improved corrosion resistance, Materials Characterization, Vol. 126, pp. 86 – 95, 2017.

[45] Sevvel, P. and Jaiganesh, V.: Effects of axial force on the mechanical properties of AZ80A Mg alloy during friction stir welding, Materials Today Proceedings, Vol.4 (2), Part A, pp. 1312–1320, 2017.

[46] Zhe Liu, Renlong Xina, XiaWu, DejiaLiua and QingLiu.: Improvement in the strength of friction-stir-welded ZK60 alloys via post-weld compression and aging treatment, Materials Science and Engineering: A, Vol. 712, pp. 493–501, 2018.

[47] Sevvel, P. and Jaiganesh, V.: Improving the mechanical properties of friction stir welded AZ31B magnesium alloy flat plates through axial force investigation, Applied Mechanics and Materials, Vol. 591, pp. 11–14, 2014.

[48] Babua, J., Anjaiah, M. and Anoop Mathew: Experimental studies on Friction stir processing of AZ31 Magnesium alloy, Materials Today Proceedings, Vol. 5, pp. 4515–4522, 2018.

[49] Dhanapal, A., Rajendra Boopathy, S. And Balasubramanian, V.: Corrosion behaviour of friction stir welded AZ61A magnesium alloy welds immersed in NaCl solutions, Transactions of Nonferrous Metals Society of China, Vol. 22, pp.793–802, 2012.

[50] Xu, R.Z., Ni, D.R., Yang, Q., Xiao, B.L., Liu, C.Z. and Ma, Z.Y.: Influencing mechanism of Al-containing Zn coating on interfacial microstructure and mechanical properties of friction stir spot welded Mg–steel joint, Materials Characterization, Vol. 140, pp. 197 – 206, 2018.

[51] Kim, M.S., Jung, J.Y., Song, Y.M. and Cho, S.H.: Simulation of microtexture developments in the stir zone of friction stir-welded AZ31 Mg alloys, International Journal of Plasticity, Vol. 94, pp. 24 – 43, 2017.

[52] Sevvel, P. and Jaiganesh, V.: Experimental Investigation on the impact of the Tool Material & geometry in joining of Al 63400 Alloy using Friction Stir Welding Process, Applied Mechanics and Materials, Vol. 592–594, pp.312–315, 2014.

[53] Sunil Solomon, R., Sevvel, P., Jaiganesh, V. and Satheesh, C.: An Investigational Review on Influence of Performance Parameters during Wire Electrical Discharge Machining of Various Grades of Steels, Journal of Advanced Research in

Dynamical & Control Systems, Vol. 9 (5), pp. 101–109, 2017.

[54] LakshmanaPrasad, B., Neelaiah, G., Gopi Krishna, M., Ramana, S.V.V., Sai Prakash, K., Sarika, G., Pradeep Kumar Reddy, G., Ravikumar Dumpal and Ratna Sunil, B.: Joining of AZ91 Mg alloy and Al6063 alloy sheets by friction stir welding, Journal of Magnesium and Alloys, *In press*, 2018.

[55] Luo, Z.A., Xie, G.M., Ma, Z.Y., Wang, G.L. and Wang, G.D.: Effect of Yttrium Addition on Microstructural Characteristics and Superplastic Behavior of Friction Stir Processed ZK60 Alloy, Journal of Materials Science & Technology, Vol. 29, 2013, pp. 1116 – 1122, 2013.

[56] Jaiganesh, V. and Sevvel, P.: Effect of Process Parameters during Friction Stir Welding of Al 6063 Alloy, Advanced Materials Research, Vol. 985, pp. 604–607, 2014.

[57] Sevvel, P., NirmalKannan, V., Parameshwaran, S. and Mohan Kumar, T.: Proof of Concept Fabrication of Multi-axis Pneumatic Mechanism for Dumpers, International Journal of Vehicle Structures & Systems, Vol. 7(4), 172–174, 2015.

[58] Mengran Zhou, Yoshiaki Morisada, Hidetoshi Fujii and Takeshi Ishikaw: Mechanical properties optimization of AZX612-Mg alloy joint by double-sided friction stir welding, Journal of Materials Processing Technology, Vol. 254, pp. 91–99, 2018.

[59] Liu, D., Xin, R., Sun, L., Zhou, Z., and Liu, Q.: Influence of sampling design on tensile properties and fracture behavior of friction stir welded magnesium alloys, Materials Science & Engineering A, Vol. 576, pp. 207–216, 2013.

[60] Booth, D.P.P., Starink, M.J. and Sinclair, I.: Analysis of local microstructure and hardness of 13 mm gauge 2024-T351 AA friction stir welds. Mater Sci Technol, Vol. 23, pp. 276–84, 2007.

[61] Sevvel, P. and Jaiganesh, V.: Influence of tool profile during FSW of Mg alloy using optimized parameters", International Journal of Applied Engineering Research, Vol. 10 (50), pp. 159–164, 2015.

[62] Kumar, S. and Pandey, G. K. N.: Application of Taguchi Method for Optimization of Friction Stir Welding Process Parameters to Joining of Al Alloy, International Journal of Advanced Materials Manufacturing & Characterization, Vol. 3(1), pp. 253-258, 2013.

[63] Kumar, K. and Satish Kalidas, V.: The role of friction stir welding tool on material flow and weld formation, Materials Science and Engineering A, Vol. 485, pp. 367–374, 2008.

[64] Sevvel, P. and Jaiganesh, V.: Friction stir welding: process parameters, defects & experimental modeling, International Journal of Applied Engineering Research, Vol. 10 (68), pp. 518–522, 2015.

[65] Mordike, B.L. and Ebert, T.: Magnesium: properties – applications – potential, Materials Science Engineering A, Vol. 27, pp. 37 – 45, 2000.

[66] Sevvel, P. and Jaiganesh, V.: Improving the mechanical properties of FSW AZ31B magnesium alloy joints through axial force investigation, Applied Mechanics and Materials, Vol. 591, pp.11–14, 2014.

[67] Xueqi Lv, ChuanSong, WuChunliangYang and Padhy, G.K.: Weld microstructure and mechanical properties in ultrasonic enhanced friction stir welding of Al alloy to Mg alloy, Journal of Materials Processing Technology, Vol. 254, pp. 144–157, 2018.

[68] Sevvel, P. and Jaiganesh, V.: Impact of Tool Profile on Mechanical Properties of AZ31B Mg Alloy during FSW Using Optimized Parameters. FME Transactions, Vol. 44, pp. 43–49, 2016.

[69] Liu, D.J., Xin, R.L., Li, Z.Y., Liu, Z., Zheng, X. and Liu. Q.: The activation of twinning and texture evolution during bending of friction stir welded magnesium alloys, Materials Science and Engineering: A, Vol. 646, pp. 145–153, 2015.

[70] He, W.J., Zheng, L., Xin, R.L. and Liu, Q.: Microstructure-based modeling of tensile deformation of a friction stir welded AZ31 Mg alloy, Materials Science and Engineering: A, Vol.687, pp. 63–72, 2017.

[71] Hong, S.G., Park, S.H. and Lee, C.S.: Role of {10-12} twinning characteristics in the deformation behavior of a polycrystalline magnesium alloy, Acta Materialia, Vol. 58, pp. 5873–5885, 2010.

[72] Shang, Q., Ni, D.R. Xue, P., Xiao, B.L. and Ma, Z.Y.: Evolution of local texture and its effect on mechanical properties and fracture bahavior of friction stir welded joint of extruded Mg-3Al-1Zn alloy, Materials Characterization, Vol. 128, pp.14–22, 2017.

ЕКСПЕРИМЕНТАЛНО ИСТРАЖИВАЊЕ УЛОГЕ ГЕОМЕТРИЈЕ АЛАТА КОД ОДРЕЂИВАЊА ЧВРСТОЋЕ И ИСПРАВНОСТИ СПОЈЕВА ОД КОВАНЕ ЛЕГУРЕ ТИПА Az80a Mg У ТОКУ ПРОЦЕСА ЗАВАРИВАЊА ТРЕЊЕМ СА АЛАТОМ

С. Тангаиах И С, Севел П, Сатеш Ц, Махадеван С.

Истражује се утицај геометрије алата при заваривању трењем са алатом на затезну чврстоћу, отпорност на корозију и брзину хабања код спојева од коване легуре типа Az80a Mg. Код заваривања трењем са алатом коришћен је алат са две различите геометрије: са степенастим цилиндричним наставком и без степенастог цилиндричног наставка при различитим комбинацијама брзине ротације и брзине пролаза алата. Истраживање је обухватило и затезну чврстоћу, губитак услед трења и отпорност на корозију код произведених спојева. Утврђено је да спојеви са степенстим цилиндричним наставком имају веће вредности затезне чврстоће код комбинације већег броја пролаза алата и мањих

вредности ротирајуће брзине. Истовремено је нађено да спојеви који имају ситнија и финија зрна у зони зрна већих димензија (грумена) имају веће губитке услед трења.