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Investigation on the Impingement of Parameters of FSW Process on the Microstructural Evolution & Mechanical Properties of AZ80A Mg Alloy Joints

An investigation was conducted to find out the impact of the speed of rotation and pin profile of FSW tool on the microstructural characterisation & mechanical properties AZ80A magnesium alloy joints produced using FSW technique. FSW tools with completely three distinct pin profiles were at discrete speeds of rotation. The fabricated joints & their fracture surfaces obtained during tensile tests were subjected to microstructural & scanning electron microscopic (SEM) investigations. Comprehensive observations & investigational measurements were also carried out regarding the wear & hardness of the fabricated joints. The joints fabricated at 750 rpm using the taper cylindrical pin profiled tool exhibited high quality joints with better tensile strength, higher microhardness values and minimum wear.

Keywords: Friction Stir Welding, AZ80A Mg alloy, Tool rotational speed, Tool pin profile, mechanical properties

1. INTRODUCTION

Since they are one of the lightest materials under the metallic category, Mg alloys provide an extensive potential for weight saving in automotive industries. Mg sheets can be used in the fabrication of automobile body parts including semi-structural and non-structural applications [1,2]. Conventional welding processes are unsuitable for fabricating alloys of Mg due to their high requirement of energy and easy tendency for corrosion towards copper electrode. Friction Stir Welding (FSW), formulated by TWI (The Welding Institute), can present higher potential for magnesium alloys [3–5], because it utilizes a non-consumable rotating tool for producing heat from friction, facilitating plastic deformation at nugget zone. It has also been observed that the aluminium lap joints using FSW are found to be stronger than the comparable resistance spot welded and riveted lap joints [6, 7]. High quality of welds, cheaper price, ability to weld various types of hard-to-weld metals & non metals is yet another reason for choosing FSW to join AZ80A Mg alloys [8 – 12].

2. MATERIALS AND METHODOLOGY

2.1 Base material

Magnesium alloy is taken as the base material in this present investigation. AZ80A Mg alloy plates were obtained in the required dimensions (150 mm X 50 mm X 5 mm) by machining the rolled plates of AZ80A Mg alloy. Table 1 describes in detail, the mechanical prop-

erties and chemical compositions of the base metal used in this investigation, namely AZ80A wrought Mg alloy. Joining of the two flat plates of AZ80A Mg alloy using FSW technique was fabricated in the form of butt type. The optical, scanning electron microscopic (SEM) and energy dispersive spectrometric (EDS) micrographs of the base metal i.e., AZ80A Mg alloy are illustrated in Figure 1 (a), (b) and (c) respectively. The presence of coarse grain structure together with a reasonable amount of sub-grains can be seen in the optical microscopic image of the base metal (Fig. 1a).

Existence of unevenly distributed Al₁₂Mg₁₇ coarse intermetallic compound structures can be observed along the entire coarse grains from the SEM micrographs (Fig. 1b) of the base metal. EDS analysis (Fig.1c) shows composition of base metal and estimates the weight percentage of elements in a quantitative manner.

Table 1. Mechanical properties & chemical composition of AZ80A Mg alloy

Composition wt %							
Al	Cu	Zn	Mn	Ni	Si	Fe	Mg
7.8	.05	0.7	0.3	.005	.1	.005	balance
Mechanical Properties							
Yield Strength		Tensile strength		Elongation			
193 MPa		290 MPa		8 %			

A semi automatic FSW machine (10kW; 1500 rpm; 5 Ton) as shown in the Fig.2 was used in this investigation. Cleaning of the base plates of AZ80A Mg alloy (before FSW process) was done by employing acetone to eradicate any type of contamination of the weldment surface.

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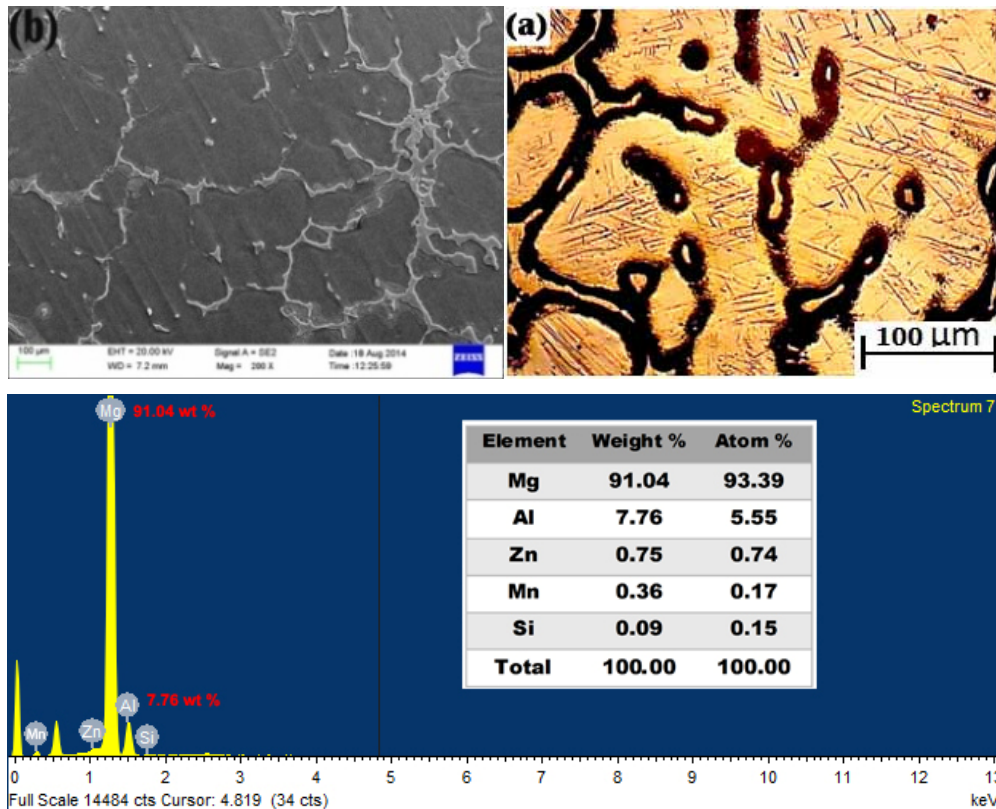


Fig. 1 (a) AZ80A Mg alloy – Optical micrograph image , (b) AZ80A Mg alloy – SEM image and (c) EDS analysis of



Fig. 2. Photographic view of FSW machine

The FSW of the Mg alloys was performed by firmly securing the flat plates with the help of specially designed fixtures. The tool is fitted in the tool holder in such a way that feed can be given at a desired traverse rate along the joint regions of the two AZ80A alloy plates to be joined together.

2.2 Tool material and geometry

The selection of the material for the FSW tool usually depends on the work piece material to be welded [13–15]. Properties including hot hardness, greater life time and high strength etc are some of the unique properties of HSS (high speed steel) which makes it suitable as the FSW tool material for this experimental investigation. Non-

consumable tool made of M35 grade High Speed Steel (HSS) is chosen as tool material in this investigation.



Figure 3. Photographic (a) front view and (b) tilted top view of the three distinct pin profiles of M35 HSS grade tools

2.3 FSW process parameters

FSW tools with completely three distinct pin profiles, specifically, taper cylindrical, threaded cylindrical and straight cylindrical, were used in this investigation. The divergent photographic images of these three distinct pin profiles of the FSW tool employed in this investigation are illustrated in Figure.3 (a). The three tools with different pin profiles have a total length of 50mm along with an inner shoulder of 15mm diameter and 20mm (diameter) outside shoulder. The length of the inner shoulder is 10mm. D/d ratio of all these distinct pin profiles is 3.

Table 2. Different combinations of parameters adopted for FSW of AZ80A Mg alloy

Joint number	Shape of the tool pin profile	Tool rotational speed (rpm)	Axial force (kN)	Feed rate (mm/min)
1	Straight cylindrical	250	5	75
2	Straight cylindrical	500	5	75
3	Straight cylindrical	750	5	75
4	Threaded cylindrical	250	5	75
5	Threaded cylindrical	500	5	75
6	Threaded cylindrical	750	5	75
7	Taper cylindrical	250	5	75
8	Taper cylindrical	500	5	75
9	Taper cylindrical	750	5	75

In this investigation, the entire process of friction stir welding was done using the three different tool pin profile geometries under three different tool rotational speeds at constant optimized values of axial force and feed rate. Here, the term feed rate indicates the speed at which tool is moving. Table 2 summarizes in detail the range and combination of tool pin profiles, tool rotational speeds and process parameters at which the experiments were conducted. In total, 9 joints were fabricated using the different combinations of the tool pin profiles, tool rotational speeds and other process parameters.

3. MATERIALS AND METHODOLOGY

3.1 Joint appearance

In conventional fusion welding techniques, the quality of the welded joints and their properties are found to be deteriorated due to the presence of defects like solidification cracks, slag inclusion and porosity [16]. As melting does not happen during friction stir welding and heat generation due to friction facilitates the joining process in the metal's solid state itself and the stirring action produced by the tool shoulder and pin profiles creates the necessary flow of materials, the friction stir welded joints are usually found to be free from these defects [17–20]. However, stir zone with insufficient consolidation of metals and improper flow of metals makes the friction stir welded joints prone to other defects namely kissing bond, piping defect, cracks, tunnel defect, pin hole etc [21, 22]. A part of the joints fabricated successfully during the friction stir welding of the AZ80A magnesium alloys using M35 grade HSS tool with three different pin profiles under various tool rotational speeds at constant axial force values and feed rate are displayed in Figure 4.

The top surface of the welded joints seems to be free from visible defects. Yet, tunnel type of defects was found to be present in different regions of the FSW zone, in some of the welded joints, which were observed visually during the examination of their cross sections. These defects were observed when the welded specimens were analyzed under the low magnification (10X) using the optical microscope.

The macrostructure of the joints successfully fabricated using the different tool pin geometries and under various axial force values are represented in a detailed manner in the Table 3. The effect of the three tool pin profiles on the macrostructure of the AZ80A

weld cross sections along the advancing side (AS) and retrieving side (RS) are clearly illustrated in Table 3.

In this investigation, the entire process of friction stir welding was done using the three different tool pin profile geometries under three different tool rotational speeds at constant optimized values of axial force and feed rate. Here, the term feed rate indicates the speed at which tool is moving. Table 2 summarizes in detail the range and combination of tool pin profiles, tool rotational speeds and process parameters at which the experiments were conducted. In total, 9 joints were fabricated using the different combinations of the tool pin profiles, tool rotational speeds and other process parameters.

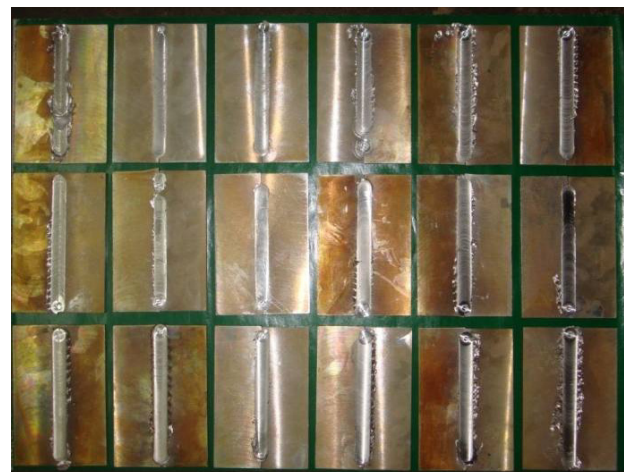


Figure 4. Photographs of the part of the joint specimens fabricated by FSW using the three different tool profiles at various tool rotational speeds

By analyzing the macrostructures of the joint surfaces fabricated in this investigation, it can be observed that the geometry of the tool pin profile and tool rotational speed value plays a significant role in determining the quality of the weld through their influence in the stirring action during the weld, flow of the plasticized material, generation of heat. From the macrostructures displayed in the Table 3, it can be seen that the defect free weld joints were obtained in Joint No.9 i.e., during the use of tool with taper cylindrical pin profile at a tool rotational speed of 750 rpm.

3.2 Microstructural Graphs of the Nugget Zone

The sample macrograph of the cross section of the defect free joint produced under joint condition number 9 is illustrated in a detailed manner in the Figure 5.

Table 3. Effect of three different tool pin profiles & tool rotational speeds on macrostructure

Joint Number	Top surface of the weld	Macrostructure		Observation
		RS	AS	
1				Pin hole on the retreating side
2				Pin hole on the retreating side
3				Tunnel defect on the advancing side
4				Tunnel defect at the bottom of weld nugget
5				Tunnel defects on the advancing side
6				Tunnel defect at two places on the advancing side
7				Very small tunnel defects at the advancing side
8				Very small pin hole at the retreating side
9				Defect free joints

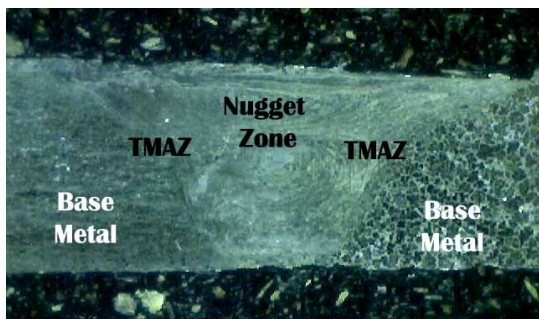


Figure 5. Macrostructure of the defect free joint produced under Joint No.9

Apart from Base Metal, heat affected zone (HAZ), the thermo mechanical transformation zone (TMTZ) and nugget zone (NZ) are the three unique distinct zones in the fabricated joint's (using FSW process) macrostructure.

Figure 6 elaborates in detail the microstructural graphs of the NZ obtained using the three different pin

profiles and at various tool rotational speeds under other constant FSW parameters.

These micrographs clearly depict that the coarse, large sized grains of the parent metal have entirely revamped into a fine sized, equidistant grains in the region of nugget due to the effect of FSW technique. Moreover, the non-uniform grain distribution found in the base metal is also turned into uniform fine grain distribution. This transformation found in the welded specimens is mainly because of rapid & effective recrystallization process, which took place due to the parallel effect provided by heat and deformation during the FSW.

Additional detailed investigation in the micrographs of the welded specimens proved that the pin profile specification & dimensions of the FSW tool plays a significant role in affecting all the three disparate zones (HAZ, TMTZ & NZ) of the joints fabricated by FSW technique.

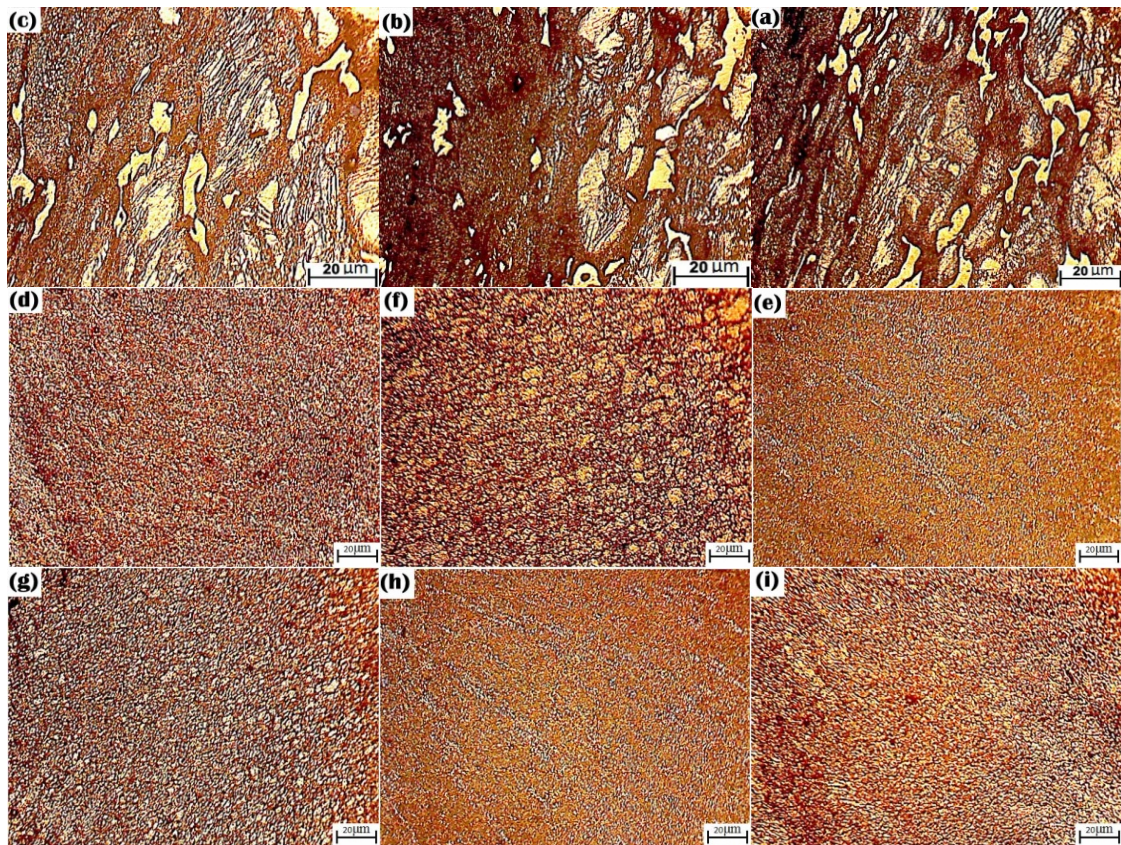


Figure 6. Microstructural graphs of the NZ obtained using the three different pin profiles and under various tool rotational speeds: (a) Joint No.1 {No.1}; (b) No.2 (c) No.3 (d) No.4 (e) No.5 (f) No.6 (g) No.7 (h) No.8 (i) No.9

3.3 Mechanical properties

In order to investigate and understand the mechanical properties of the specimens obtained using FSW under three different pin profiles and at various tool rotational speeds, a series of tensile shear tests were conducted and the tensile specimens were prepared as per ASTM: B557M-10 standard guidelines [23]. The photographic view of the prepared tensile specimens as per the above mentioned processes can be seen in the Figure 7. Two to three specimens obtained during FSW using three different tool pin profiles at various tool rotational speeds are subjected to tensile testing and the average of these results are presented in Figure 8.

4. DISCUSSIONS

4.1 Joint appearance

Figure 6 illustrates that the joints produced during the joint number 9 is free from defects and the joints produced during the joint numbers is found to have a major defect described as the “Tunnel defect”, ultimately leading to the reduction in the fabricated joint’s mechanical properties. Inadequate generation of heat and was found to be one of the major reasons for the occurrence of this defect in joints fabricated by FSW process. It is now practically evident that, the tools with different pin profiles can generate variations in the plastic deformation. As a result, the FSW tools designed with cylindrical (straight) type of profiled pin were not able to generate the adequate volume of plastic deformation, because of the absence of the

threaded features on their profile region & inadequate region of contact. This indirectly resulted in an inadequate flow of material leading to the formation of tunnel defects in the nugget zone.

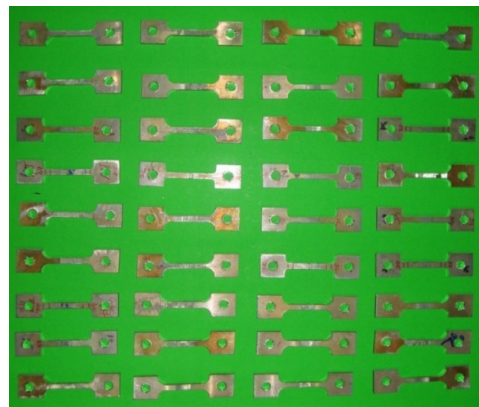


Figure 7. Photograph of tensile test prepared specimen

4.2 Grain size distribution

Table 4 describes in detail the average size of the grains in the centre of the nugget zone in the entire samples displayed in Figure 6. From this table, it is evident that compared with the remaining two pin profiles, the taper cylindrical pin profile has produced a fine grain structure. This is because, the total contact surface between the joint samples of AZ80A Mg alloy and the FSW tool with cylindrical (taper) profiled pin is less when compared with the other two pin profiles namely threaded cylindrical & straight cylindrical.

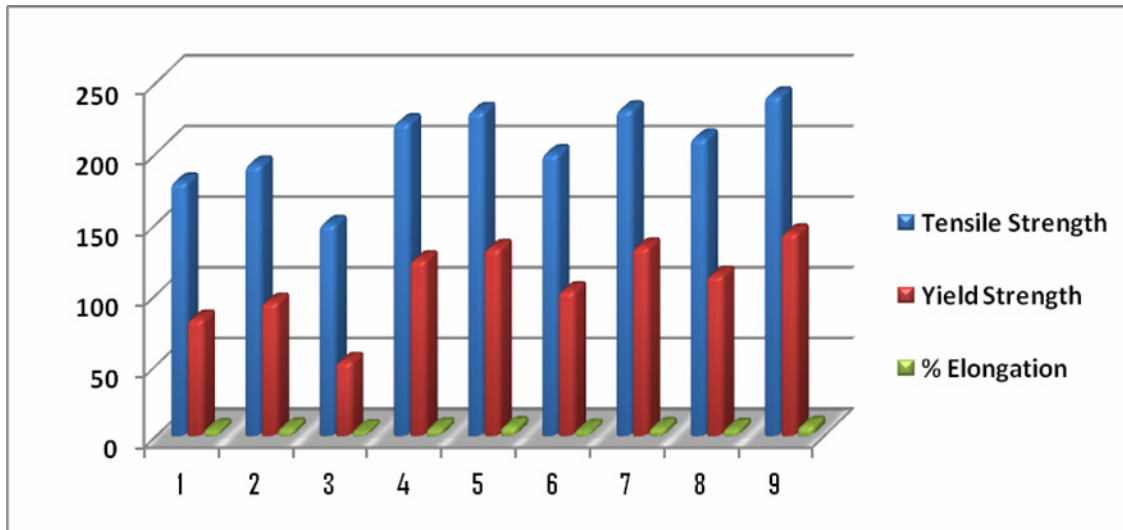


Figure 8: Graphical representation of the mechanical properties obtained during tensile testing of joints under different tool pin profiles & tool rotational speeds

Subsequently, the FSW tool with cylindrical (taper) profiled pin has produced adequate level of heat input and flow of materials at reduced levels leading to the formation of fine sized grain segments.

Table 4. Average grain size in the centre of the NZ during all FSW conditions in this investigation

Joint No.	1	2	3	4	5	6	7	8	9
Grain Size, μm	16.5	14.7	28.2	12.6	10.9	15.4	11.9	7.6	6.8

4.3 Tensile Strength, Yield Strength & elongation

From Figure 8, it can be observed that out of the three different pin profiles, the largest values of tensile strength are found to be produced by taper cylindrical pin profile at 750 rpm. Table 5 summarizes in detail the various mechanical properties obtained using the adopted conditions.

Table 5. Summary of the various mechanical properties obtained under adopted conditions

Joint No	Ultimate Tensile Strength MPa	Yield Strength MPa	Elongation (%)
1	178	81	2.94
2	190	93	3.71
3	148	51	2.12
4	220	123	3.77
5	228	131	4.94
6	198	101	2.44
7	229	132	3.98
8	209	112	3.45
9	239	142	5.34

Because of the fine grain structure, uniform grain distribution and defect free joints, the yield strength and percentage of elongation values produced by this tool are also higher. Likewise, use of threaded cylindrical pin profile has resulted in better values of mechanical properties when compared with the straight cylindrical pin profile.

4.4 Distribution of Micro hardness

The size of the grain plays an important role in deciding the hardness of a welded joint. The slip due to dislocations is restricted by the boundaries of the grain and hence the material containing smaller size of grains will have higher values of hardness or greater strength [24]. The hardness values are measured across the weld region with the help of Vicker's micro hardness testing machine and the values are mentioned in Table 6.

Table 6. Micro hardness values in the nugget zone in this investigation

Joint No.	Grain size, μm	Micro hardness (HV)
1	16.5	72
2	14.7	69
3	28.2	63
4	12.6	84
5	10.9	78
6	15.4	74
7	12.9	80
8	7.6	76
9	6.8	87

From the Table 6, it is evident that there is a decrease in the hardness values of the joints produced by straight cylindrical pin profiled tool. This is due to the increase in the grain size at the nugget zone when compared with that of the base metal. Larger the grain size, lesser the value of the hardness. So, when there is a decrease in the grain size, it will lead to a drastic increase in the hardness of the joints. In this way, by producing very fine grain sizes in the nugget zone compared with that of the base metal, higher values of hardness can be achieved in the nugget zone. As an example, the values of micro hardness of the welded specimens fabricated using the taper cylindrical pin profile under three different tool rotational speeds are graphically demonstrated in the Figure 9. Starnik et al. [25] discussed that the waviness in the micro hardness values as seen in Figure 9 takes place due to the difference in grain size orientation in the nugget zone.

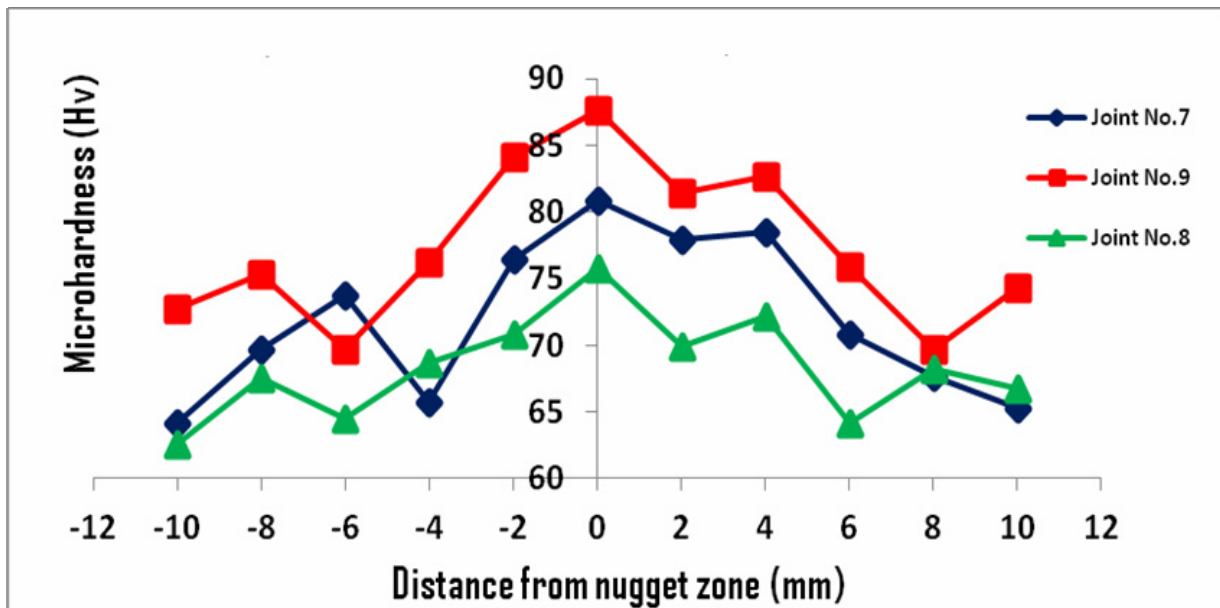


Figure 9. Graphical representation of the micro hardness values for the joints fabricated using taper cylindrical pin profiled speed at different tool rotational speeds

4.5 Lower hardness distribution profile (LHDP)

In the welded specimen, the weaker sections (regions with lower hardness profiles, i.e., LHDP) will be prone to failure in an easier manner. Chen et al. [26] investigated and proved that the hardness profiles taken along the bottom, center and top of the FSW welded plates or along the centre thickness of the welded section, due to their limited numbers of hardness points cannot give a clear measure of the fracture behavior of the welded joints.

They also suggested that the path of the fracture in the joints can be identified by developing a hardness profile distribution around the HAZ covering the entire thickness of the FSW alloy plates.

In this investigation, the hardness profile distribution maps are developed by calculating the Vickers micro hardness at an interval of 0.5mm along the cross section of the joints fabricated by FSW using the three different pin profiles at different tool rotational speeds, as shown in Figure 10.

It can be seen that there exists a consistency between the profile of distribution of lower hardness values & fracture path and the exact location of the fracture is

shown in the Figure 11 for the welded joint using a taper cylindrical pin profile and 750 rpm. The FSW joint was found to be under fracture at the advancing side, where the lowest value of hardness was recorded.

4.6 Losses due to wear

The interaction between the tool rotational speed and feed rate on the wear of the FSW AZ80A magnesium alloy during the use of three different pin profiles at different tool rotational speeds are shown in Figure 12. It can be observed that the wear is minimum at the highest tensile strength values. This can be justified by comparing the values of wear in Figure 12 with the tensile strength values in Table 5. The minimum wear was found to be observed during the use of taper cylindrical pin profiled tool at 750 rpm.

And with this same tool pin profile and at 750 rpm, we achieved the highest tensile strength value of 239 MPa. Thus, it can be understood that the minimum wear can be experienced in the joints under the FSW conditions where highest tensile strength is achieved.

Joint No	Distance from the weld centre (in mm)														W E L D C E N T R E
	-21	-19	-17	-15	-11	-9	-7	-6	-5	-4	-3	-2	-1	0	
1	73.6	72.1	59.6	70.3	64.3	58.2	67.3	62.4	66.9	68.1	56	69.1	59.2	60.0	W E L D C E N T R E
2	68.4	69.0	60.8	64.6	63.9	57.5	59.1	61.1	56.1	51.0	59.6	58.1	63.4	62.6	
3	62.7	61.9	60.0	61.6	59.6	57.9	58.2	50.3	57.3	56.7	58.3	59.2	57.2	59.4	
4	83.2	84.2	72.4	75.3	67.8	63.2	65.9	77.9	60.1	62.3	72.2	68.9	67.2	70.0	
5	78.0	72.4	76.3	68.8	60.9	58.7	64.7	66.8	55.2	66.5	67.7	67.5	62.0	61.9	
6	86.4	85.1	81.4	74.3	75.9	76.3	84.1	57.1	69.7	58.6	69.2	74.7	60.4	65.2	
7	84.1	87.6	75.6	69.7	75.9	85.1	81.4	57.3	69.2	72.8	65.2	76.3	74.3	60.4	
8	75.5	68.6	72.2	66.7	67.3	62.6	50.4	65.6	59.6	63.7	55.5	51.3	64.2	52.3	
9	80.9	76.5	77.9	69.7	76.0	52	73.8	58.5	65.5	55.3	54.0	70.8	67.7	65.3	

Figure 10. Lower hardness distribution profile (LHDP)

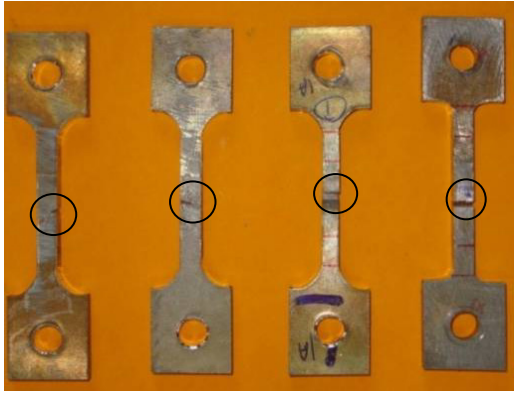


Figure 11. Photographic representation of the fracture location of the tensile specimens fabricated by FSW using taper cylindrical tool at 750 rpm

Similarly, by comparing the grain size values tabulated in Table 4 and the wear values (in mg) in the Figure.12, it can be seen that the refined fine grain size and uniform distribution grain in the nugget zone leads to minimum wear compared with the coarse & large grain structures. Finally, it is evident that the taper cylindrical pin profiled tool produces minimum wear at 750 rpm.

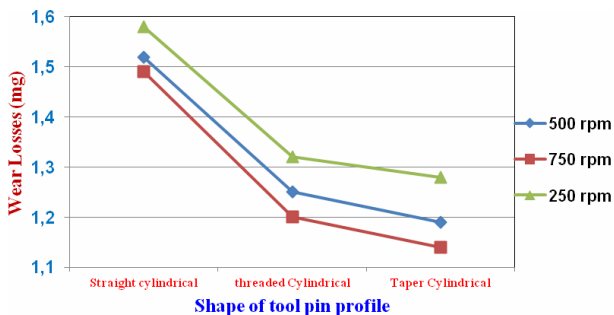


Figure 12. Graphical representation of the wear during FSW of AZ80A Mg alloy using three different pin profiles at various tool rotational speeds

5. CONCLUSION

The influence of the Friction Stir Welding (FSW) process parameter, namely, tool rotational speed and the impact of tool geometry on the mechanical properties of AZ80A magnesium alloy was experimentally investigated in this paper. Straight cylindrical, Threaded Cylindrical and taper cylindrical were taken as the three different tool pin profiles and the FSW of AZ80A magnesium alloy plates were done using these tools at various tool rotational speeds. The results produced in the present investigation allow us to draw the following conclusions:

- The microstructural & SEM graphs of the welded joints showed the transformations of large size coarse grains present in the base metal into equidistant fine sized grains in the nugget zone and the non-uniform grain distribution found in the base metal is also turned into uniform fine grain distribution due to the FSW process.
- The joints welded using the taper cylindrical pin profiled tool at 750 rpm under a constant 5 kN axial force value and 50mm/min feed rate exhibited the maximum tensile strength value of 239 MPa

(82.41% of the base metal) compared with other joints.

- Materials having smaller sizes of grains are found to possess higher values of hardness or greater strength.
- It was noted that there exists a consistency between the profile of distribution of lower hardness values & fracture path and majority of the joints fabricated during the investigation are found to undergo fracture at the advancing side, where the lowest value of hardness was recorded.
- It was experimentally observed that the wear is minimum at the highest tensile strength values. And the minimum wear were experienced in the specimens fabricated using the taper cylindrical pin profiled tool at 750 rpm.

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**ИСТРАЖИВАЊЕ УТИЦАЈА ПАРАМЕТАРА
ФСВ ПРОЦЕСА НА РАЗВОЈ
МИКРОСТРУКТУРЕ И МЕХАНИЧКА
СВОЈСТВА ЗАВАРЕНИХ СПОЈЕВА ЛЕГУРЕ
ТИПА AZ80A Mg**

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Циљ истраживања је био да се утврди утицај брзине ротације и профила електроде ФСВ алата на карактеристике микроструктуре и механичка својства заварених спојева легуре типа AZ80A Mg применом ФСВ технике. ФСВ алати са три различита типа електроде имали су три различите брзине ротације.

Код заварених спојева и њихове површине лома, који су добијени испитивањем затезне чврстоће, извршено је истраживање микроструктуре и електронско микроскопирање. Такође су обављена обимна посматрања и мерења хабања и чврстоће заварених спојева.

Спојеве добијени при брзини од 750 rpm коришћењем конусне цилиндричне електроде имали су

висок ниво квалитета, бољу затезну чврстоћу, боље вредности микрочврстоће и минимално хабање.