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Influence of Tool Pin Profile and Welding Parameter on Tensile Strength of Magnesium Alloy AZ91 during FSW

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Abstract

Magnesium is flammable material and to avoid its limitation of fusion welding solid state welding process, called friction stir welding (FSW), is applied for joining two plates together. The friction stir welding uses a non-consumable tool for joining abutting plates of magnesium alloy AZ91 having 6 mm thickness. FSW process joins the plates with advantages such as low distortion, no shielding gas required, and fine recrystallized microstructure. In Friction stir welding, process parameters such as welding speed, tool rotation speed, tool dimensions and axial force play an important role during welding. In the present work, the 6 mm thick plates of the said alloy are joined at welding speed of 28 mm/min to 56 mm/min with tool rotation speed ranging from 710 rpm to 1400 rpm. Tensile testing was carried out to know the best parameter from the selected ones. Observations are also made for any defects by using fluorescent penetrant testing and photo micrographs.

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1. Introduction

Welding is most important and widely used process in fabrication industries. There are number of welding techniques used for fabrication according to the applications, environment and material to be welded. Welding techniques are divided into different categories; friction stir welding is one of the categories of solid state welding process. Friction stir welding (FSW) was invented at The Welding Institute (TWI) of The United Kingdom in 1991 as a solid state (fusion less) joining technique [1]. Friction stir welding is considered to be the most significant development in metal joining in decades and, in addition, is a “green” technology due to its energy efficiency, environmental friendliness, and versatility. As compared to conventional welding methods, FSW consumes

considerably less energy, no consumables such as a cover gas or flux, and produces no harmful emissions during welding, thereby making the process environmentally friendly [2].

Nomenclature

FSW	Friction Stir Welding
TSCP	Threaded Straight Cylinder Pin
TCP	Tapper Cylindrical Pin
SCP	Straight Cylindrical Pin
DOE	Design of Experiment
SZ	Stir Zone

Further, because FSW does not involve the use of filler metal and since there is no melting, any aluminium alloy can be joined without concern for compatibility of composition or solidification cracking issues associated with fusion welding. Also, dissimilar aluminium alloys and composites can be joined with equal ease [2]. The FSW basically uses a non-consumable rotating tool with a specially designed pin; and for the welding, shoulder is inserted into abutting edges of sheets or plates to be joined and subsequently traversed along the joint line.

1.1. Zones in FSW

There are four different micro structural zones/regions existing after friction stir welding [2].

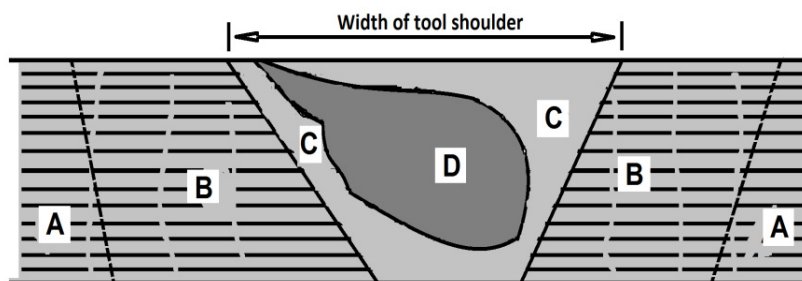


Fig. 1. Various microstructural zones in the transverse cross section of FSWed metal plates

- Unaffected material or parent material [A]:

This is material remote from the weld joint that has not been deformed and that, although it may have experienced a thermal cycle from the weld, is not affected by the heat in terms of microstructure or mechanical properties.

- Heat affected zone (HAZ) [B]:

In this region, which lies closer to the weld joint, the material has experienced a thermal cycle that has modified the microstructure and/or the mechanical properties. However, there is no plastic deformation occurring in this area.

- Thermo- mechanically affected zone (TMAZ) [C]:

In TMAZ, FSW tool plastically deforms the material, and the heat from the process will also have exerted some influence on the material. In the case of aluminium, it is possible to obtain significant plastic strain without recrystallization in this region, and there is generally a distinct boundary between the recrystallized zone (weld nugget) and the deformed zones of the TMAZ.

- Weld nugget [D]:

The fully recrystallized area, sometimes called the stir zone, refers to the zone previously occupied by the tool pin is called as weld nugget. The term stir zone is commonly used in friction stir processing, where large volumes of material are processed.

2. Literature Survey

FSW has been primarily applied for the joining of nonferrous materials such as aluminium and to a lesser extent for magnesium alloys. Nonferrous materials such as aluminium and magnesium have many attractive properties in structural field. Magnesium and its alloy are grouped under rare earth metal category, and these metals have been used for structural application because of its strength to weight ratio (more compared to other metal). Magnesium is the third-most-commonly-used structural metal, followed by iron and aluminium. There are many magnesium alloys used for different applications, AZ 91 one of the magnesium alloys, which was used for investigating the effect of FSW parameters on tensile strength. S. Ramesh Babu et al. investigated the microstructural and mechanical properties of extruded AZ31B during FSW and found that good welding and defect free stir zone is obtained with tool rotation speed of 1000 rpm with shoulder diameter as 24 mm, tool traversing speeds of 75 and 105 mm/min [3].

K Panneerselvam et al. found that at constant rotational speed and welding speed threaded tool pin profile produces less force but square pin profile produces defect free welds of polypropylene plates [4]. Extruded Mg-2.0Nd-0.3Zn-1.0Zr (wt.%) alloy was used by F. Y. Zheng et al. for investigating the change in microstructure and mechanical properties of friction stir welded plates and they observed that by increasing the number of passes of welding average grain size decreases firstly and then increases and also that the Vicker's hardness of stir zone is higher than parent material but tensile strength of advancing side of stir zone is lower than that of parent material [5]. Chaitanya Sharma et al. analysed the heterogeneity of microstructure and mechanical properties of friction stir welded joints of Al-Zn-Mg alloy AA7039 and found that weld nugget grain size was found to decrease from top to bottom (with optical and scanning electron microscopy); top layer of joint was the strongest while middle layer was the weakest [6].

Mohsen Bahrami et al. investigated the influence of different pin geometry such as threaded tapered, triangular, square, four-flute square, and four-flute cylindrical, of AA7075/SiC nano-composite on microstructure using optical microscopy(OM) and scanning electron microscopy (SEM), measured tensile strength on tensile test machine and concluded that the highest UTS was obtained with triangular pin geometry. Macroscopic fracture observed for specimen welded by four-flute cylindrical pin tool (which is failed in SZ) and remaining specimens fractured in base metal far outside the SZ [7].

Emad Salari et al. observed influence of tool geometry and rotational speed on mechanical properties and defect formation on 5456 aluminum alloy sheets and observed that optimum microstructure and mechanical properties were obtained for the joints produced with the stepped conical threaded pin profile and rotational speed of 600 rpm [8]. Investigation made by S. Ugender et al. shows that the joint fabricated using tapered cylindrical pin profile exhibited more temperature and superior tensile properties compared to the joints fabricated by straight cylindrical pin profile for friction stir welding of AA2014 Aluminium Alloy [2]. K. Elangovan et al. found out the influences of tool pin profile and welding speed for AA2219 aluminium alloy fabricated by the friction stir welding and observed that the square pin profiled tool produces mechanically sound and metallurgical defect free welds compared to other tool pin profiles [9].

3. Experimental work

The dimensions of the plate of magnesium alloy AZ 91 with a chemical composition as shown in table-1 were selected as 100mm x 150mm x 6mm. HCHCr D2 grade material was used for FSW tool with different tool pin geometries and hardness of tool was set as 60 to 61 HRC taken for all tool geometries. The chemical composition and physical properties of tool material are shown in table- 2 and 3 respectively.

Table 1. Chemical composition of AZ 91 magnesium alloy (mass %).

%Al	%Zn	%Mn	%Si	%Cu	%Ni	%Fe	%Mg
9.2	0.32	0.84	0.12	0.03	0.01	0.003	Balance

Table 2. Typical composition of HCHCr - D2 (wt.%).

%Carbon	Magnesium	Silicon	Chromium	Molybdenum
1.55	0.3	0.3	12.0	1.0

Table 3. Physical & thermal properties of HCHCr - D2

Density (kg/m ³)	Quenching Temp. (°C)	Modulus of Elasticity (GPa)	Hardness(hardened) (HRC)	Thermal Conductivity (W/m-K)	Specific Heat Capacity (J/kg-K)
7.7×10 ³	980-1100	210	60-61	20	461

Three tool pin geometries were selected as: (1) Threaded straight cylindrical pin, (2) Tapper cylindrical pin and (3) Straight cylindrical pin as shown in the figure-2 (tools before heat-treatment), common basic dimensions such as shoulder diameter, shoulder length, pin diameter, pin length, shank diameter, and shank length for FSW tools are shown in table-4.



Fig. 2. Tools after heat treatment

Table 4. Basic dimensions of FSW tools

Shoulder diameter (mm)	Shoulder length (mm)	Pin diameter (mm)	Pin length (mm)	Shank diameter (mm)	Shank length (mm)	Total tool length (mm)
18	20	06	05.8	15	25	50.8

Taguchi technique for design of experiment (DOE) has been implemented for finding number of experiments to be performed for selected variables for welding such as tool pin geometry, welding speed, and tool rotation speed. These design models have been prepared by choosing three levels shown in table-5. Taguchi design was used for experimentation by applying L9 orthogonal array, taking three levels for each factor.

Table 5. FSW Parameters for DOE

Sample	Control factor	Unit	Level 1	Level 2	Level 3
A	FSW Tool		TSCP	TCP	SCP
B	Rotational Speed	rpm	710	1000	1400
C	Welding Speed	mm/min	28	40	56

Table-6 shows the tool, rotational speed and welding speed along with experiment number showing the order of experiment to be performed.

Table 6. FSW Parameters for Experiments

Experiment No.	Tool	Rotational Speed (rpm)	Welding Speed (mm/rev)
1	TSCP	710	28
2	TSCP	1000	40
3	TSCP	1400	56
4	TCP	710	40
5	TCP	1000	56
6	TCP	1400	28
7	SCP	710	56
8	SCP	1000	28
9	SCP	1400	40

4. Results and Discussions

Tensile testing was performed for knowing tensile strength of weld joint and Fluorescent Penetrant Inspection (FPI) as per ASTM E1417, type I method at sensitivity level III on only welded area was made for detecting surface discontinuity (table-7).

Table 7. Results of Tests

Experiment No.	Tensile Strength (MPa)	FPI Results
1	76.1667	PASS
2	57.4000	PASS
3	23.5400	FAIL
4	58.2000	FAIL
5	11.1167	FAIL
6	1.1100	FAIL
7	8.9100	FAIL
8	26.83333	PASS with small crack
9	22.3667	FAIL

After performing all experiments, observation made by observing the weld pool of friction stir welded plates under optical metallurgical microscope at 100X magnification, all weld pool were found different, variation in parameters affects the welding and these is clearly visible. Microscopic images were taken for observing the inside defect/s or crack/s in the weld pool by magnifying the cross-section of weld pool, perpendicular to the weld top surface. In experiment 1, as shown in figure-3, only inside defect (Void) was observed but no defect or crack was present on the top surface or back surface of the welded plates.



Fig. 3. Experiment 1 (a) weld pool close view; (b) microscopic view (100X).



Fig. 4. Experiment 2 (a) weld pool close view; (b) microscopic view (100X).

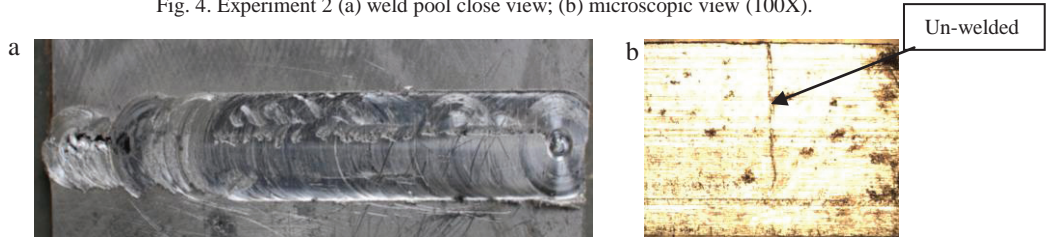


Fig. 5. Experiment 3 (a) weld pool close view; (b) microscopic view (100X).



Fig. 6. Experiment 4 (a) weld pool close view; (b) microscopic view (100X).

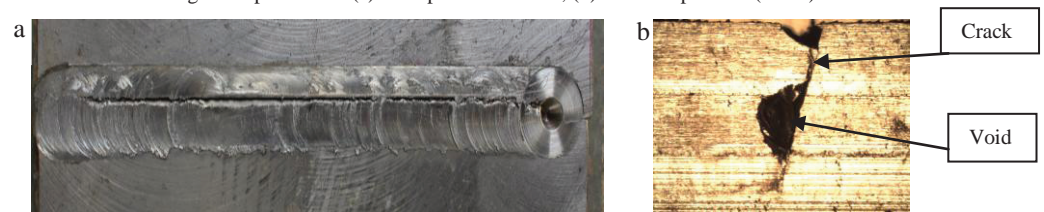


Fig. 7. Experiment 5 (a) weld pool close view; (b) microscopic view (100X).

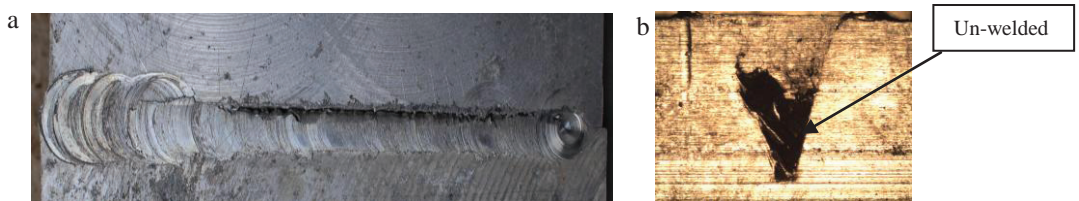


Fig. 8. Experiment 6 (a) weld pool close view; (b) microscopic view (100X).



Fig. 9. Experiment 7 (a) weld pool close view; (b) microscopic view (100X).



Fig. 10. Experiment 8 (a) weld pool close view; (b) microscopic view (100X).



Fig. 11. Experiment 9 (a) weld pool close view; (b) microscopic view (100X).

During experiment 2, as in figure-4, defect (void) present inside the weld pool was observed and tool was broken at the middle of the length of the welding line due to increase in the speed of tool rotation. Tool got broken at near to just starting of the operation in experiment 3 and welding was not done; and only top surface slightly joined together but the full thickness of two plates were not welded, it could be observed (un-welded portion) in microscopic view as shown in figure-5.

During experiment, 4, 5 and 6, no tool was damaged but the welding was not proper because of lack of heat generation due to tool geometry used (tapper cylindrical pin tool). Crack was detected in the top surface of the weld pool and defects such as voids were found inside of the weld pool as shown in figure-6, -7 & -8. Experiment 7, 8 & 9 were performed with straight cylindrical pin tool and the weld joint obtained by these experiments was having defects (crack and void) on the weld pool top surface as well as inside of the weld pool as shown in figure-9, -10 & -11.

5. Conclusion

In this investigation, observations were made for the tensile strength of weld zone, FPI for surface discontinuity and optical microscopy of cross section of weld pool to select proper tool pin profile, proper welding speed and tool rotational speed. From this investigation, the following conclusions are derived:

- (1) Heat generation is the main reason for proper welding and this is only due to friction between shoulder and plates, here shoulder diameter of 18 mm using threaded straight cylindrical pin profile used at the rotational speed of 710 rpm and welding speed of 28 mm/min is suitable for good welding using selected welding parameters.
- (2) Tapper cylindrical pin profile of the tool is not suitable with shoulder diameter 18 mm for welding the plates without any defect.
- (3) Straight cylindrical pin profile tool with tool rotational speed of 1000 rpm and welding speed of 28 mm/min gives somewhat small defect at top surface of weld zone.
- (4) High tensile strength was obtained with threaded straight cylindrical pin profile tool at 710 rpm of tool rotational speed and 28 mm/min welding speed.
- (5) Tool material, HCHCr D2, with hardness of 60 to 61 RC and selected dimensions is not capable to sustain the force during the welding with threaded straight cylindrical pin profile of the tool.

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