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Study of Mechanical Properties and Temperature Distribution of Dissimilar Friction Stir Welded Aluminium Alloys 1100 and 5052

M. Latheef*, Renju Mohan, R.Manu
Department of Mechanical Engineering
National Institute of Technology Calicut - 673601, Kerala, INDIA

Abstract

Friction stir welding (FSW) is a solid-state joining technique, which is widely used in similar and dissimilar joining of Al, Cu, Mg, Ti, and their alloys. It can be also used to weld steel. The major advantages are no wastage of material, filler material is not needed, less energy consumption and less finishing required. Aluminium alloys have a major advantage of high strength to weight ratio and high corrosion resistance. They are being extensively used in automobile and aerospace industries. In the present study, friction stir welding of dissimilar aluminium alloys 1100 and 5052, was done at different combinations of tool rotation speeds and tool traverse speeds in a conventional vertical milling machine. The speeds used were 1000, 1400 and 2000 rpm. Tool transverse speeds used were 20, 28 and 40 mm/minute. A hot die steel tool of 18 mm shoulder diameter and 6mm pin diameter was used to weld a 3 mm thick workpiece. The tensile testing and Vickers hardness test evaluation of these specimens showed good mechanical properties. The temperature distribution is found out using thermocouples fitted at specific intervals from the weld centre. The conclusion was that the maximum temperature obtained is at the centre and the temperature gradually reduces going away from the centre with a lower rate in the retreating side compared toadvancing side when AA1100 was used in the retreating side.

Keywords: Friction stir welding, Dissimilar FSW, Mechanical properties of FSW joints, Temperature profile in FSW

1. INTRODUCTION

Aluminium alloys are one of the mostly used materials across the world for many applications due to their good strengthand ductility while being lighter. This makes thema suitable material to work under variety of working environments.Naturally, the need for joining aluminium effectively had arisen since its discovery. There are different types of aluminium alloys available in the market with different composition and different properties. So as to suit the needs, different type of aluminium alloys may be used for the different components in a system. Therefore an efficient joining technique for dissimilar aluminium alloys should be developed. Friction stir welding (FSW) is relatively a newer joining technique developed to solely weld the aluminium which is widely used in the modern day industry. It was invented at The Welding Institute of the UK in 1991 [1-2].FSW is a solid state welding process. Since materials like aluminum were difficult to weld, the introduction of FSW was an instant hit and it solved major issues in manufacturing sector like aerospace industry and marine industry [3].

FSW's success is due to a relatively simple concept. The process consists of a non-consumable rotating tool having a pin on a shoulder surface. The workpiece should be firmly clamped and the joining surfaces should have minimum gap between them because of the absence of filler material. As a first step, the rotating tool penetrates into the joining surface until the shoulder of the tool touches the top surface of the base metal. Then the tool transverses along the joining line under a load. The combined translation and rotation of the tool results in high frictional heating between tool and workpiece and this will change the weld zone to plastic stage and thus form a strong defect-free weld upon cooling. The temperature will not go beyond the melting temperature of the base metal since there is no complete melting involved [4]. Since there is no macroscopic melting involved, the controls needed in fusion welding to avoid phenomena such as solidification and liquation cracking, porosity, and loss of volatile solutes can be avoided[5]. These recognized advantages of solid-state joining have led to attempts to use FSW for a wide range of alloys (e.g., Al, Mg) is of particular interest in aerospace and automotive applications although hard combinations have not achieved commercial viability. Constant research and developments in FSW widened the application to relatively harder metals like steel, titanium, etc. and also to non-metals like plastics and HDPE[6] recently.

Murr[7]has reviewed the FSW of a wide variety of dissimilaralloys and demonstrated that it is possible, on alaboratory scale, to friction stir weld aluminium metalmatrix composites and other difficult materials not prone to fusion processes. In many of these casesthere are no alternatives available to friction stirwelding. The primary difference between the FSW of similarand dissimilar alloys is that the discontinuity in propertiesacross the butting surfaces, which has a large influenceon the patterns of material flow during stirring. Achange in the direction of tool rotation, causing a switchin the advancing and retreating sides, leads to complexspikes in the micro-hardness values. It is well knownthat much of the material flow occurs along theretreating side.

AA1100 is one of the purest alloys of aluminium and the alloying elements constitute only 1%. It can be shaped into many different products such as chemical equipment, pipes, tanks, name plates, cooking utensils, rivets, reflectors and sheet metal. It cannot be hardened by heat treatment and is very formable [8]. Table 1 shows the chemical composition [9] and table 2 shows the thermal properties of AA1100 [8].

Table 1. Chemical Composition of AA1100

Fe	Si	Cu	Mg	Ti	Mn	V	Al

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0.52	0.16	0.11	0.02	0.02	0.01	0.011	Bal

Table 2. Thermal properties of AA1100 and AA5052

Alloy	Approximate melting range (°C)	Thermal conductivity at 25 °C
AA 1100	645-655	234
AA 5052	607-650	138

AA 5052 is comparatively harder and has higher tensile strength than AA1100[8, 10] because of the influence of magnesium and other alloying elements. Typical applications include aircraft manufacturing, marine filed, architecture, general sheet metal work, fuel lines and tanks, heat exchangers, flooring panels, streetlights, appliances, rivets and wire.The exceptional corrosion resistance of 5052 alloy against seawater and salt spray makes it a primary candidate for the failure-sensitive large marine structures, like tanks of liquefied natural gas tankers. The composition of alloying elements of AA5052 is shown in table 4[10] and the thermal properties are shown in table 2.

Table 3. Mechanical Properties of AA 1100 and AA 5052

Alloy	Tensile strength indicated during tensile test (MPa)	Vickers hardness range from hardness test (HV)
AA 1100	118.974	35-40
AA5052	229.433	70-80

Table 4. Chemical Composition of AA5052

Mg	Fe	Si	Cr	Mn	Cu	Al
2.7021	0.3614	0.426	0.16	0.0706	0.0399	Bal

Since there is significant difference in mechanical (listed in table 3) as well as thermal properties of AA1100 and AA5052, the dissimilar FSW of these two materials is difficult due to their variation in material properties. The number of papers discussing the FSW of these two alloys is comparatively less and there is a need to analyze the changes in mechanical as well as thermal behavior of FSW weld of these two alloys.Also, the optimum process parameters among the selected range will be discussed by analyzing the quality of the weld obtained.

2. EXPERIMENTAL SETUP

The experimental setup consists of a vertical milling machine (Batliboi FA3V) and a welding fixture which is to be mounted on the work table to carry out friction stir welding. The FSW tool is connected to the spindle using a collet.

2.1 Vertical Milling Machine

The conventional vertical milling machine having spindle speed up to 2000 rpm, feed range of 14-900 mm/min and spindle swivel from -45° to 45° was used for the present work. Automatic table movement by engaging the lever and manual movement is also possible in this machine.

2.2 Fixture

The fixture consists of mild steel plate of thickness 18 mm having a cavity of 4 mm depth with 150 mm X 100 mm size is prepared for fixing the base plates firmly. Two mild steel angular strips are used for holding the work pieces with four bolts. The cavity along with the strip arrest all the degrees of freedom.

2.3 FSW Tool

In the present study, a FSW tool with plane shoulder along with atapered probe or pin is used to increase the contact area ofthe probe with the workpiece. This will lead to an increase in the frictional heat causing more plastic deformation. The tapered probe alsopromotes a high hydrostatic pressure in the weld zone,which is extremely important for enhancing the materialstirring and the nugget integrity[11].

2.3.1. Tool material: Tool steel is the most widely used tool material for aluminium alloys which possesses a combination of high temperature strength and stiffness. The selection of tool material is determined by the approximate temperature reached during processing of Al alloy (in the range of 500-600 ºC).Therefore any tool steel with tempering temperature higher than 600 ºC is ideal for FSW tool. In this study, the tool material was chosen as Hot Die Steel (H13 tool steel), which was heat treated to a hardness of 50 HRC.

2.3.2. Tool geometry: Tool pin profile was selected as tapered cylindrical shape. The selection of pin length is based on workpiece thickness, which is to be approximately 0.90-0.95 times of workpiece thickness. Figure 3.3 shows the view of FSW tool. It is having 18mm shoulder diameter and a tapered pin. The pin diameter is 6.5 mm diameter on the top (nearer to shoulder surface) and 6 mm at the bottom surface.Length of the pin used was 2.9 mm in order to avoid contact with the mild steel backing plate. The FSW tool is shown in fig.1.

Fig. 1. FSW Tool and Collet

2.4 Workpiece

The weld coupons was prepared with 75x50 mm dimensions so as to get a total width of 100 mm in order to tightly fit in the fixture and for readily preparing the workpiece for doing the tensile testing according to ASTM E8 standard. Thickness of both sheets was 3 mm. The sheets were cut perpendicular to rolling direction in order to get maximum tensile strength. Extreme care was taken in aligning the weld coupons together and tight fit is ensured to arrest all degrees of freedom before carrying out welding. AA1100 was placed at the retreating side and AA 5052 was placed at the advancing side.

2.5 Temperature Measurement

Six K-type thermocouples fitted at specific intervals from weld centre were used to measure the temperature throughout the experiment.1 mm dia. holes were drilled on the workpiece using a conventional drilling machine to insert the thermocouples.The temperature was recorded with the help of National Instruments data acquisition (DAQ) system with 8 channels. 6 thermocouples were connected to channels 1-6 and the DAQ was connected to a PC having National Instruments software to analyze the data during welding. 3 thermocouples were placed on one side of the sheets with distances 15 mm, 25 mm, and 35 mm from weld centre respectively. The same is repeated for other side also. Acrylic sheets were used to protect thermocouples from damaging due to high pressure fromthe top clamping on the fixture. The complete experimental setup is shown in fig.2.

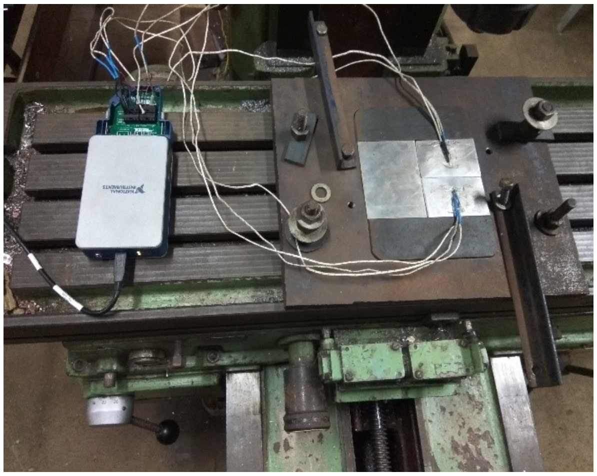

Fig. 2. Experimental Setup

2.5 Tensile and hardness testing machines

Tensile test samples were prepared from the weldedsheets as per ASTM-E8 standard with the help of Electronica made wire electrical discharge machine (WEDM). Tensile specimens were cut perpendicular to the welding direction. Tensile testing was carried out on a Shimadsu AG-X Plus Universal Testing Machine (UTM) of 10 kN capacity with strain rate of 0.5 mm/min.

Vickers Hardness was measured usingMatsuzawa VMT-X hardness tester as per ASTM E384-11 standard. Hardness was measured on the polished top surface with a load of 3 kgf and dwell time of 10 s at different points on the welded sheet on a straight line across the weld. The specimens were named as shown in table 5 and the welded specimens are shown in fig. 3.

3 RESULTS AND DISCUSSIONS

3.1 Temperature profile across the weld

Fig. 4 shows the transient temperature plot of the thermocouple fitted at 15 mm away from weld centre. The temperature increases exponentially with time during the welding and reaches a value less than the melting temperature of the alloy and then gradually decreases as the tool passes the centre of workpiece. The maximum temperature obtained was 404.009 °C at 2000 rpm and 20 mm/minute and the minimum temperature obtained was 293.092 °C at 1000 rpm and 40 mm/minute. The maximum temperature was obtained at the retreating side of the weld pool where AA1100 was placed which is opposite to the general trend observed in FSW. This is due to the significant difference in thermal properties of the alloys used..The peak temperature obtained in the case of each specimen is shown in Fig. 5.

Table 5. Specimen Nomenclature

Name of Specimen	Feed rate (mm/minute)	Speed(RPM)
S1	20	1000
S2	28	1000
S3	40	1000
S4	20	1400
S5	28	1400
S6	40	1400
S7	20	2000
S8	28	2000
S9	40	2000

Fig. 3. Friction stir welded specimens

3.2 Temperature and tool rotational speed / feed rate relationships

Fig.6 shows the relationship between the temperature and feed rate. As the feed rate increases, the temperature gradually decreases because the shoulder will not get enough contact time with the workpiece to produce sufficient frictional heat. The relationship between rotational speed and temperature is plotted in fig.7. The temperature found to be increasing with respect to increase in rotational speed due to high frictional heat developed between tool and workpiece. The maximum temperature obtained was at maximum speed and minimum feed. It is observed that the effect of feed rate is more at higher rotational speeds compared to lower rotational speeds.

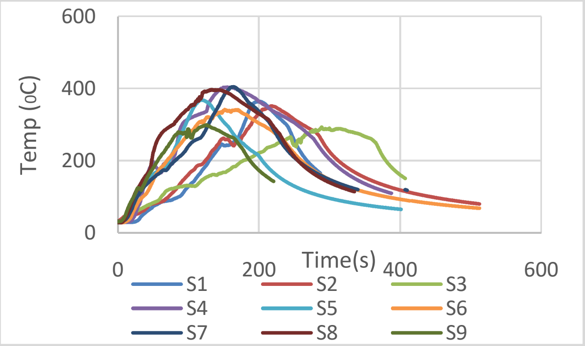

Fig.4. Transient temperature profile

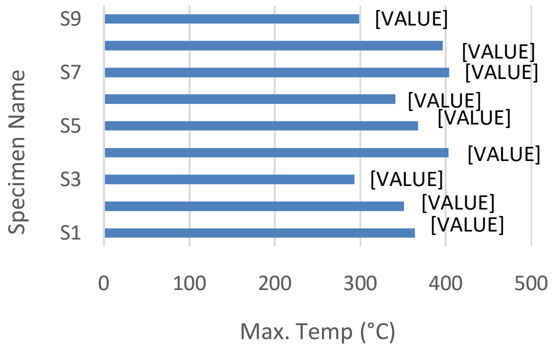

Fig.5. Peak temperature obtained in the specimens

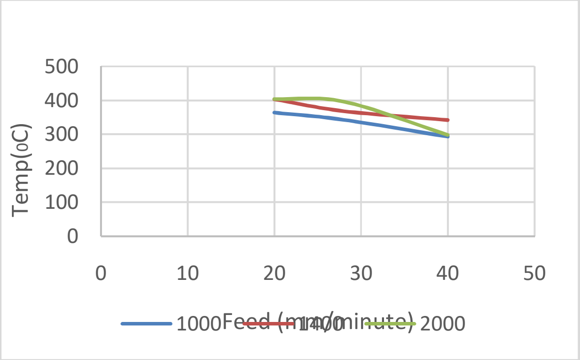

Fig.6. Effect of feed rate on temperature

3.2 Hardness across the weld

The hardness of AA 5052 is in the range of 70-80 HV and that of AA 1100 is 35-40 HV. The hardness decreases while moving from advancing side (AA5052) to retreating side (AA1100). But the hardness in nugget zone (NZ) tend to be varying. Minimum hardness recorded at the weld centre was 34.4 HV whereas the maximum hardness at the weld centre was 54.3 HV. A slight upward trend in hardness near the AA5052 side and downward trend near AA1100 side was observed. The variation of hardness in weld zone is due to the stirring effect. The harder AA5052 and the softer AA1100 phases mixed together in the weld zone resulting in variable hardness. The effect is observed more at the weld centre than at the ends as shown in fig.8.

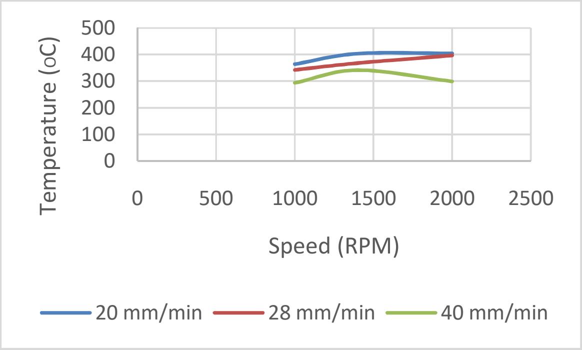

Fig.7. Effect of speed on temperature

3.3 Tensile strength across the weld

The tensile strength of unwelded AA1100 recorded was 118.974 MPa whereas that of AA5052 was 229.433 MPa. The maximum tensile strength of welded samples obtained was 94.3875 MPa at 1400 rpm and 28 mm/min (S5) and the minimum tensile strength obtained was 43.0953 at 1000 rpm and 20 mm/min (S1). The relationship between tensile strength and rotational speed is shown in fig.9. It is observed that with the increase in speed the tensile strength increases up to a maximum value and then decreases except for 20 mm/min which is the lowest feed used. At 20 mm/min, the result showed an increase in tensile strength with rotational speeds. With increase in feed rate, the tensile strength shows an increase up to a limit and then decreases gradually which is shown in fig.10. At 1000 rpm, the tensile strength recorded was less (In the order of 50 MPa) compared to higher speeds.

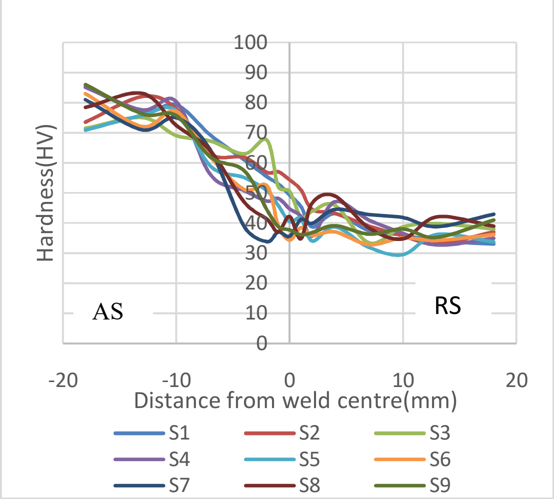

Fig.8. Vickers hardness profile of welded samples

The failure location of each tensile test specimen is shown in fig.11.It can be seen that the failure location of specimens with

1000 and 2000 rpm speeds was in the NZ or closer to thermo mechanically affected zone (TMAZ). The failure of the specimen with 1000 rpm and 28 mm/min (S5) occurred at heat affected zone (HAZ) which is evident in its highest tensile strength among all the specimens. The formation of coarse grains in the weld zone due to optimum operating parameters increased the ductility, the defects observed were little in this case. The quality of the welded joint obtained was good when medium speed and medium feed were used. Tunnel defect and cracks were observed at low and high speeds reducing the tensile strength. The variation in tensile strength is due to formation of tunnel defect, voids, surface grooves and excessive flash formed during FSW. At lower rpm, the defects observed were more due to insufficient heating which led to less tensile strength whereas high feed rate acted as a barrier against proper stirring in the weld zone.

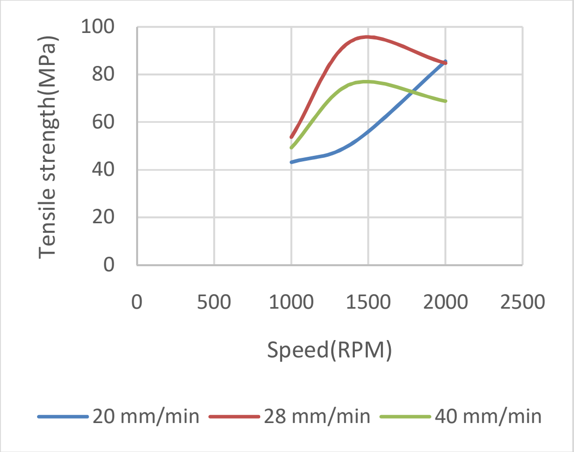

Fig.9. Effect of speed on tensile strength

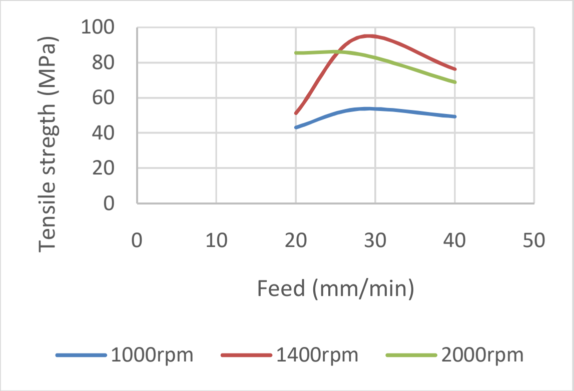

Fig.10. Effect of feed rate on tensile strength

Fig.11. Failure location of tensile test specimens

4. CONCLUSIONS

Friction stir welding is an effective joining process to weld similar as well as dissimilar metals and nonmetals. It is widely used in many industries since there are many advantages over conventional fusion welding processes. In the present study, a dissimilar FSW of aluminium alloys 1100 and 5052 was carried out on a conventional vertical milling machine. The tool rotational speeds used were 1000, 1400 and 2000 rpm and the feed rates selected were 20, 28 and 40 mm/min respectively.

The temperature was measured with the help of six K-type thermocouples fitted on the workpiece at specific intervals and the same is recorded with a National Instruments DAQ system. The temperature obtained at the retreating side of the weld was higher compared to advancing side due to thedifference in thermalproperties of AA110 and AA 5052. It is found that with the increase in rotational speed, the temperature increases because of the high frictional heating between the tool and workpiece. With the increase in feed rate, the temperature developed was decreased due to insufficient time of contact between shoulder of the tool and workpiece leading to less frictional heat development.

The hardness of the welded specimen was measured using Vickers hardness tester and found that the hardness of the nugget zone differs compared to the base metals.The tensile test was carried out and the results show that the tensile strength achieves a saturation value for each speed and feed and then gradually decreases. This is due to the weld defects developed with lower and higher speeds and feeds. The best quality weld was achieved at 1400 rpm and 28 mm/min.

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