Influence of Rotational Speed on the Formation of Weld Zone in Friction Stir Welded AA6063 Aluminium alloy

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***Abstract* - AA6063 is an aluminium alloy with medium strength. There is a high demand for this type of alloy in the construction and automotive industries. In this paper, the influence of axial thrust on the formation of weld zone in Friction stir welded AA6063 aluminium alloy is studied. An unthreaded tool pin was used to produce butt joints at five rotational speeds of 1200 rpm, 1300 rpm, 1400 rpm, 1500 rpm, and 1600 rpm. The axial thrust and welding speed of the tool were maintained constant at 6000 N and 50 mm per minute respectively. Specimens for tensile test were prepared from the joints, and tensile test was carried out. The ultimate tensile strength and percentage of elongation were calculated. The microstructure in the weld zone was also examined. The joints produced at the rotational speeds of 1400 rpm and 1500 rpm exhibited defect free weld zone without defects such as Kissing Bond and cavity. The joint produced at the rotational speed of 1500 rpm possessed superior values of ultimate tensile strength and percentage of elongation.**

Keywords: Friction stir welding, Ultimate tensile strength, Kissing Bond

I. INTRODUCTION

AA6063 is an aluminium alloy with medium strength. It is widely used in the extruded form in making flat bars, doors, window frames and in other architectural applications. There is a high demand for this type of alloy in the construction and automotive industries. However, butt joints made in this alloy by conventional fusion welding methods suffer from severe defects. The prevailing high temperature for a long duration leads to the formation of coarse grains in the fusion zone. This leads to the deterioration of mechanical properties of the joint in fusion welding. Friction stir welding (FSW) is a solid-state joining technique invented at The Welding Institute (TWI) (1991). Peel et al. (2003) reported that it is a new welding technique with potentially significant application in the automotive and aerospace industries. Using FSW, long aluminium alloy butt joints can be fabricated which are difficult to join by fusion welding method without porosity, cracking and distortion. In this method, a rotating non-consumable tool pin extending from a shoulder of large diameter is inserted into the joint line and moved along the length of the joint. Lee et al. (2003) suggested that the edge of the weld where the direction of the tool rotation is opposite to the tool travel (anti-parallel) is referred to as the retreating side, and the opposite case, where the direction of tool rotation is same as the travel, is referred to as the advancing side. As the rotating tool pin is plunged into the joint line, it shears and extrudes the material to the surface of the joint at the place of insertion. The extruded and plasticised material is then squeezed into the weld zone by the large shoulder to make the weld. Elangovan and Balasubramanian (2008) reported that when the rotating tool is traversed along the joint line, the motion of the tool pin propels the material after it has under gone the plastic deformation. Cavaliere et al. (2008) found that in FSW, the work piece does not reach the melting point, and the mechanical properties of the weld zone are much higher compared to those provided by traditional techniques. Elangovan and Balasubramanian (2008) found that when aluminium alloys are friction stir welded, phase transformations that occur during the cool down of the weld are of a solid state type. Elangovan and Balasubramanian (2008) also suggested that due to the absence of parent metal melting, the new FSW process is observed to offer several advantages over fusion welding. Elangovan et al. (2008) reported that FSW joints are prone to other defects like pin holes, tunnel defects, Kissing Bonds, etc., due to improper plastic flow and insufficient consolidation of metal in the friction stir processed region. In FSW, the quality of weld zone depends on welding parameters such as axial thrust, welding speed, rotational speed, pin profile, etc. There are a number of articles discussing the effect of the above process parameters on the mechanical properties of the FSW joints. In these articles, the formation of defects such as tunnel defect, pin holes, etc. is mainly discussed. But, the literature available for the formation of Kissing Bond defect and its elimination to produce good quality weld zone is very minimal. Oosterkamp et al. (2004) proposed that Kissing Bond is a specific type of solid-state bonding defect, where two separate regions are in contact with little or no metallic bond present. Kissing Bond can be observed only by using microscopes under high magnification. Sato et al. (2005) suggested that optimisation of the FSW process can prevent the formation of Kissing Bond. Rotational speed of the tool pin plays a major role in the formation of Kissing Bond which in turn influences the quality of weld zone in FSW. In this experiment, an unthreaded tool pin was used to produce the joints at five rotational speeds. The axial thrust of the tool is maintained constant at 6000 N. The working principle of FSW is shown in Fig.1. In case of unthreaded tool pin, as there are no threads on the tool pin, the material is removed by the rubbing action of the pin on the parent metal. The material removed by the pin flows in the upward direction by the process of extrusion. Subsequently, as the tool shoulder makes contact with the parent metal, material is removed by the shoulder due to sliding friction. There is complete mixing of materials removed by the pin and shoulder in the weld zone, and the formation of weld takes place by the forging effect of shoulder. It is observed that the mixing of materials depends on axial thrust of the tool pin. In this article, the influence of rotational speed on the formation of weld zone in AA6063 aluminium alloy is discussed.

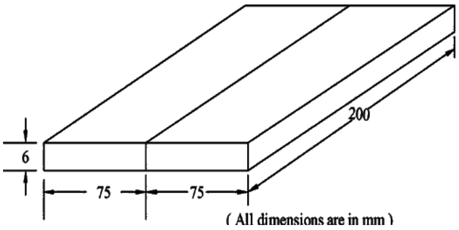


Fig 1: Principle of FSW Process

II. Experimental work

The extruded plates of 6 mm thickness, AA6063 aluminium alloy, were cut into the required size (200 mm x 75 mm). Rectangular butt joint configuration, as shown in Fig.2, was prepared. The chemical composition and mechanical properties of the parent metal are given in tables 1 and 2 respectively. A special purpose friction stir welding machine with a capacity of 10 kW was used to fabricate the joints. The rectangular plates were fitted to the machine table and clamped. An unthreaded tool with a pin length of 5.7 mm and diameter 6 mm, made of high carbon steel with a shoulder diameter of 20 mm was used to produce the joints. In this experiment, the axial thrust and welding speed of the tool pin were maintained constant at 6000 N and 50 mm per minute respectively, and the rotational speed was varied to make the joints. Five FSW butt joints were made at five different rotational speeds of 1200 rpm, 1300 rpm, 1400 rpm, 1500 rpm and 1600 rpm. Single pass welding method was adopted to make the joints. Specimens for tensile test were prepared from the joints as shown in Fig.3. Tensile test was carried using 100 kN electro-mechanical controlled universal testing machine. The specimens fractured after necking, and the fracture load was recorded for each specimen. The elongation of each specimen at fracture was also measured. Three specimens were tested under each condition, and the average values were noted down. The specimens for the microscopic examinations were also sectioned from the joints in the transverse direction of the weld and polished with different grades of emery paper and etched using Keller's solution. Microstructures in the weld zone of the joints were captured using an optical microscope.

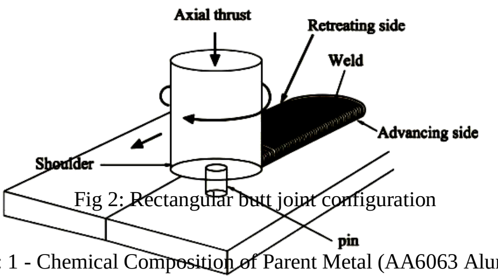


Fig 2: Rectangular butt joint configuration

Table: 1 - Chemical Composition of Parent Metal (AA6063 Aluminium Alloy)

Element	Weight
Si	0.4
Fe	0.25
Cu	0.1
Mn	0.1
Mg	0.8
Zn	0.1
Ti	0.09
Cr	0.09
Al	Balance

Table: 2 - Mechanical Properties of Parent metal (AA6063 Aluminium Alloy)

Material	Parent Metal
Ultimate Strength (MPa)	245
Elongation (%)	14
Vickers Hardness (0.5Kg)	80

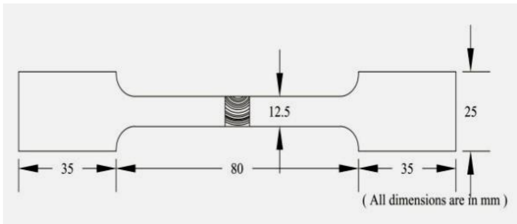


Fig 3: Tensile specimen

III. RESULTS

[1] Ultimate tensile strength

The ultimate tensile strength of the joints is presented in Table 3. It increased with increase in rotational speed to a certain maximum value and started decreasing when the rotational speed was increased further. The ultimate tensile strength of the joint produced at the rotational speed of 1200 rpm is 175 MPa and that of the joint produced at the rotational speed of 1300 rpm is 198 MPa. Whereas the ultimate tensile strength of the joint produced at the rotational speed of 1400 rpm is 216 MPa and that of the joint produced at the rotational speed of 1500 rpm is 225 MPa. But, the ultimate tensile strength of the joint produced at the rotational speed of 1600 rpm is 200 MPa.

Table 3 Ultimate Tensile strength

Rotational Speed (RPM)	Ultimate Tensile Strength (MPa)
1200	175
1300	198
1400	216
1500	225
1600	220

[2] Percentage of Elongation

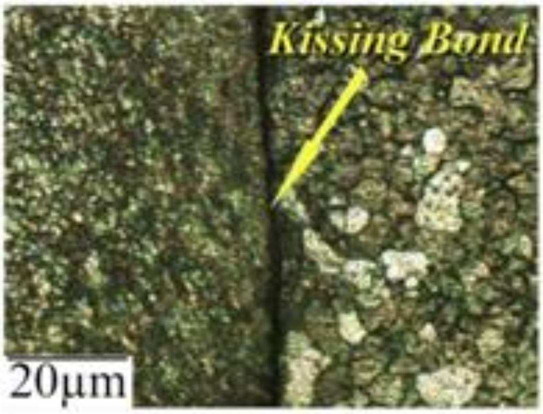
The percentage of elongation of the joints is shown in Table 4. It also showed a similar trend to that of the Ultimate tensile strength. The percentage of elongation of the joint produced at the rotational speed of 1200 rpm is 9.6 and that of the joint produced at the rotational speed of 1300 rpm is 11. Whereas the percentage of elongation of the joint produced at the rotational speed of 1400 rpm is 12.6 and that of the joint produced at the rotational speed of 1500 rpm is 13.8. But, the percentage of elongation of the joint produced at the rotational speed of 1600 rpm is 10.9.

Table 4 Percentage of Elongation

Rotational Speed (RPM)	Percentage Elongation (%)
1200	9.6
1300	11.0
1400	12.6
1500	13.8
1600	10.9

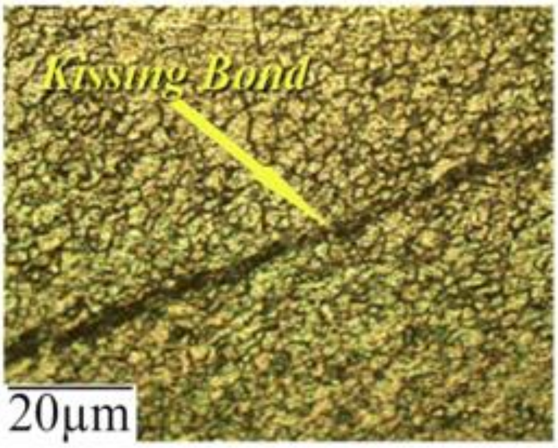
[3] Microstructure

The microstructures of the transverse section of the joints in the weld zone were examined. The joint produced at the rotational speed of 1200 rpm possessed Kissing Bond on the retreating side of the weld zone as shown in Fig.3. The joint fabricated at the rotational speed of 1300 rpm possessed Kissing Bond at the root of the weld zone as shown in Fig.4 and cavity on the retreating side of the weld zone as shown in Fig.5. Whereas the joint produced at the increased rotational speed of 1500 rpm exhibited fine grained microstructure in the weld zone without Kissing Bond and other defects as presented in Fig.6. Similarly, the joint produced at the rotational speed of 1500 rpm possessed fine grains in the weld zone as shown



in Fig.7. But, the joint produced at the rotational speed of 1600 rpm exhibited coarse grains in the weld zone as shown in Fig.8.

Fig 4: Kissing Bond at the root of the weld zone



(Rotational speed: 1300 rpm)

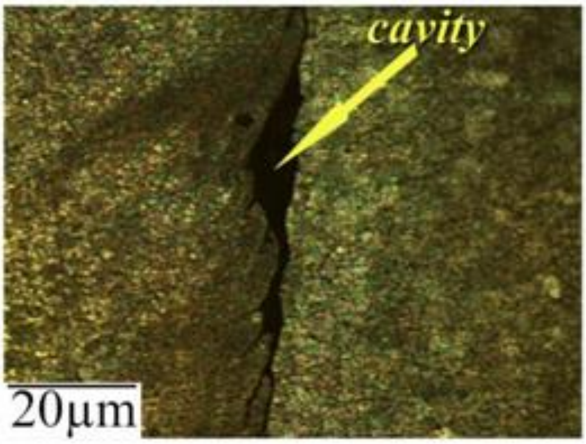


Fig 5: Cavity on the retreating side of he weld zone (Rotational speed: 1300 rpm)

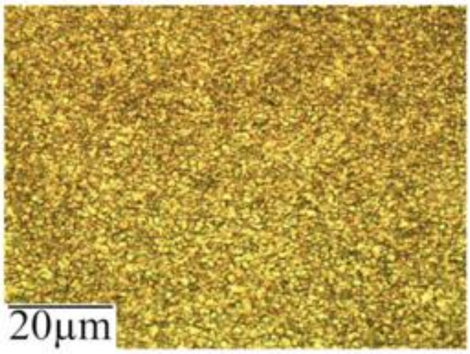


Fig 6: Fine grain microstructure in the weld zone (Rotational speed: 1400 rpm)

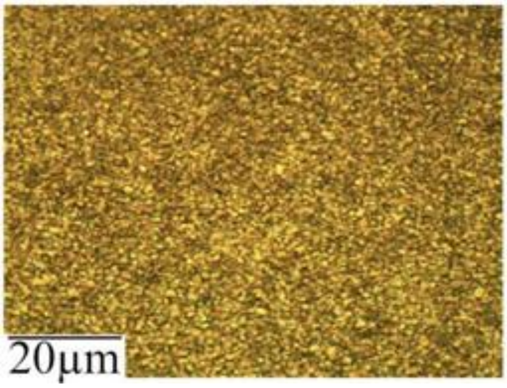


Fig 7: Fine grains in the weld zone (Rotational speed: 1500 rpm)

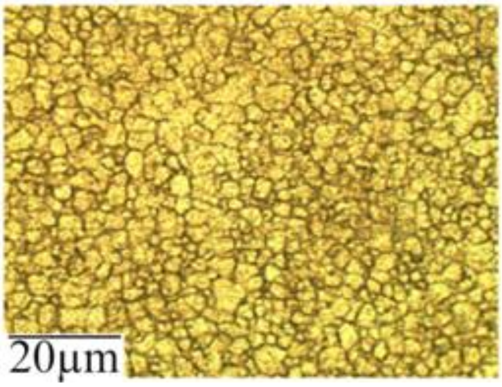


Fig 8: Coarse grains in the weld zone (Rotational speed: 1600 rpm)

IV. DISCUSSION

The role of rotational speed in the formation of weld zone in FSW is an important phenomenon. There exists sliding friction between the tool and parent metal. The sliding friction occurs in two regions. First region is the interface between the horizontal surface of the tool shoulder and the parent metal, and the second region is the interface between the vertical surface of the pin and the parent metal. Of the above two regions, the first region plays a major role in the generation of heat in FSW. The heat generation due to sliding friction in the first region depends on rotational speed of the tool pin.. Hence, the quality of the weld zone is determined by the rotational speed. When the rotational speeds are low at 1200 rpm and 1300 rpm, the sliding friction between the rotating tool shoulder and the joining surfaces of parent metal is insufficient. This leads to lower heat generation and reduced thermal cycles. Lower heat generation causes lower temperature rise. Due to lower temperature rise, the material sheared by the tool shoulder is not completely plasticized, and there is incomplete bonding between the material stirred by the pin and material stirred by the shoulder. Subsequently, the stirred material is not effectively pushed into the weld zone due to inadequate downward force exerted by the tool shoulder. The material slides along the side wall of the tool pin. Hence, there occurs Kissing Bond in the weld zone. Khodir and Shibayanagi (2008) reported that the Kissing Bond defect results from insufficient material flow due to lack of heat input. There is formation of Kissing Bond on the retreating side of the weld zone in the joint produced at the rotational speed of 1200 rpm. The retreating side of the weld zone exhibits different textures on both sides of the Kissing Bond. This could be because of the temperature gradient. The Kissing Bond at the root of the weld zone in the joint produced at the rotational speed of 1300 rpm could be due to insufficient downward pressure exerted on the stirred material and the cavity on the retreating side of the weld zone might have formed due to improper vertical flow of stirred material. Hence, the ultimate tensile strength and the percentage of elongation of the joints were lower due to the formation of Kissing Bond. Therefore, the rotational speed must be sufficiently increased to avoid Kissing Bond and cavity.

When the rotational speed is increased to 1400 rpm and 1500 rpm, there is a significant increase in heat generation at the interface between the shoulder and parent metal surface. This causes increased sliding friction and shear strain at the interface between the tool shoulder and parent metal. Oosterkamp et al. (2004) found that high local strain enhances the diffusion process which increases the intimacy of contact at the interface. Hence, there is adequate heat generation in the weld zone due to increased sliding friction. The increased sliding friction causes sufficient temperature rise in the weld zone. Kumar and Kailas (2008) found that increase in temperature reduces the flow stress of the material and the pressure required to consolidate the transferred material. This leads to complete plasticisation and mixing of material stirred by the pin and shoulder in the weld zone. Lorrain et al. (2010) reported that the strength of the joint depends on the degree of mixing of the two weld pieces. There is no sliding of stirred material along the side wall of the pin, and the weld zone is completely filled with the stirred material without separation of layers. Further, increased heat input causes dynamic re-crystallisation in the weld zone. Wei et al. (2007) investigated that when dynamic re-crystallisation happens, the original base metal grain structure is completely eliminated and replaced by a very fine and equi-axed re-crystallised grain structure. Cao and Kou (2005) found that high plasticity of the material in FSW has been attributed to very fine grains produced by dynamic re-crystallisation caused by the intense plastic deformation associated with the movement of material around the pin and frictional heating. There is effective bonding of the weld metal with the parent metal. This leads to the formation of defect free weld zone with fine grains. Hence, these joints possessed higher values of ultimate tensile strength and percentage of elongation.

When the rotational speed is further increased to 1600 rpm, there is very high sliding friction between the tool shoulder and parent metal, and it leads to large thermal cycles and excessive heat generation in the weld zone. This causes slow cooling and reduced nucleation favouring grain growth. Though there is complete plasticisation and mixing of stirred material, the excessive heat generation due to very high sliding friction leads to the formation of coarse grains. This leads to the deterioration of quality of the weld zone. Hence, this joint possessed lower values of ultimate tensile strength and percentage of elongation.

V. CONCLUSION

The influence of rotational speed on the formation of weld zone is studied, and the following conclusions were derived.

Of the five rotational speeds used to produce the joints, the joints produced at the rotational speed of 1400 rpm and 1500 rpm exhibited defect free weld zone with fine grained microstructure and without defects such as Kissing Bond defect and cavity.

The joint produced at the rotational speed of 1500 rpm exhibited superior ultimate tensile strength and higher percentage of elongation in the weld zone compared to other joints.

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