Influences of welding parameters on friction stir welding of AA 6063 Al-alloy and copper plates – An experimental study

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Abstract. Friction stir welding is a solid state welding technique for the welding of metallic compounds. The Aluminium alloy 6063 and commercially available copper of 6 mm thickness are welded in circular butt joint geometry by friction stir welding (FSW) process, using vertical milling machine. The Friction stir welding was carried out at each rotational speed of 800 rpm and 1000 rpm for different travel speed 20 and 40 mm/min at constant probe depth of 2.9 mm, towards the trailing edge and a dwell time of 3 sec. One of the critical elements for the achievement of this method is the friction stir welding tool. It comprises of a distinct geometry cylindrical shoulder and a pin. The said instrument was intended for friction stir welding of the dissimilar metal plates in the experimental job with cylindrical pin profile. The results have been correlated with the micro structural characteristics at the bond interface using scanning electron microscopy. The results show the characteristics of different types of intermetallic compound formed at the interface derived from energy input.

1. Introduction

Friction-stir welding (FSW) process is a simple joining technique. In the year 1991, Thomas et al., patented the friction stir welding. The Welding Institute (TWI) located at United Kingdom discovered a new method of friction stir welding method for joining aluminium alloy during the initial period [1]. As both the constituents have minimum melting point, the friction stir welding is less demanding to perform and is less weight in a favourable position, they has been widely used as part of many companies, such as car and aircraft companies. The device has a threaded pin and featureless shoulder. The rotational tool is leaped along the joints of double metallic plates that are tightly fixed on a back plate as shown in Figure 1. The friction is emerged as the upper-most surface of the plates comes into interaction with the featureless shoulder surface. In the weld region along the joint heading, plastic metal deformation occurs. The joint activity of the featureless shoulder and threaded pin affects this. The threaded pin forms a mixing action at the intersection point and subsequently exchanges metallic from the advancing side to the extraction side and bad habit vice-versa. The sideways of the partial plate that challenges the rotation of the hardware in the clockwise direction along the welding course is known as the advancing side, while the other side is called the retreating side. Hardness of the withdrawal side is found to be lower in most cases than the advancing side. This is owing to the continuous transfer of material to the heat cycle advancing side that gives more competent grains [1].

The main types of joints are butt joints, lap joints and fillet joints. Block diagram of the friction stir welding method is a variant of butt joint, with the remaining kinds of joints being the square butt, edge butt, T butt joint, lap joint, T lap joint and fillet joint. The widespread joint form is the butt joint and the lap joint. The partial plates are put adjacent to one another in a butt weld, whereas the plates are positioned above each other in the lap joint, where the plates are positioned in the right corners, as in
the filet joint. The relation between the characteristics of welds and different materials forming fragile intermetallic elements and the period accessible for compounds formation. It was appealed that satisfactory soldering could be performed if the joining circumstances were that fusing period is lesser than maturation period. Nevertheless, the presence of maturation for intermetallic compounds formation, however is doubtful and regulator due to be founded on restricting the thickness of intermetallic elements as opposed to on utilizing a maturation period [6]. Even though there are problems with forging temperatures due to maximum thermal conductivity variances and the creation of fragile intermetallic elements, friction stir welding is likely to be suitable within a restricted sort of welding circumstances. The geometry of tools is the supreme important feature of the improvement of processes. The geometry of the tool assumes a basic part of the material flow and controls the cross-sectional rate at which friction stir welding could be directed. As mentioned earlier, the instrument has binary important capacities are limited warming and material flow. The heating of the plunge occurs during the first phase of the tool due to the rubbing in- between the threaded pin and the work material. Some extra heating results from material twisting. Table 1 shows the vital beneficial of friction stir welding.

Table 1. Vital beneficial of friction stir welding

| Metallurgy beneficial | Eco-friendly beneficial | Energy beneficial |
|-----------------------|-------------------------|-------------------|
| • Solid state process | • No protective gas required | • Enhanced materials use (e.g., joining different thickness) allows reduction in weight. |
| • Low distortion of work piece. | • No surface cleaning required. | • Only 2.5% of the energy needed for a laser weld. |
| • Good dimensional stability and repeatability | • Eliminate grinding wastes. | • Decreased fuel consumption in light weight aircraft, automotive and ship applications |
| • No loss of alloying elements. | • Eliminate solvents required for degreasing | |
| • Excellent metallurgical properties in the joint area | • Consumable materials saving, such as rugs, wire or any other gases | |
| • Fine microstructure | | |
| • Absence of cracking | | |
| • Replace multiple parts joined by fasteners | | |

The threaded tool is forced to contact the work piece until the shoulder comes into contact. Larger part of heating is produced due to the abrasion between featureless shoulder and work material. From the heating portion, the comparative size of featureless shoulder and threaded pin is vital and the remaining components are not serious. With addition to, featureless shoulder provides restriction to the heated material. The device's secondary task is "mixing" and "moving" of the material is the
secondary task for the equipment. Properties of microstructure and operation loads are consistently performed by the tool design [5]. A curved shoulder and threaded pins are normally used. The microstructure of friction stir welding welds would be prominently varied from their therefore matching part of FSW. The greater the diameter of the shoulder, the greater the pressure. In conclusion, FSW flow of material is intricate and the distortion method understanding is restricted. It is significant to note that the material flow through friction stir welding can be subjective by several factors. These components include device geometric factors such as threaded pin and featureless shoulder design and dimensions. Welding factors are rate of tool revolution, direction, depth of plunge, spindle angle, traverse velocity, types of material and work piece temperature. Probably the material stream inside the work piece during friction stir welding comprised of several self-governing distortion forms. For the purpose of designing a tool in optimum and to achieve maximum auxiliary effectiveness joints it is significant to have the knowledge on material flow characteristics.

This led to various inquiries into the behavior of material stream during friction stir welding process. Different methodologies has been used to visualize material flow design in friction stir welding for instance tracer unit by marker, joining of exclusive metallic elements. Furthermore, some computer strategies, including finite element analysis, were used to display the material flow [5]. The heat generated during the FSW procedure is often expected to occur predominantly under the shoulder; due to its more prominent surface and equivalent to the power required to overcome the contact constraints between the device and the work piece. To an extent, the heat contribution to the welds increments as the shoulder diameter increments. Local warming from the featureless shoulder permits the deformation and transport of a material that is both in contact and in closeness to the threaded pin.

Different types of zones
Friction stir welding includes intricate connections stuck between different types of instantaneous thermal and mechanical methods. This associations impact the joint phenomena of warming and cooling, plastic distortion and streaming, dynamic fractional crystallization [9]. Friction stir welding is made up of a number of joints

Parent or unaffected material
This is the material removed from the joint that has not twisted and despite the fact that it may have encountered a heat rotation from the joint, considering in expressions of mechanical characteristics or micro-structure, is not influenced by temperature.

Weld nugget
The completely fractional crystallized region known as the stir region. It indicates the previous zone engaged by the threaded pin. The central nugget or piece section enclosing the appearance of the "onion - ring" is the individual that encounters the maximum extreme distortion and is the result of the route by which the stringed instrument stores material as of the front-facing to the rear-facing of the joint.

Thermo-mechanically affected region (TMAR)
The mechanically influenced thermal region lies between the heat affected region and the piece in this area, the grains of the leading microscopic structure are kept regularly in a twisted condition. The friction stir welding device has plastically deformed the material in this region, and the heat of the process will also have an impact on the material. In case of aluminum alloy, a significant plastic straining can be obtained in this region without fractional crystallization. During friction stir welding the design of tools, welding parameters and mixture category contribute to the contact condition. Further away from the tool center, more heat is generated. The similar can be whispered about the rate of heat generation under the threaded pin. The non – uniform heating results from a difference in relative velocities on the pin surface at different angular locations. Due to the rapid recirculation of plasticized material along the pin surface, local heat generation differences do not lead to large variations in local temperatures.
2. Literature Survey
Pradeep et al., [1] in this article examined in what way the threaded tool design and joining procedure factors contributes in the establishment of weld among comparable and distinctive welds. Butt and lap joints are the prominently utilized varieties of joints. A large portion of the welds are performed on butt variety of joints as opposed to lap joint on the grounds that no need of surface planning, simple to fix, brace and accomplish welding. In the greater part of the cases the friction stir welding is finished with round and hollow strung stick; however there are not many applications in decreased stick. Decreased strung stick can give better quality and uniform weld all through the length of the plate as referenced in instrument plan. The device tilt point relies upon the thickness of plates to be used. Experimentation discovered that thermal mechanical affected zone isn't found if there should be an occurrence of friction stir welding steel however for heat affected zone and thermal mechanical affected zone zones are clearly distinct. Moreover threaded tool wear is a basic standard to be considered before envisioning friction stir welding of steel. One useful solution for controlling the instrument wear is preheating the apparatus and work piece and the other is as said before that choosing an appropriate alloying component. Erosion and apparatus wear isn't just the properties for study, there is bunches of portrayal think about that is requirement for friction stir welding of steels to experience and understand. M. Grujicic et.al [2]. A short diagram of the preparing/property/execution relations and the basics of warmth and mass stream going with contact blend welding friction stir welding is directed. A completely coupled thermal-mechanical, finite element analysis examination of the friction stir welding procedure and the friction stir welding behaviour of a solution reinforced and strain-solidified aluminum composite is done. The fundamental friction stir welding process parameters which govern both the quality of weld and simplicity of the welding procedure (i.e., procedure efficiency) are (a) device rotational speed (b) tool travel speed (c) vertical weight connected to the device; (d) tool inclined point and (e) tool design. The thermal-production rate, thermal field, rate of cooling, force of tool-travel and the friction stir welding torque control all rely upon these procedure factors. It was demonstrated that the present computation system can account, subjectively great for the majority of the trial perceptions relating with the impact of different friction stir welding procedure parameters on the thermal/material stream and the friction stir welding-joint development. G.K.Padhy et al., [3]. In this article starts the auxiliary vitality helped by friction stir welding forms expected to exceed the restriction of the traditional friction stir welding process. The auxiliary energies used for this intention are thermal energy from electric resistance and induction heat etc., and mechanical energy as ultrasonic waves. The cutting edge, experimentation and advances in these friction stir welding variations are overviewed and collected. Secondary energy helped friction stir welding forms show extraordinary guarantee by having various favorable circumstances over the traditional friction stir welding in expressions enhanced procedure window, thermal generation, material stream, diminished burden on the threaded tools and mechanical properties of joints. Such momentous points of interest would lead these procedures to rethink numerous worldwide innovations and markets in the twenty-first century. Nonetheless, these variations are still in their primer phases of examination, and increasingly precise examinations are vital for their basic evaluation. In this perspective, some unsolved issues and difficulties are ignored. N. Bhanodaya Kiran Babu et al., [4] this paper expels about the FSW of welding thermal treatable aluminum composites for aero and automobile enterprises. These welded joints have higher inflexibility to weight extent and better scaled down scale structure. Friction stir welding of aluminum blends can hold extraordinary metallurgical and mechanical characteristics. Friction stir welding incorporates the joining of metallic elements without mix or filler resources and is acquired from traditional friction joining. At present, AA6061 is one of the basic choices for light plane skin, which requires acceptably excessive yield strength and hardness. Amongst aluminum compounds aluminum-magnesium-silicon (Al-Mg-Si) thermal improvable composites, appear to have an advantage over high - quality aluminum combinations among aluminum alloys, despite the fact that they are only medium in size. The tensile strength of the aluminum alloy AA 6061 is conferred for optimum process parameters of revolving speed, welding speed and axial force based on the consequences of different scientists. The geometry of the tool Mishra et.al [5] is a very important factor in the production of sound joints. From the review, a cylindrical threaded pin and concave shoulder are widely used for welding tool structures. With
addition to tri-fluted pins other pins such as MX trifute TM and flared-trifute TM have furthermore created. Welding parameters including the rotation rate of the tool, cross speed, incline angle of the spindle and target depth precarious to supply sound and flaw free weld. As in traditional fusion welding, the most widely recognized joint configurations in friction stir welding are the butt and lap joint designs. Jiahu Ouyang et al., [6] this paper focuses on temperature dispersion and microstructural development in the soldering of the copper mixture of aluminum 6061 (T6-temp). The direct friction stir welding of 6061 aluminum alloy to copper was troublesome due to the weakness of the intermetallic mixtures framed in the welding part. For the production of sound welds Esther T. Akinlabi Member et.al [7] butt welds of aluminum alloy and copper alloy were produced by Friction Stir Welding by differentiating the feed rate and keeping each other constant. The last welding matrix was made of joints created by a stable rotational speed of 600 rpm and the feed rate varies from 50 to 300mm/min. The joint interfaces’ microstructure and fracture surfaces have been investigated. The results found that the joint interface was depicted with mixed layers of the two joined materials. The combination of two unique materials, Aluminum (Al) and Copper (Cu), for example, is of tremendous interest for modern applications. I.Galvao, A. Loureiro and D. M. Rodrigues et.al [8] this research article examines the comprehensive Al-Cu friction stir joints, which have great surface finishing and larger mechanical characteristics, are still far from reliable. Significant changes in both base metals’ physical and mechanical characteristics and their extraordinary chemical attraction obstruct the achievement of a reasonable welding parameter window. However, in recent years, a generous increase in Al-Cu friction stir welding learning has been achieved, as outlined in the accompanying comments. Revolution and transverse speeds, the comparative location of the base materials, the geometry of the instrument, the counterbalance of the device and the aluminum and copper mixtures have a strong impact on friction stir welding. The weld surface intermetallic substance adversely affects the quality of the surface. The basic types of deformities in Al-Cu FSW are internal discontinuities, divisions and poor surface finishing.

3. Experimental Design
This research set - up in the joining method of friction stir technique consists of a friction stir welding machine as shown in Figure 1. In single couple tests, the center line of the joint has two sides. In the welding procedure, one sideways is denoted as the "propelling side" as the rotating movement of the threaded pin and its welding movement are in similar path. The "withdrawing side" is the side in which the rotating movement is the other route to that of the joining motion. The machine can be functioned with equipment revolving quicken to 2000rpm and plunge rates from 20 to 200 mm/min. The axis power, torque and depth of penetration data’s could be measured in the meantime in the midst of each welding task. All the butt joints were made under dislocation control mode for example the penetration depth has kept consistent yet the axis power reaction and torque are not straightforwardly controlled. X and Y power, and torque were recorded for all welds. The apparatus geometries of tool with featureless shoulder and threaded pin diameter across of 6mm and 20mm Figure 2. In this friction stir welding methodology is administered by the effect linked with material stream and significant mechanical distortion, which hence is impacted by procedure parameters for instance speed of rotational and welding and axis power as shown in Figure 3 and Figure 4. And table 2 represents the optimum process parameters.
Figure 1. Friction Stir Welding Machine

Figure 2. HSS tool used for FSW butt joint

Table 2. Optimum Process Parameters

| Spindle Speed (RPM) | Welding speed (mm/min) |
|---------------------|------------------------|
| 1000                | 20                     |
| 1200                | 40                     |

Figure 3. Photographs of Trial welded Plate
4. SEM Study
The scanning electron microscope (SEM) is one of the significant supply devices available for the investigation and testing of morphological characteristics of the microstructure and composition of chemical properties. An unassisted eye can distinguish substances in a visual angle of approximately $1/60^\circ$, conforming to a resolution of approximately 0.1 mm (at an optimal observing distance of 0.25m). The determination point of optical microscopy is approximately 2,000 Å by escalating the optical direction by the visual lens. Here, the electrons interconnect with the atoms that make up the specimen that create singles containing data on the examples of surface geography, parts and various properties, such as electron conductivity. JEOL JSM-8360 (SEM) is used to examine the crack surfaces of the tensile ruptured surfaces of the work piece. A new instrument of OXFORD model no.7582 incorporated to INCA computer software with SEM has been performed on the in-between zone is made to know the cracks mode. Fracture surfaces of broken test specimen were examined with the help of scanning electron microscope and photographs were taken at different magnifications i.e. x500 and x250.

There is a bulk Cu with an incessant slip in lengthened forms in the upper part of the joint and some Cu with uneven forms is extruded on topmost. In addition, the Cu bulk with an extended profile specifies that during FSW there has been severe plastic distortion. Compared to the previous one, a complex macro-structural stream happened inner part of the nugget, with many tiny Cu particles dispersed throughout the nugget along with incessant Al strips. A thick lamallae of Al-Cu intermetallic can be seen as a fluid pattern. The golden yellow colour is rich in Cu, while the black/silverfish colour is rich in Al at a speed of 1200 rpm and 20 mm per min. The picture shows that the area of influence of the shoulder was limited to the topmost of the surface, where the transportation of Al from the retreat to the progressing side of the tool is promoted. The amount of Al drawn from the retreat to the
forward side of the joint drastically decreases the threaded pin of the tool. In this situation, owing to inferior energy input and lesser revolving speed, the greater part Cu is extruded from the forward side and streams down to the region affected by the minor part of the threaded pin. It blends with Al and creates brittle mixing regions with varying values of extraordinary hardness.

![Figure 6. Macro structural flow of 6063 Al and Cu](image)

But when the elongated Cu tries to push up behindhand the tool pin, it hinders the material stream to the topmost of the joint. Due to the lesser energy input, inferior plasticisation of Cu with a greater torque and force reaction, the sliding circumstance is extra prevalent, which confines the material stream to the ascendant side and the creation of a limited vacuums on the progressing side of Cu. In the middle or bottom of the joint nugget, the greater part Cu that is extruded and blended with Al persisted. The Al is blended in the Cu matrix due to the rotation of the tools, which results in intricate configurations in the superior mid area of the joint. In the blending region, maximum hardness values point out the existence of intermetallic. The “C” rectangle is a mechanically blended region influenced by the shoulder. Due to the friction act of the upper threaded surface region with the base metal of the DHP Cu, some nearby plasticized Cu was extruded and Al was mixed under the featureless shoulder due to greater thermal production. These can be linked to interpolated whirlpool configurations that manifest the solid phase stream in different FSW. Al and Cu side optical macrostructure and EDS plotting (Figure 5 and Figure 6) the flow of preferred value is clearly represented by the parameter 1000rpm and the motion speed 20mm per min without an obvious welding defect in the stir region. Most of the copper substance remained unbroken in the upper part of the weld as shown in Figure 7.

![Figure 7. Magnified view of Fracture surface at different location for 1200 rpm and 20 mm min-1 travel speed](image)

5. Conclusions
By the FSW process, the butt joint of Al 6063 alloy (6 mm) to copper (6 mm) was effectively produced without offset on the weld line and the enlighten weld efficiency of the primary base metal aluminum was achieved. The factors such as revolving speed, motion speed and energy input is
proportional to the average strength of the weld. Revolving speed of 1200rpm and motion speed of 40mm per min gives poor strength. The energy input and maximum temperature is relatively greater in parameters of 20mm per min and 1000rpm. Additionally rate of cooling is inversely proportional to the thermal input. Owing to this maximum input of energy, dual materials such as aluminium and copper are properly elasticized; as a result thermodynamically stable Al4Cu9 and copper rich intermetallic AlCu4 are composed in larger amount with relative to the parameter of 20mm per min and 1000rpm.

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