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A REVIEW ON FRICTION STIR WELDING OF DISSIMILAR MATERIALS BETWEEN ALUMINIUM ALLOYS TO COPPER

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Abstract -- Friction Stir Welding (FSW) is a solid state welding process used for welding similar and dissimilar materials. The process is widely used because it produces sound welds and does not have common problems such as solidification and liquefaction cracking associated with the conventional welding techniques. The FSW of Aluminium and its alloys has been commercialised and recent interest is focused on joining dissimilar materials. FSW has inspired researchers to attempt joining dissimilar materials such as aluminium to copper which differ in properties and sound welds with none or limited intermetallic compounds has been produced. In this paper, we review the current research state of FSW between aluminium and copper with a focus on the resulting weld microstructure, Optimizing parameters and the tools to produce the welds and also the future research in this field of study.

Keywords --Aluminium, Copper, Friction Stir Welding, Intermetallic compounds, Microstructure.

I. INTRODUCTION

Friction stir welding (FSW) is one of the solid-state joining process. This joining technique is environment friendly, energy efficient, and versatile. In particular, it can be used to join high-strength aerospace aluminium alloys and other metallic alloys that are hard to weld by conventional fusion welding. Friction Stir Welding (FSW) is a solid–state joining technique invented by The Welding Institute (TWI) in 1991 for welding of ferrous and non–ferrous metals and plastics. FSW is considered to be the most significant development in metal joining in recent times. Friction stir welding process uses a non-consumable rotating tool consisting of a pin extending below a shoulder that is forced into the adjacent mating edges of the work pieces as shown in Fig. 1**.** The heat input, thestirring action and forging action of the tool induces a plastic flowin the material, forming a solid state weld. In this process there is no melding takes place.

The tool geometry plays a critical role in material flow and in turn governs the traverse rate at which FSW can be conducted. FSW tool consists of a shoulder and a pin as shown in Fig. 2. The tool has two primary functions: (a) localized heating, and (b) material flow. In the initial stage of tool plunge, the heating results primarily from the friction between pin and work piece. Some additional heating results from deformation of material. The tool is plunged till the shoulder touches the work piece. The friction between the shoulder and workpiece results in the biggest component of heating. From the heating aspect, the relative size of pin and shoulder is important, and the other design features are not important. The shoulder also provides confinement for the heated volume of material. The second function of the tool is to ‘move’ and ‘stir’ the material. The uniformity of microstructure and mechanical properties as well as loads are depends on the tool design. Mostly a concave shoulder and threaded cylindrical pins are used.

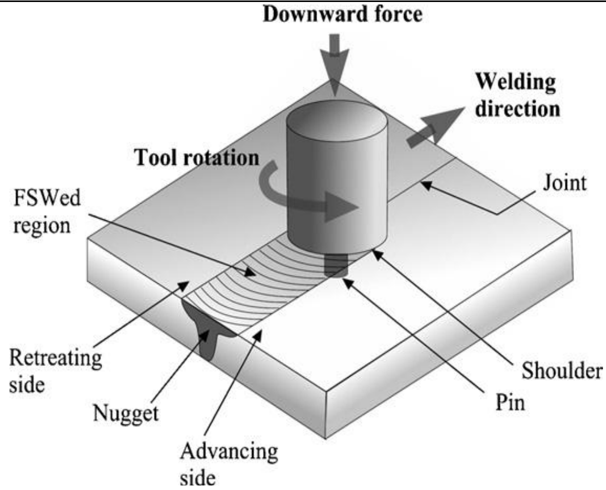

Fig.1. Schematic diagram of the Friction Stir Welding process [1]

FSW joints consist of different regions as shown in Fig. 3 following the terminologies used by Thread gill [3] which are; parent metal or the unaffected material, the Heat-Affected Zone (HAZ), the Thermo mechanically Affected Zone (TMAZ) and the weld nugget zone.

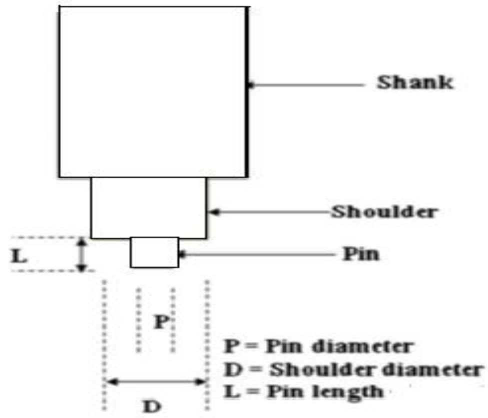

Fig.2. A Schematic View of FSW Tool (S. Raja Kumar) [2]

The Unaffected material or parent material is the material that has not been deformed. The Heat Affected Zone (HAZ) is the region, which lies closer to the weld-center; the material has experienced a thermal cycle that has modified the microstructure and/or the mechanical properties. But no plastic deformation occurs in this area. The Thermo Mechanically Affected Zone (TMAZ) is the region in which the FSW tool has plastically deformed the material, and the heat from the process has also make 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 adistinct boundary between the recrystallized zone (weld nugget) and the deformed zones of the TMAZ and the Weld nugget is the fully recrystallized area, sometimes called the Stir Zone (SZ) or Stir Nugget (SN), it refers to the zone previously occupied by the tool pin [3].

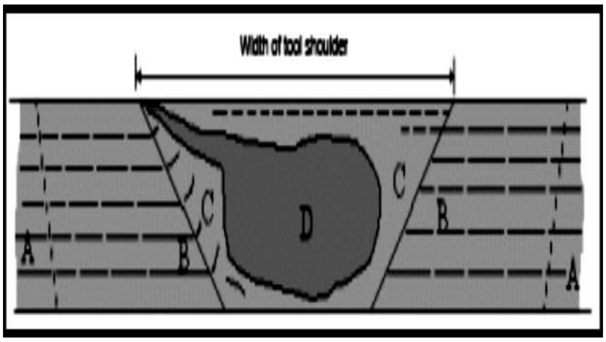

Fig.3. Illustration of different microstructural regionsof a friction stir welded material. A-parent metal or unaffected material, B-heat-affected zone, C-thermomechanically affected zone and D-weld nugget[3].

Friction stir welding of dissimilar materials remains not fully researched. Friction stir welding of dissimilar materials such as aluminum to copper in particular need to be fully understood due to their different properties and melting temperatures. The high chemical affinity of both base materials caused the formation of brittle intermetallic Al/Cu phases, so it require extensive research. Furthermore, aluminum and copper are difficult to weld with conventional welding processes due to their high reflectivity and thermal conductivity. These intermetallic phases lower the toughness of the weld and caused the cracks during and after the welding. Moreover, aluminium to copper welding is increasingly used in some practical applications such as heat transfer equipments, electrical and electronics industries, and aesthetical applications. Aluminium alloys are widely used to produce aerospace components with high specific strength. However, researchers published that when conventional welding processes are applied to these aluminium alloys, they often result in disadvantages that have sometimes discourage the use of welded components.

However, Di Paola *et al* [5] published that when traditional welding processes are applied to these aluminium alloys, they often result in disadvantages that have sometimes discourage the use of welded components. Many researchers have published reviews on friction stirwelding and processing focusing on the tools employed [6], dissimilar alloys [8], Friction stir processing [7] and on aluminium alloys [9]. To the best of our knowledge, one review focusing on friction stir welding of aluminium to copper has been published [10] but in that they haven't focused optimization techniques. Therefore, this paper critically reviewed the existing published literature by focusing on the recent work done on friction stir welding of aluminium to copper alloys especially on optimization. The rest of the paper is focused on the resulting microstructural evolution, the mechanical properties characterization, Optimization techniques and the tools employed to produce the welds between aluminium and copper.

II. RELATED STUDIES ON FRICTION STIR WELDING BETWEEN ALUMINIUM ALLOYS TO COPPER

A. OPTIMIZATION OF FRICTION STIR WELDING PARAMETERS

In an emerging field, optimization will be considered as an important one to improve its application fields. Generally optimization deals with acquiring process parameters precisely to certain value from a range of values having long spam. It helps to reduce the process of machining with so many parameters having less efficiency or output. So precise value acquirement will reduce cost and also improve its output parameters. The following are the some optimized technique done in Friction stir welding.

M.H.Shojaeefard, *et, al.*,[11] conducted research on Al–Mg and CuZn34 alloys were lap joined using friction stir welding during which the aluminum alloy sheet were placed on the CuZn34 and the process parameters were optimized using Taguchi L9 orthogonal design of experiments (DOE). The rotational speed, tool tilt angle and traverse speed were theparameters taken into consideration. The optimum levels of the rotational speed, tile angle andtransverse speed are 1120 rpm, 1.5 and 6.5 mm/min respectively. In this investigation rotational speed plays a important role and contributes 40% to the overall contribution. In verification test, it can be observed that the deviation between the predicted value of the tensile shear force and the experimental value of that is found as 2.5%. Increasing the rotational speed of the tool at constant welding speeds entail increase of the tensile shear force to maximum, and then a decrease in tensile shear force occurred.S. Raja Kumar and V. Balasubramanian[2] investigated FSW joints on six different grades of aluminum alloys (AA1100, AA2219, AA2024, AA6061, AA7039, and AA7075) using different levels of process parameters. Macro structural analysis was took out to identify the feasible working range of process parameters. The optimal welding conditions to attain maximum strength for each alloy were identified using Response Surface Methodology (RSM). The yield strength, the hardness and the ductility of the aluminium alloys play a vital role in deciding the weld quality of the FSW joints.

G. Elatharasan, and V.S. Senthil Kumar[1] central composite design technique and mathematical model was developed by response surface methodology with three parameters, three levels and 20 runs, was used to develop the relationship between the FSW parameters (traverse speed,rotational speed, axial force,) and the responses (tensile strength, Yield strength (YS) and %Elongation (%E) were established. They have concluded that UTS and YS of the FS welded joints increased with the increase of tool rotational speed, welding speedand tool axial force up to a maximum value, and then decreased. And also TE of joints increased with increase of rotational speed and axial force, but decreased by increasing of welding speed, continuously. A maximum tensile strength of 197.50 MPa, Yield strength of 175.25MPa and % of Elongation of 6.96 was found by the FSW joints fabricated with the optimized parameters of 1199 r/min rotational speed, 30 mm/min welding speed and 9.0 kN axial force.

M. Koilraj, et, al.,[12] were optimized friction stir welding process parameters with respect to tensile strength of the joint and the optimum level of settings were found out. They concluded that the optimum levels of the rotational speed, transverse speed, and D/d ratio are 700 rpm, 15 mm/min and 3 respectively. The cylindrical threaded pin tool profile was found to be the best among the other tool profiles considered. The D/d ratio plays a important role and contributes 60% to the overall contribution.

J. Gandra, et, al.,[13] addressed the deposition of AA 6082-T6 coatings on AA 2024-T3, while focusing on the effect of process parameters, such as, axial force, rotation and welding speed. Sound aluminium coatings were produced with limited intermetallic formation at bonding interface. It was observed that low welding and rotation speeds contribute to an increase of coating thickness and width. Bonding at coating edges deteriorates for faster travel speeds. The axial force is determinant in achieving a fully bonded interface.

R. Palanivel, et, al.,[14] developed an empirical relationship between FSW process parameters to predict wear resistance of friction stir welded dissimilar aluminium alloys. Five levels, Four factors, central composite rotatable design has been used to reduce the number of experiments. The working range of optimized welded parameters for well quality FSW joints of dissimilar aluminium alloys AA5083H111-AA6351T6 was found.

L. Dubourg, et, al.,[15] were investigated the effects of process parameterson good weld quality of 1.5-mm 7075-T6 stringers lap-joined on 2.3-mm 2024-T3 skins. Weld quality was assessed by optical microscopy and bending tests. They concluded that: (i) the tensile strength of FSW joints approached that of the base material but with a significant reduction in the fatigue life, (ii) the probe plunge and removal locations served as the key crack nucleation sites in specimens with discontinuous welds, and (iii) double pass welds with overlapping advancing sides showed good fatigue life and tensileoutstanding properties.

Y. Javadi, et, al.,[16] optimized residual stresses produced by friction stir welding (FSW) of 5086 aluminum plates and concluded that the peak of longitudinal residual stress is occurred in the advancing side (AS) of FSW. The position of peak couldbe accurately determined by employing the LCR ultrasonic method. They concluded that the pin and shoulder diameter of FSW tool has noconsiderable effect on the longitudinal residual stress peak.

B. FSW TOOLS USED FOR ALUMINIUM AND COPPER

Tool geometry and design are very important factor to producing sound welds. So, here we listed the different types of tools used by researchers.

In most of the research work conducted on FSW between aluminium and copper, the tool geometry and design is generally not fully disclosed. Eventhough tool geometry is a very important factor for producing sound welds. Rai*et al* [17] done a review on FSW tools but did not provide more information on FSW tools used for the joining of aluminium and copper in particular. Nevertheless, few researchers disclosed the tools used in their studies to friction stir weld aluminium to copper. Akinlabi*et al* [18] successfully welded 5754 aluminium alloy and C11000 copper by using the threaded pin and concave shoulder tool machined from H13 tool steel and hardened to 52 HRC.

Abdollah-Zadeh*et al* [19] welded aluminium alloy 1060 rolled plate to commercially pure copper with thicknesses of 4 and 3 mm employing a SPK quenched and tempered tool steel and had a shoulder diameter of 15 mm with a threaded pin of 5 mm diameter and 6.5 mm long. Galvão*et al* [20] employed conical and scrolled shoulder tools to weld oxygen-free copper with high phosphorous content (Cu-DHP, R 240) and AA 5083-H111. Esmaeili*et al* [21] employed a hot working alloy steel which was hardened to 45 HRC to weld AA 1050 to brass (CuZn30). The mentioned tool used was composed of a 15 mm diameter shoulder and a tapered slotted pin [21]. Saeid*et al* [20] welded rolled plates of 1060 aluminum alloy and commercially pure copper by using a quenched and tempered tool steel. The tool had a 15 mm diameter shoulder and a left-hand threaded pin (φ5mm×6.5 mm).

Furthermore, Li et *al* [23] used a tool with a concaved shoulder and a cone-threaded pin of 16 mm in diameter and 5.2 mm in diameter respectively. The tool pin was 2.75 mm in length to weld pure copper and AA 1350.

Agarwal *et al* [23] used a tool made of AISI H13 tool steel and High Speed Steel (HSS) and had a shoulder 18 mm and 15 mm in diameter and the tool pin 7 mm in diameter and 3.7 mm pin length [24]. The above mentioned tool was used to weld AA 6063 to commercially pure copper plates. Guerra *et al* [25] successfully welded AA 6061 with a thin high purity copper one-piece pin and shoulder from D2 tool steel heat treated to HRC62. The nib was 6.3 mm diameter and 5.8 mm long with standard 0.25/20 right-hand threads and 19 mm diameter shoulder. FSW tools are of importance in successfully welding similar and dissimilar materials why because tools produce the thermo mechanical deformationand work piece frictional heating necessary for friction stirring. Therefore, it is important to further improve the FSW tool geometry and design especially for dissimilar materials toproduce high quality welds.

C. MICRO STRUCTURE AND MECHANICAL CHARACTERISATION

Researchers focused on microstructure and mechanical characteristics of friction stir welded pieces to improve the quality of the weld and enhance the reliability.

P. Cavaliere, et, al.,[25]was studied the microstructural and mechanical behaviour of 6056 aluminum alloy Friction Stir Welded by using three different traverse speeds (40, 56 and 80 mm/min) and three different tool rotation speeds (1000, 800 and 500 rpm). The tensile tests took place on room temperature showed that the material ductility reaches the highest values for 40 and 56 mm/min traverse speed and the lowest rotating speed, decreasing strongly as increasing the rotating speed and the welding speed. The highest tensile strength is reached in correspondence of the higher rotating speeds (800 and 1000 rpm) for the highest traverse speed used in the present analysis. The fatigue endurance curves showed very different response of the material as a function of the different processing parameters.

M.P. Mubiayi and E.T. Akinlabi[26] reviewed that the friction stir welding ofdissimilarmaterials focusing on aluminium and copper has been successfully conducted. Furthermore, new studies on FSW between aluminium and copper with respect to the process optimization and selection of cost effective FSW tools to producesound welds still has to be developed. Thus, the use of the FSW technique to join aluminium and copper alloys and material shapes is of importance in the development of their industrial applications.

H. Barekatain,et, al.,[27]conducted friction stir welding between dissimilar metals AA 1050 aluminum alloy and commercially pure copper. The annealed and severely plastic deformed sheets were subjected to friction stir welding (FSW) at different rotation and welding speeds. They have kept Cu in advancing side. A range of welding parameters which can lead to acceptable welds with appropriate mechanical properties was found. For the FSWedCGPed samples, it was observed that the welding heat input caused grain growth and decrease in hardness value at Al side of the stir zone. Further investigations showed that several forms of intermetallic compounds were produced.

H. Bisadi, et, al.,[28] used FSW to join sheets of AA5083 aluminum alloy and commercially pure copper and the effects of process parameters including rotational and traverse speeds on the microstructures and mechanical properties of the joints were investigated and different joint defects were analyzed. They were observed that very low or high welding temperatures lead to many joint defects. Also intermetallic compounds and their effects on the mechanical properties of the joints were investigated. The best joint tensile shear properties were achieved at the rotational speed of 825 rpm and traverse speed of 32 mm/min.

P. Xue, et, al.,[29] produced butt joints of 1060 aluminum alloy and commercially pure copper by friction stir welding (FSW) and the effect of welding parameters on surface morphology, mechanical properties and interface microstructure was investigated. The mechanical properties of the FSW Al–Cu joints were related closely to the interface microstructure between the Al matrix and Cu bulk. A thin, uniform and continuous intermetallic compound (IMC) layer at the Al–Cu butted interface was necessary for achieving sound FSW Al–Cu joints. Stacking layered structure developed at the Al–Cu interface under higher rotation rates, resulting in the poor mechanical properties due to crack initiated.

J. Ouyang, et, al.,[30]concentrated on microstructural evolution and the temperature distribution of the friction stir welding of 6061 aluminum alloy(T6-temper condition) to Cu. The mechanically mixed region in the joining of the dissimilar metals 6061 aluminum alloy and Cu weld consists mainly of several intermetallic compounds(IMC) such asCuAl, $CuAl_2$ and Cu_9Al_4 together with small amounts of alpha-Al and the saturated solid solution of Al in Cu. The measured peak temperature in the weld zone of the 6061 aluminum side reaches 580 ◦C, which is distinctly more than the melting points of the Al–Cu eutectic or some of the hypo- and hyper-eutectic alloys. Higher peak temperatures are expected at the near interface regions between the weld metal and the stirred tool pin.

L.X. Wei, et, al.,[31] investigated dissimilar friction stir welding of pure copper 1350 aluminum alloy sheet with a thickness of 3 mm. They found no intermetallic compounds in the nugget. The hardness distribution indicates that the hardness at the copper side of the nugget is more than that at the aluminum alloy side, and the hardness at the bottom of the nugget is generally more than that in other regions. The elongation and ultimate tensile strength of the dissimilar welds are 6.3% and 152 MParespectively.

W.B. Lee and S.B. Jung[32] conducted friction stir welding on copper. Defect free weld were produced on 4 mm thick copper plate at welding speed of 61 mm/min and tool rotation speed of 1250 rpm using a general tool steel as the welding tool. The stir zone showed the very fine and equaxied grain structure compared to the base metal which had a elongated grain. The heat-affected zone (HAZ) which lies beside the stir zone had a near-equaxied and larger grain structure than that of the base metal Cu due to annealing effect. Transverse tensile strength of FSW joint reached about 87% of that of the base metal and showed slight higher value than that of the EBW Cu joint.

Y.F. Sun and H. Fujii [33] conducted friction stir welding on commercially pure copper, which included a traverse speed ranged from 200 to 800 mm/min, a rotation speed from 400 to 1200rpm and an applied load from 1000 to 1500 kg. The mechanical properties of the joints can be improved further by increasing the applied load, rather than only decreasing the rotation speed at lower applied load. The mechanism of the mechanical property changes in the Cu joints were put forward and clarified from the viewpoint of microstructural evolution.

A. Heidarzadeh and T. Saeid[34] carried out experiment to predict the mechanical properties of friction stir welded pure copper joints. The three welding parameters considered were welding speed, rotational speed and axial force. The increase in welding parameters entail increasing of tensile strength of the joints up to a maximum value. Elongation percent of the welded joints increased with increase of rotational speed and axial force, but decreased by increasing of welding speed, continuously.

III. CONCLUSIONS AND FUTURE RESEARCH

FSW process is an eco-friendly and energy efficient solid state joining technique compared to the traditional welding techniques. The joining of aluminium to copper using FSW has been reviewed to open a research window to researchers in order to expand the technique to other aluminium and copper alloys with the aim of achieving optimized the welding parameters. Moreover, leading to the commercialization of joints between these dissimilar materials. Research on friction stir welding between aluminiumalloy and copper has not yet been thoroughly researched. There ishowever, a strong need in developing the industrial applications of FSW between aluminiumalloy and copper in the manufacturing sector for the improving of the industries.

Thus, the use of the FSW technique to join aluminiumalloy and copper alloys and material shapes is of importance in the development of their industrial applications.

In summary, the review of the friction stir welding of dissimilar materials focusing on aluminiumalloys and copper has been successfully conducted. This will provide a comprehensive insight for the current and also provide the current state of research on FSW between aluminiumalloys and copper in order to fill the gaps with new research approaches and ideas. Furthermore, new studies on FSW between aluminiumalloys and copper with respect to the selection of cost effective FSW tools and process optimization to produce sound welds still needs to be developed.

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