A review on friction stir welding of aluminium alloys and the effects on tool geometry

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Abstract. Friction stir welding (FSW) is a novel technique used to join similar and dissimilar alloys. Aluminium alloys of 2XXX, 6XXX and 7XXX are reviewed and presented in this paper. In FSW welding process, heat is generated during the process and workpieces are joined without melting the aluminium alloys. The tool moves along the soften surface for joining aluminium alloys. Tool materials, tool geometry, welding speed, rotational speed, axial forces are examined and the effects on welding surfaces after welding process has been analysed. Friction stir welding can be widely used in aviation, marine and vehicle body construction industries because of its mechanical properties where fusion welding process revealed deformities on the welding materials to be joined. In this review article, the recent research of friction stir joining of aluminium alloys and its applications in various industries are explicated, including the quality of weld of aluminium alloys, the evaluation on microstructure in weld nuggets, and tool wear. The conclusion of this review is unequivocally recommended that aluminium alloys are suggested for future research with numerous industrial applications.

1. Introduction

Friction stir welding is a technique used to join Aluminium alloys, invented by The Welding Institute (TWI), UK in 1991. In FSW technique, a rotating non consumable welding tool is used for heat generation between workpiece due to friction and causes deformation at welding nugget. FSW has vast applications in aircraft, ship building, automobile body construction, and railway industries. Thus fundamental studies on rotational speed, weld nugget, microstructure, mechanical properties and process parameters have recently been studied.

The formation of the oxide layers in conventional welding is significant due to coefficient of thermal expansion, high thermal conductivity, and shrinkages during solidification process. After welding aluminium alloys using fusion welding technique, oxide formation at weld nugget cannot be avoided and mechanical properties are also not improved on the surface of workpiece. To overcome this problem, solid state welding technique such as FSW is used to join Al alloys. Further, FSW has a certain advantages over conventional welding methods because it reduces distortions, residual stresses in weld nugget.
2. Principle of FSW Technique

Friction Stir Welding is a solid state welding process in which a cylindrical shape shouldered tool rotates on the surface of the workpiece to be joined. The workpiece is which firmly clamped in the fixture of FSW machine and during the rotation of the tool, the axial force is applied on the welding surface. A non-consumable tool is used to join workpieces without melting it during the welding process and the workpiece is plasticized due to the generation of heat and friction.

3. Microstructure and Mechanical Properties of FSW Joints

In Automobile, Aerospace and Railway industries, reduction of weight is important to fabricate heavy machine parts because of limitation in the strength to weight ratio. Due to this property, materials such as copper alloys steels, wrought iron, titanium and magnesium alloys are replaced by aluminium and its alloys. Thomas et al. [1] investigated the microstructure, hardness and tensile strength of aluminium alloys Al Mg4.5Mn0.7 (AA5083) and AlZn6Mg2Cu (AA7075). During hot working process microstructures of aluminium alloys are similar and the hardness is varied in alloy AA5083. The mechanical properties of welded AA5083 and AA7075 6.0 mm alloys are as high as 100% and 72% respectively compared with base material.

After welding process, grain structure of aluminium alloys are improved drastically due to recrystallization of microstructure. Liu et al [2] investigated the microstructure of AA6061-T6 alloy by varying the welding speeds from 300 to 1000 rpm and traverse speeds of 0.15 to 0.25 cm/s. TEM (Transmission Electron Microscope) and light microscopy are used for microstructure analysis and they have divided the result in two phases. The first phase and the second phase results the variation in residual hardness between 55 WHN to 65 WHN. In weld nuggets, the grain size is 10μm and the hardness of work piece is 100μm approximately. Residual hardness is improved in the first and second phase after the solidification process but the effects of microstructure at low temperature is not investigated. Z.H. Fu et al. [3] studied the dissolution in weld nugget and the effect on microstructure during the joining of aluminium alloys at low temperature which eliminates the major problem of conventional welding processes and it is performed in the presence of inert gas. During the welding process, oxidation is drastically reduced due to the presence of inert gas.

By varying rotational speed of welding in Friction Stir Welding, harness of weld nugget has been improved by Micro hardness test. P. Cavaliere et al. [4] investigated the mechanical properties and micro structure of AA 6056 by varying rotational speeds of 500, 800 and 1000 rpm and welding speeds of 40, 56 and 88 mm/min. The joints after welding process are characterized by using micro hardness test. Residual micro hardness is also important parameters during the welding process and grain structure is also improved after solidification process. Li et al. [5] studied the residual microstructures of AA2024 and AA6061. The super plastic flow is found by residual, equiaxed grain ranging from 1 to 15 mm and reveals 40% reduction in residual micro hardness and 50% residual micro hardness reduction in the AA2024.

However, post weld treatment has not been absorbed by many researchers after the welding process. Rhodes et al. [6] investigated the mechanical properties and the behaviour of micro structure after post treatment of AA7075 alloy with the speed 5m/ min and they observed the low dense dislocation and also nugget is recrystallized and the strength of weld is enhanced after welding process. After solidification process, hardness and microstructure has been improved but dispersion of other elements over the weld nugget is not observed after post weld treatment.

Dispersion of alloying elements such as Si and Cu, Mg are used to improve the hardness during the welding process. Ghosh et al. [7] studied the phase transformation in weld zone and grain refinement of A356 and A6061-T6 aluminium alloys and studied the dispersion of Si particles on weld nugget.
Phase transformation from liquid state to solid state is played a vital role during the welding process but mechanical properties by post weld aging weld for base metal during the initial stage are not observed during the process. Yan et al. [8] attempted the effect of base metals T7451, T62 and also studied the post weld heat treatment of AA7050 aluminium alloy. The mechanical properties of base 7075 aluminium increases during initial temper the joint strength is also increased by post weld aging method. However, ultimate tensile strength improves the similar and dissimilar metals.

During welding process, ultimate strength has been improved at low welding speed and high welding speed. Sakthivel et al. [9] attempted the metallurgical and mechanical properties of the similar and dissimilar aluminium alloys by varying speed from 50 mm/min to 175 mm/min and they have found that parent material has ultimate tensile strength of 84 MPA at low welding speed of 50 mm/min and 80 at higher welding speed 175mm/min. By varying welding speed, strength of parent metal has been improved after welding process.

Super plastic impairment of Aluminium alloy improves the grain structure after welding process. S. Benavides et al. [10] investigated a study on low temperature FSW of aluminium 2024 and studied super plastic impairment using active reformation of superfine equiaxed grains. At low temperature, the hardness and the equiaxed grains are developed after the solidification process. The effect of heat affected zone is recorded during the welding process. Priya et al. [11] studied the microstructure and metallurgical properties of AA6061 and it is observed that hardness is increased in weld nugget and the hardness is not improved in HAZ (Heat Affected Zone).

Formation of onion ring and the microstructure are observed on the surface of weld nugget by many researches and similarly hardness has been improved after the welding process. Da Silva et al. [12] investigated the features of microstructure and mechanical properties of dissimilar AA2024-T3 and AA7075-T6 joints and performed hardness and tensile test. The SEM result reveals the formation of onion ring is negligible.

Aluminium alloys and its compositions are used by many researchers but they use only one or two type of similar and dissimilar aluminium alloys to analyse the microstructure and metallurgical properties. Rajakumar et al. [13] investigated six types of aluminium alloys including 7xxx series alloy such as AA7075 and AA7039. The micro structural analysis is performed in weld nugget. Ductility of aluminium alloys and tensile strength are analysed after the welding process. Leitao et al. [14] found the mechanical and metallurgical behaviour of AA5182-H111 and AA60616-T4 and the size of grains of AA5182-H111 are based on tensile strength and ductility of aluminium alloys.

Tensile strength and mechanical properties are varied at low welding speeds and higher welding speeds. O F Flores [15] attempted to find the tensile characteristics in weld nugget. It is observed that at the lowest spindle speed tensile strength is decreased. Palanivel et al. [16] investigated AA5083-H111 and AA6351-T6 using tensile strength aluminum alloys. The tensile strength and welding surface without any defects are developed during the FSW process. Sato Y.S. et al. [17] studied on aluminium alloy 1100 using stored roll bonding and the grain structure is relatively improved after FSW process. Shujun Chen et al. [18] absorbed the effect of tensile strength in weld zone and HAZ. The tensile strength of the welded joint of 100–400 A has improved by 2.74%–7.38%, and for 500A and 600A has increased by 17.11%. In HAZ and weld zone, tensile strength has not been improved after the welding process.

Researcher are not only analysed the mechanical and metallurgical properties and they are also observed concentric formations, cavities and smooth crown during the welding process. Lombard et al. [19] investigated the properties of friction stir welded AA5083-H321 aluminum alloys parameter and observed concentric ring in the weld zone and the width of the nugget was of the order of the pin
diameter. Scialpi, et al. [20] investigated on the mechanical and microstructures properties of Friction Stir welded joints based on shoulder geometries. It is recorded that smooth crown with fillet and cavity is produced after the FSW process.

Thermo-mechanically affected zone (TMAZ) is affected by varying welding speeds and mechanical properties are also affected after post weld treatment process. Singh et al. [21] studied the mechanical properties and microstructure of 7039 Al alloys after the joining process. The rotary speed of 635 rpm and the welding speed of 8 and 12 mm/min are used to weld aluminium alloys. It is recorded that the stir zone has maximum coarse grain than the thermo-mechanically affected zone (TMAZ) and the strength based on yield and tensile strength are relatively improved in the friction stir welding joints. Rajamanickam et al. [22] attempted to study the mechanical properties of aluminium alloy AA2014 based on tool rotation. From the analysis of tensile property data of joints, it is observed that tensile properties have been influenced based on parameters such as rotational and welding speed. From the above literature surveys, researchers have been attempted to analyse mechanical, metallurgical properties, concentric rings, cavities, HAZ and TMAZ by Friction Stir Welding process. From the above literatures surveys, researches are used only similar metals for their research.

4. Analysis on Tool Geometry

Microstructure, generation of heat, flow of material affects the tool geometry and the life of tool is an important feature which depends on parameter during the welding process. The parameters such as axial force, rotation, tool tilt angle, shoulder and pin diameter, welding speed have been studied and mechanical characteristics of Friction Stir Welded joints are also studied including tool life. Important parameters such as axial tool pressure (F), rotational speed (N) and traverse speed (S), on weld properties have been studied by researchers. Acerra.F et al. [23] investigated the aluminium alloy of AA7075-AA2024 and observed that heat generation is higher when the diameter of shoulder in tool is increased after the welding process and the major defects are analysed in welding zone and the elements of coating blank.

Tool geometry, shoulder diameter and pin are also an important parameters which affect the microstructure and mechanical properties. Fonda R.W. et al. [24] studied the morphology of aluminium alloys based on grain structure in FSW Process and observed that FSW tool has free from damages after the post welding process and grain structure is relatively improved near the welding tool. Finer type of grains is developed and texture follows FCC structure during the welding process. Texture of FSW welded aluminium alloys have been analysed and FCC structure is formed after the post welding process. Zaho et al. [25] the pin and shoulder plays a vital role in material flow which controls the characteristics of welding during the joining process. FSW has a weld defects and contours belong to the tool design and geometry. Material flow during the welding process is done based on pin and shoulder diameter.

Researchers are also used simulations such as CFD (Computational fluid dynamics), Analysis of variance (ANOVA) based on FEM (finite element model) to analyse the FSW aluminium alloys. Buffa.G et al. [26] made a study on the simulation based on model has been developed in which studies the geometry of tool in weld nugget. The three dimensional finite element model (FEM) based on cylindrical geometry has been investigated using FSW tool and behaviour of tool over the weld, microstructure of tool have been analysed. Mechanical properties and tensile strength has been analysed by Analysis of variance (ANOVA). Mohanty et al. [27] investigated the parameters such as speed of tool and other geometries of AA1100 aluminium alloys and Analysis of variance (ANOVA) are utilized to find the mechanical properties and tensile strength is relatively increased by increasing rotational and welding speeds.
Trivex tool and Triflute tools are compared by varying the transverse and axial forces and the mechanical properties and metallurgical properties of aluminium alloys have been compared after the welding process. Colegrove [28] investigated the material flow of FSW process using the CFD. Trivex as well as MX are used to weld alloys and the result is compared with Triflute tools. The transverse and axial force are relatively decreased by using Trivex tool and increased by using Triflute tool. CFD analysis is also used for the comparisons of aluminium alloys.

The morphology of aluminium alloys have been varied by Tool geometry, Transverse, longitudinal motions. Mahoney et al. [29] investigated the properties based on transverse and longitudinal motions. Tool geometry and microstructure have been analysed after the aging of 7075T65 Al alloy. It is observed that the yield strength, tensile strength is poor in HAZ after the post weld treatment process. Fujii Hidetoshi et al. [30] studied the microstructure and metallurgical properties after the post welding treatment and triangular type of profile is used to weld aluminium alloys. The tool has less impact at low welding speed. The strength is relatively decreased in HAZ by researchers and they are also made an attempt to modify the shape of the tool. It results that the strength in weld nugget is improved after the post treatment process.

The microstructure and mechanical properties are relatively improved by varying the tool diameter, shoulder diameter and pin. Elangovan et al. [31] studied the pin and shoulder diameter of tool on FSW of AA6061 aluminum alloy and shoulder diameters with different profiles of tool pin are used to join the welds. Their study is shown observations such as macrostructure analysis and transverse tensile properties. Micro structure and mechanical properties are relatively improved based on tool shoulder and pin profile.

Optimization Techniques such as Taguchi method is used to analyse the factors on tool geometry. Lakshminarayanan et al. [32] studied Taguchi method to find the factors which affect the tensile strength of the welded of FSW RDE-40 aluminium alloy and it observed that the influence of tensile strength of the weld is based on tool geometry. Mechanical properties such as tensile strength have been improved for FSW welded aluminium alloys.

Researchers are also used threaded and unthreaded tools to analyse the material flow in the weld nugget after the welding process. Oliver Lorrain et al. [33] investigated threaded pins and its application in industries. In the first phase, it is not unthreaded and this is because of the tool wear. The material flow has been analysed both threaded and unthreaded pin profiles. From above literature surveys, it has been found that they are varied the tool shape, shoulder diameter, pin to improve the weld nugget and analysed the material flow after FSW Process.

5. Conclusion
In this review, the friction stir welded Aluminium alloys have been presented and the simulation techniques are also validated with its process parameters. It is observed that similar and dissimilar FSW welded aluminium alloys have been utilized for industrial applications owing to its mechanical properties. For the past decades, few researchers are examined dissimilar aluminium alloys and analysed mechanical and metallurgical properties. In this paper, the grain structure of FSW joints, cavities, formation of onion rings in weld nugget zone of 2XXX, 6XXX, 7XXX series aluminium alloys are examined and SEM analysis reveals the deformities in aluminium alloys. In future, dissimilar aluminium alloys are recommended to enhance the quality of weld in industries and commercial applications.
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