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CONTENTS

A review onfriction stir welding parameters and their effect on microstructure behavior of weld joint

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ABSTRACT: This work aims to study the role of friction stir welding parameters and their effect on the microstructure behavior of weld joint. Due to differences in mechanical, physical, chemical, and metallurgical properties, etc. it is difficult to join dissimilar metals. Sometimes this is not possible to join dissimilar metals by other methods. This type of problem can be solved by using friction stir welding. Friction stir welding reduces the presence of distortions, residual stresses, defects like porosity, shrinkage, cracking etc. Properties of friction stir welded joints are nearer to the properties of parent metal because friction stir welding is performed below the melting temperature. That makes friction stir welding process suitable for dissimilar metals and various applications. The quality of FSW joint is mainly depends on selection of FSW parameters. The study of the microstructure of FSW joint helps in understanding the flow of plastically deformed material, grain structure, grain size, the bonding between the grains and to analyze the cause of various defects formed during the process.

Key words: Effects on microstructure,friction stir welding process, friction stir welding parameters

Aluminium and its alloys are widely used in various application such as aerospace, marine, space, railway, automobile industry etc. due to its light weight and high strength. In order to manufacture a single structure, comprising several components of different materials that exhibit various desirable properties, to fabricate this type of structure, it is very complicated to join different metals together in order to fulfill the requirement. Welding of different series of aluminium alloys having desirable mechanical and thermal properties due to their high specific strength, thermal conductivity, and corrosion resistance are in large demand. Joining of dissimilar metals with optimum quality is very difficult by other conventional welding method and this is done by using friction stir welding(Khan *et al.*, 2017). If these dissimilar metals are joined or connected by nut and screw then the life of the component is reduced due to cyclic loading. The main purpose of using friction stir welding in place of traditional joining process is replacing joints that are riveted in aerospace, automobile, army tank and automotive structure part etc. in order to increase the strength of joint and reducing the maintenance cost (Akinlabi *et al.*, 2014)(Bussu and Irving, 2003). FSW is a green manufacturing method because FSW is energy efficient and environment friendly. If comparing the FSW process with traditional joining method, FSW disregards the formation of residual stresses and distortions because in friction stir welding material does not reach the melting temp hence improves the mechanical properties. The crack growth rate depends on microstructure and hardness change(Bussu and Irving, 2003). FSW is a thermo-mechanical solid-state joining method, because in friction stir welding material is joined by making metallurgical bonding, below the melting point, without use of filer material hence problem related to solidification and eutectic phase is eliminated(Khan *et al.*, 2017)(Rhodes *et al.*, 1997). FSW process was introduced by Mr. Wayne Thomas in the welding institute in December 1991. Friction Stir Welding is newest method of joining either two similar or dissimilar metals(Khan *et al.*, 2017)(Thomas and Nicholas, 1997). In FSW heat required to soften or plastically deform the material is generated by friction between work piece and non-consumable tool. Due to friction between tool and workpiece the max temp generated during FSW is about 80 to 90% of melting temp of the specimen. To join the dissimilar material having different properties by conventional method is very difficult sometime it is not possible to join the dissimilar metal(Khan *et al.,* 2017)(Jata and Semiatin, 2000). This problem occurs because of difference in mechanical properties, physical properties, chemical properties, and metallurgical properties of the materials being joined. Differences in melting temp, thermal conductivity, thermal expansion coefficient, etc. of dissimilar metal can results failure at the weldment during the process of welding(Mishra and Ma, 2005). This type of problem is solved by friction stir welding in place of traditional welding process. FSW is generally used for material having low-melting-temperature such as (brass, aluminum, copper, etc.). It is very difficult to join some aluminum alloy by traditional welding process because of the formation of oxide at the weld joint.

But while using FSW in place of traditional welding there is no formation of surface oxides and no need of cleaning operation required before welding. In FSW heat required to soften or plastically deform the material is generated by friction among work piece and the tool. FSW reduces the formation of distortion, residual stresses and defects like porosity, and cracking etc. Properties of friction stir weld joints are very similar to the property of parent metal as comparing to other type of traditional welding or joining processes, this is because FSW is performed below melting temperature of the base metal that makes FSW process suitable for a variety of applications. The flow of plastically deformed materialgenerally depends on tool profile, in which the tool tip controls the material movements at lower side of the jointand tool shoulder influences material movements at the top layer of the joint. As the stirring is vital phenomenon in the FSW, the quality of weld depends on how optimally the material is plastically deformed at the joint. While comparing friction stir welding with fusion welding or other traditional joining process, the formation of grain in more homogeneous and better mechanical and microstructure properties are achieved in case of friction stir welding(Khan *et al.,* 2017)(Mishra and Ma, 2005)(Ma *et al.*, 2019)(Hajian *et al.*, 2015).

Working principal of friction stir welding

- During friction stir welding first both the weldable plates are clamped together rigidly in a bench vise.
- Now rotating tool is inserted or plunged at the center of both weldable plates, until the tool shoulder will reach near the surface of both weldable plates.
- Due to friction between rotating tool, tool shoulder and work pieces heat is generated this heat plastically deforms or softens the material.
- The rotating tool continuously moves forward along the joint line of both weldable plates. Uniformly mixing of plastically deforms material is done by tool shoulder, unlit the whole weld will be completed. After the joining process, the tool is removed from the workpiece.

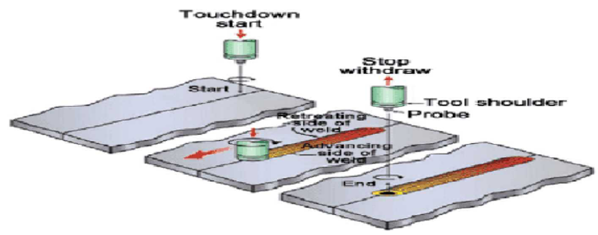

Fig.1:Friction stir welding process adapted from (Khan, Khan, & Siddiquee, 2015).

Processing zones during FSW

During FSW generally three types of zones are formed these are shown in Fig.2.

Nugget or (DXZ) dynamically recrystallized zone -DXZ zone is the one where stirring of plastically deformed metal takes place by the tool pin and tool shoulder. In the DXZ region recrystallization of metal take place which results grain refinement. Grains in DXZ are equiaxed, and are very smaller in size as compared to BM. In this region hardness is maximum.(Khan *et al.*, 2017)(Mishra and Ma, 2005).

TMAZ - This zone lies between the DXZ and HAZ zone. This region is deformed and experiences thermal cycle, which results in change in microstructural. This region is affected by lower temperature and low deformation compared to DXZ, which results partial recrystallization of the grains hence hardness will decrease in this zone as compared to DXZ.[(Khan *et al.*, 2017)(Mishra and Ma, 2005)].

HAZ(Heat affected zone) - This region is found in between BM and TMAZ. It does not deform but it is affected by heat and the microstructure of this zone is similar to the BM. This region generally Show reduction in the hardness.(Khan *et al.*, 2017).

Unaffected material or parent metal (BM) - This region is next to the HAZ. In BM zone there is no deformation, however it experiences thermal cycle but there is no significant changes in microstructure.(Khan *et al.*, 2017)

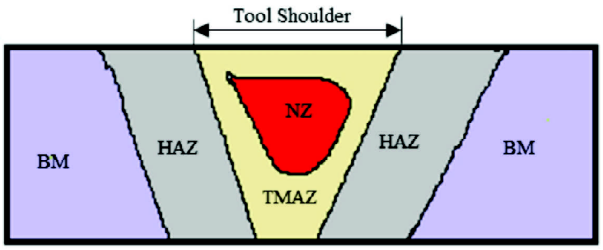

Fig.2: Various processingzones generated during FSW adapted from(Chaudhary *et al.*, 2019) Various parameters in F.S.W

Tool rotational speed
The heat required to soften and plastically deform the material mainly depends on tool rotation speed. The tool rotation speed improves the material movement and flow of plastically deformed material around the tool pin and mixes the softened or plastically deform material to produces the joint. When tool rotational speed increases, it will increase friction heat between tool tip, tool shoulder and workpiece, which leads to good joint strength. Further increase in tool rotation speed reduces the strength of joint because at very high tool rotation speed the flow of deformed material is not uniform. At very low tool rotation speed insufficient heat will produces, which results lower joint strength. Therefore, for better quality joints optimum tool rotational speed must be selected. (Khan *et al.*, 2017)(Mishra and Ma, 2005).

Tool traverse speed
The rate of heat distribution along the length of weld mainly depends on how fast tool moves. Increase in tool traverse speed will decreases the peak temp in (SZ)structural zone while low tool traverse speed will provide better mixing of plastically deformed material.When tool traverse speed is too large, it may result wear in tool tip. Therefore, for better FSW joint the tool traverse speed should be optimum(Khan *et al.*, 2017).

Tool tilt angle
Angle made between tool axis and normal line of workpiece surface called tool tilt angle. Tool tilt angle generally affects: the rate of heat generation, material movement, and consolidation of flowing material. Increase in tool tilt angle up to certain limit results in more heat generation and hence more material is plasticized. The general range of tool tilt angle is around 1° to 4° (Khan *et al.*, 2017)(Mishra and Ma, 2005).

Plunge depth
The depth from lowest point of the toolshoulder below the welded plate is plunge depth. The increase in plunge depth results increase in axial force, that results increase in frictional heat near the tool and workpiece interface and it also control the forging of plastically deform material further, rise in plunge depth results more heat input, that leads to grain growth. Lower plunge depth results low heat formation, that causes inadequate plasticize of material and due inadequate plasticize of material the mixing of material from advancing side to retreating side is insufficient that may cause the formation of defects(Khan *et al.*, 2017)(Mishra and Ma, 2005).

Tool pin offset
Shift of tool axis from the joint line is called tool pin offset. Tool pin offset results in distribution of frictional heat on retreating and advancing side, and it also effects mixing of plastically deform material. When joining the dissimilar metal by FSW the tool pin offset is taking toward softer material in order to obtain defect-free joints. The higher strength of joint is obtained while taking tool offset toward stronger material. FSW weld Joints quality can be improved by taking appropriate tool offset.(Khan *et*

al., 2017)(Mishra and Ma, 2005).

Tool geometry

For effective mix up and proper diffusion of both side metals advancing and retreating side, the tool geometry (tool tip length, tip shape, shoulder size and tool design) should be optimum because it affects the production of friction heat between tool and material, and flow of plastically deformed material from advancing to retreating side.*(Khan et al.,* 2017)(Mishra and Ma, 2005).

Microstructure

The study of the microstructure of the weld joint is important because it will help to understand how the FSW joint will perform under various conditions and has a strong influence on weld strength(Galvao *et al.,* 2016). The microstructure of Friction stir weld mainly depends on FSW parameters (tool rotation speed, traverse speed, tool geometry, tool tilt angle etc.(Sharma *et al.*, 2015). Tool rotation speed and tool traverse speed are two important factors, which affects the rate of heat generation hence these parameters are selected as input parameters.

Effects of tool rotation and tool traverse speed on microstructure behavior of FSW joint

In the past, lots of work has been done to examine the microstructure of friction stir weld joints. Some of the research work is mentioned here who studied or worked on the effect of FSW parameters on the microstructure of weld joints.

At high tool traverse speed the microstructure of nugget zone is more fine and uniform because at high tool traverse speed the recrystalization is optimum. (Cavaliere *et al.*, 2006). The microstructure behavior of weld joint depends on tool rotation and tool traverse speed. At very high tool rotation speed the surface finishing of the weld joint is very poor because of the formation of defects, but there is good metallurgical bonding between cu and Al matrixes at high tool rotation speed. Increase in tool rotation speed causes formation of brittle intermetallic phases and defect free internal structure(Xue *et al.,* 2011).Joining of dissimilar aluminum alloy and copper by FSW produces a mixed layer of aluminum and copper(that includes $CuAl_2$, CuAl). From XRD results it was analyzed that the thickness of mixed intermetallic compound layer in FSW can be controlled by selecting optimum tool rotation speed and forge pressure(Ouyang *et al.,* 2006). Joining of aluminum alloy and copper by FSW produces Cu(Al) solid solution and intermetallic compound including $CuAl_2$ CuAl Cu_3Al near the weld nugget zone. The distribution of copper in the weld depends on tool rotation speed. When the tool rotation speed high the circulation of Cu is homogeneous and at low tool rotation speed large Cu fragment are left on the aluminum alloy side and Cu fragments are concentrated. (Liu *et al.,* 2011).At high tool rotation speed the grain size in the stir zone is finer as compared to base m*et al.*

Fig.3: Influence of tool rotation speed (Fig.1)600 revolution/ min and (Fig.2)1000 revolution /mint(adapted from (Liu *et al.*, 2011)

Increase in tool rotation speed increases the frictional heat and grain growth rate, but decreases the hardness. (Barekatain *et al.,* 2014). At high tool rotation speed the internal structure is less defective and there is increase in formation of intermetallic phase due to proper mixing and sufficient heat(Abdollah *et al.*, 2008)(Xue *et al.*, 2011).At higher tool traverse speed improper base material intraction was found and at low tool traverse speed there is extensive formation of brittle material phase(Muthu & Jayabalan, 2015)(Barekatain *et al.,* 2014).At very high traverse speed deterioration of weld surface properties was found. (Muthu & Jayabalan, 2015).By increasing tool rotation speed and tool traverse speed causes homogeneity of the mixed area and intermetalic phase content was noticed(Galvao *et al.,* 2011).The tool rotational speed and traverse speed causes formation of coarser grain in the structure zone(Jamshidi *et al.,* 2011).Masoumi *et al.,* investigate that very high tool rotation and traverse speed causes the formation of tunneling and kissing bond defects and he observed that large pin creates high yield strength joints and high tool traverse speed increases hardness of the TMAZ, HAZ and nugget zone. (Masoumi *et al.,* 2018).Palanivel *et al.*(2012) analyzed that at high tool rotation speed (1300 rpm) dissolution and overaging of precipitates are formed during the FSW, which reduces the tensile strength of the weld joint(Palanivel *et al.,* 2012).

Tool geometry

The heat generation and plastic deformation of metal mainly depends on tool geometry. The tool tip and shoulder geometry of the tool also influences the weld quality of the joint and the tool wear rate. The selection of optimum tool geometry helps the friction stir welding by the following ways: To generate accurate heat for plastically deformation of the material by friction between tool and workpiece, to achieve proper stirring action for proper flow of plastically deformed material in the stir zone.

Effects of tool geometry on microstructure behavior of FSW joint

The microstructure of nugget zone consists of fine and equiaxed grain on both advancing and retreating side. It was observed that tool having flat shoulder and cylindrical threaded probe generates minimum temp, while tool with concave shoulder and conical probe produces maximum peak temperature. At maximum temperature there is homogeneous flow of material.(Jamshidi *et al.,* 2011). Masoumi *et al.,* in his study selected three tool shoulder profiles (flat, raised fan, raised spiral) and five tool tip profiles (cone, straight cylindrical tapered cylindrical, straight cylindrical, cone). Preliminary investigation was conducted on AA2198 and AA2024 in order to select optimum geometry of tool shoulder. In his study he observed that raised fan shoulder profile creates smooth surface finish in comparison to flat and raised spiral shoulder profiles and use of straight cylindrical, tapered cylindrical and cubic pin profiles produces defects free joints.(Masoumi *et al.,* 2018).Scialpi *et al.*investigated the effects of various shoulder geometries (cavity and filet, scroll and filet, only filet) on mechanical and microstructural properties of AA6082 joined by FSW. It was observed that the best joint was achieved by shoulder with cavity and fillet type shoulder geometry(Scialpi *et al.,* 2007).Palanivel *et al.* in his study he selected 5 different tool pin profiles straight square, straight octagon, straight hexagon, tapered octagon, tapered square. During his experiment he observed tool pin profile influenced material flow behavior and the formation of mixed flow region. The joint fabricated by straight tool profiles showed mixed flow region, while joint fabricated by tapered pin profiles showed absence of mixed flow region.(Palanivel *et al.,* 2012).

Effects of tool tilt angel and plunged depth and tool pin offset on microstructure behavior of FSW joint

Muhayat *et al.* (2014) selects 4 different tool tilt angle 1^0,2^0, 3^0,4^0 and different tool plunge depths were used 3.85mm, 3.90mm, 3.95mm. at tool rotation speed 1125rpm and 30mm/min. he observed that increase in plunge depth and tool tilt angle increases the rate of heat generation in both advancing and retreating side of the weld joint.(Muhayat *et al.,* 2014). The maximum temperature is generated on the advancing side of the weld joint due to the non-uniform flow of frictional heat at the contact surface of tool and workpiece.(Dialami *et al.,* 2018). Eyvazian *et al.*investigated the effect of tool tilt angel, tool pin offset and plunged depth of tool in FSW. He observed that at increasing tool tilt angel (2^0) and plunged depth (0.2mm) increases the rate of heat generation.(Eyvazian *et al.*, 2019). Increase in plunge depth increases welding temperature and produces fine grains in the structured zone.(Zheng *et al.,* 2017)

CONCLUSION

The microstructure regions of friction stir weld joint joined at the different tool rotation speed, traverse speed, tool tilt angle, plunge depth, tooltip profile and other FSW parameter was studied in this work.

With the help of information about friction stir welding parameter and their effects on microstructure collected by several researchers in their research work following conclusions are drawn-

- As the tool rotational and traverse speed increases the temperature between tool and workpiece also increases which results in adequate plastic deformation of material and higher temperature causes slower cooling rate which causes formation of coarse grains. By further increasing of tool rotation and traverse speed causes turbulence and inhomogeneous flow of material between the joint.
- An increase in tool tilt angle increases temperature of the advancing side weld plate which promotes the inhomogeneous flow of plastically deformed material that causes improper surface finish.
- Based on the microstructure study of the welded joint it was analysed that the following common defects (cracking, poor surface finish, internal discontinuities, improper interaction of both base materials, and formation of intermetallic phase) are the cause of defective weld joint and can be removed by selection of optimum FSW parameters.
- The microstructure study of weld joints helps to understand the grains structure, grain size, amount of each phase, composition, distribution or flow of material in both advancing and retreating side of the joint, etc.

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