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A Review paper on Friction Stir Welding (FSW)

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Research Article

Abstract

Friction Stir Welding (FSW) is a new solid-state welding technique which finds application in various industries. It involves the joining of metals without any help of fusion or filler material. The joint between two metals can be formed through the combined action of frictional heating and mechanical deformation which is developed due to a rotating tool. The material that flows around the tool undergoes an extreme level of plastic deformation. Rotation generates enough friction and the friction generates sufficient heat to plastify the material. FSW is handy for welding aluminum alloys. However, interest is growing in utilizing the process in a wider range of applications that also employ non aero engine metallic materials. Therefore, it is the objective of this to provide a broad view of the capabilities of the FSW process for joining metals. This review article covers various work performed on friction stir welding, and the basics of the process and the fundamental aspects of operating an FSW. This includes a description of the different parameters that have been involved in this process. And also studied the material flow, forces, and other output responses, including defects, and strain rates that is produced.

Key words: Friction stir welding, FSW, Welding technique; Temperature Distribution, Surface defect.

1. Introduction

Friction stir welding (FSW) is a recently developed solid- state welding by The Welding Institute (TWI) in 1991 [1]. In this technique, joints between two metals can be formed through excessive friction which leads to a plasticized layer at the interface of the adjoining specimens. The material will deform due to a rotation of the tool and a sufficient amount of heat is generated by the friction forces acting between the welding tool and workpiece. The tool shoulder rubs the workpiece and generates sufficient heat, such that material will become soft enough to stir it. The complete process can be divided into three stages. The first stage is known as plunging, which is analogous to a drilling operation. Here, the small nib kind of thing which penetrates along the joint and along the thickness. In FSW, instead of a welding electrode or a welding torch, it has a welding tool that rotates at a given RPM. So that tools come in to contact with the plate material, it generates a sufficient amount of friction required for the welding operation. Plunging is followed by the dwelling operation, which is the second stage [Fig. 1]. Here, the tool rotates at a constant rotational speed at the same plunging position generating more and more heat. During this period, generated heat spreads in the vicinity of the tool nib softening the adjacent material and stabilizing material flow around the tool nib. Metal reaches such a state of plasticizing where the metal can be moved as one's wish at that temperature. In the third stage, the rotating tool travels along the welding line, and mixing of viscous material takes place under the influence of an axial force, the material is forced to flow from the leading edge to the trailing edge of the tool. With the increase in temperature, the stress level needed to yield the metal reduces as both are inversely proportional to each other. Since the working temperature in FSW is above the recrystallization temperature, new grains form in the weld zone. In addition to the high-temperature rise, work material is also under the compressive loading. Therefore, new grains, formed in the weld zone, are smaller in size and almost identical in shape Fig. 2. The mechanical properties of the joint in as-welded condition provide higher strength than the parent material. This improves weld strength. There have been a few brief literature reviews on FSW, but they have tended to focus on specific areas of the process, such as the variation of forces and temperature in a friction stir welding process, defects identification, temperature and strain distribution, and influence on material flow. Neither of the reviews has attempted to give a wide-ranging and in-depth overview of the process, which this document aims to do. Therefore, this review should be a beneficial addition to the publicly available literature on FSW.

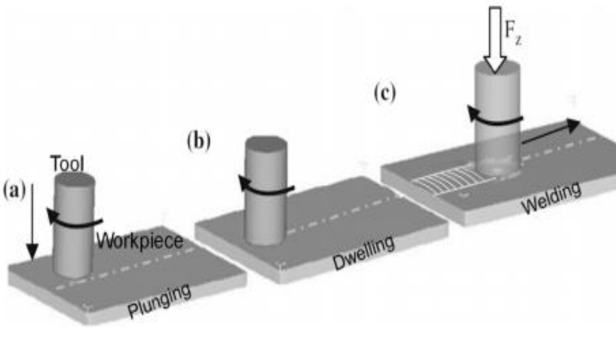

Fig.1 Different stages of friction stir welding [2]

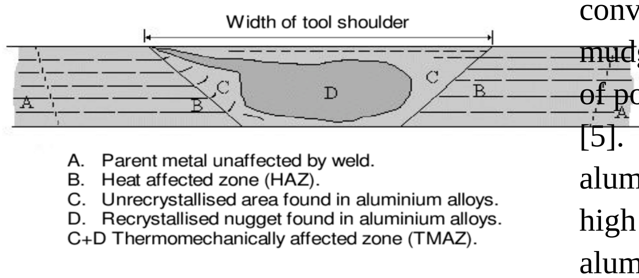

Fig.2 Metallurgy in FSW [3]

1.2 History

The need of energy has increased drastically in the last two decades resulted in the country made dependent on fossil fuels such as coal, oil and gas. The potential shortages of oil and gas due to price rise and over-exploitation of energy which in turn, raised uncertainties about the security of energy supply in the future. Since aspiration of humankind to curb fuel consumption has emerged out as an utmost priority. Fuel efficiency can be achieved by technological up-gradation, or by weight reduction. Technological revamp means replacing the old technology with a newer and better one, for example in the automobile sector, two-wheelers which were launched in the late 1990s gave an average mileage of 35–45 km/l; whereas two-wheelers of 2015 give an average mileage of 60–70 km/l, even more. This was possible with the refurbishing of an engine from two-stroke to four-stroke to electronically controlled four-stroke engines, but technological revamp is a time-consuming process, and also there is a limitation [4]. On the other hand, use of lower density material instead of higher one without compromising quality and functionality of product can improve fuel efficiency, e.g., Honda replaced a part of a steel subframe of chassis with aluminum–steel lap welding to reduce 25 % of weight of the subframe as compared to conventional steel sub frame. Two-wheelers mudguards and some other parts are made up of polymer instead of metals to reduce weight [5]. Various light-weight materials like aluminum, magnesium, etc. are alternative to high -density material, out of which aluminum is the best-suited candidate because of high strength-to-weight ratio. None of the low-density material can permanently replace steel, since they cannot provide the required stiffness for the functionality; therefore, use of higher and lower density material must go hand in hand, which makes joining of material a vital factor. Aluminum is known as a difficult to weld material because of following reasons.

The Solubility of hydrogen is higher in a liquid state than that in a solid-state. This leads to the formation of defects like porosity, blowholes, etc. due to hydrogen entrapment during conventional fusion welding processes. Aluminum has got a strong affinity toward oxygen, which leads to the formation of hard and brittle aluminum oxide layer, having melting point three times higher than that of pure aluminum. The High thermal conductivity of aluminum causes higher heat dissipation. High thermal expansion (almost twice that of steel) and high shrinkage volume (approx. 6 % of volume) increase distortion and weld crater size. Various fusion welding techniques like TIG and MIG are used to weld aluminum, but the maximum joint efficiency achieved is in the range of 50–60 % of the base metal strength. This may not be sufficient for high-strength applications like aerospace and marine sectors. To overcome these difficulties, researchers in TWI Cambridge developed a new solid-state joining process, called FSW. This process was initially intended to weld aluminum alloys only. Since the potential of the process is so high, presently it is used to weld all kinds of materials, starting from aluminum to titanium alloys, and even to plastics.

1.2 **FSW TECHNIQUE AND Different Affecting Parameter**

Friction stir welding is the technique where the material will deform due to heat generated by a rotation of the tool and a sufficient amount of heat is generated by the friction. In the FSW deformation of material and temperature are independent. Large deformation generates heat which reflects in the form of a reduction in yield strength of a material. This phenomenon should be captured by several coupled temperature-displacement model. The Temperature during FSW is above the recrystallization temperature of material which leads to the formation and refinement of new grain and also changes in mechanical properties of a material.[4] There are various Terminologies fig. [3] which are used in the FSW technique and as follows

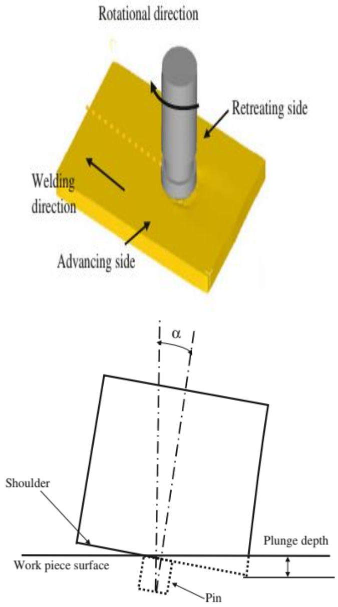

Fig.3 Terminologies used in FSW: α Spindle tilt angle [4]

There are several factors which affect the process of FSW and they are as follow

1.2.1 **Temperature Distribution over tool and workpiece**

Jain et al. 2017, [2] have performed simulation on friction stir welding to study temperature distribution and strain distribution in aluminum (Grade AA2024) using the finite element method (DEFORM-3D software). In this study, a three-dimensional coupled thermo-mechanical method based on the Lagrangian implicit method is proposed. They defined Workpiece is as rigid viscoplastic material. And von-mises yield criteria are used for stress and strain rate calculation. Sticking condition is defined between tool and workpiece. Adaptive re-meshing is used to tackle high mesh distortion. Effect of tool rotational and welding speed on plastic strain is studied and insight is given on the asymmetric nature of the FSW process. During the process total heat generation is equal to frictional heat generation and heat generation due to plastic deformation. The Temperature distribution is best defined by Fourier law of heat conduction and maximum temperature is found in the nugget zone and it is 546^{o}c fig.[4] and pin of the tool having a temperature of 146^{o}c fig.[5]Dimension of workpiece is 80 mm × 60 mm × 5 mm. the Shoulder diameter of tool is 24mm. Tapered cylindrical pin is used with the larger diameter of 7 mm with an included angle of 40 and pin height of 4.6 mm.

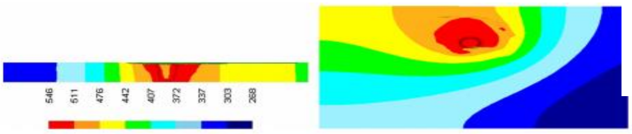

Fig.4 Temperature profile in the longitudinal direction and top surface of workpiece for 1000rpm and 60mm/min speed [2]

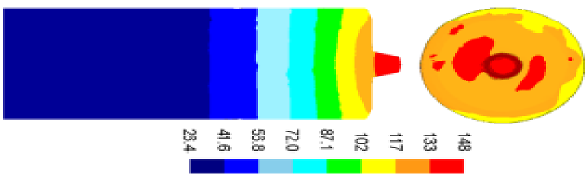

Fig.5 Temperature distribution on FSW tool for 1000rpm and 60mm/min speed [2]

1.2.2 Strain Profile

Jain et al. 2017, [2] have successfully performed simulation and found that maximum strain developed at the top surface as compared to the bottom and they found rotating shoulder generates more deformation as compared to pin. Effect of the rotational speed on deformation has been observed it has found that it increases with an increase in rotation speed whereas its opposite trend while an increase in welding speed. an inverted trapezoidal shape Strain distribution forms, which indicate the nugget zone. Which is asymmetric and formed due to stirring action of the pin. Fig.[6] and fig.[7] shows the strain profile for 600rpm and 1000rpm and fig.[8] shown Effects of rotational speed on plastic strain distribution

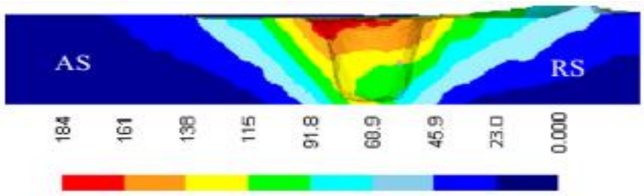

Fig.6 Strain, mm/mm profile along y-z section for 1000 rpm and 60mm/min [2]

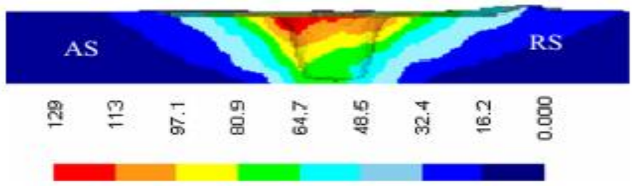

Fig.7 Strain, mm/mm profile along y-z section for 600rpm and 60mm/min [2]

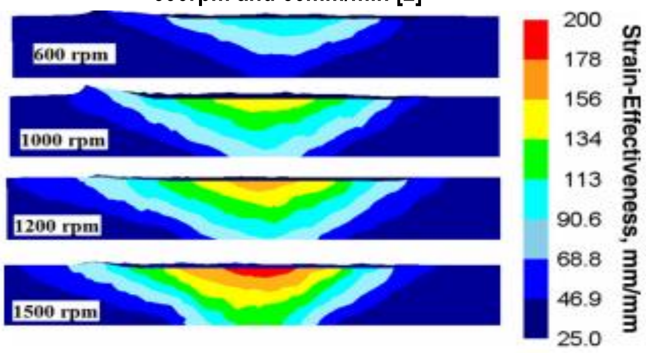

Fig.8 Effects of rotational speed on plastic strain distribution for 60mm/min welding speed [2]

1.2.3 Forces and Torque

Plunging force and Rotational torque are the key factors for performing Friction Stir welding. a variation on these affects welding speed and rotational speed. Jain et al. 2016[6] have experimented to see that effect of axial force with time during the FSW process and also a variation of spindle torque with time. for that aluminum AA2024-T4 metal having a thickness of 5.9mm is used. They observed that with increase in welding speed the requirement of rotation and torque is decrease for getting sound weld and maximum force obtain during the plunging phase fig.[9] & fig.[10] in addition to this it is more beneficial to use conical pin shape plunge as its produce higher material velocity as compared to cylindrical shape plunge and they found advancing side having more plastic strain as compare to retreating side which indicates asymmetry nature of the FSW process.

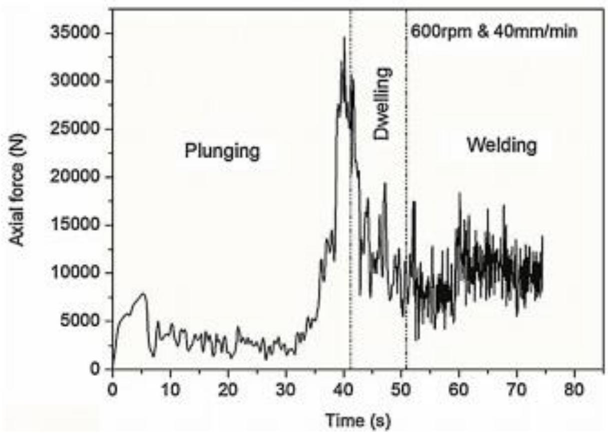

Fig.9. Evaluation of axial force with time during FSW process [6]

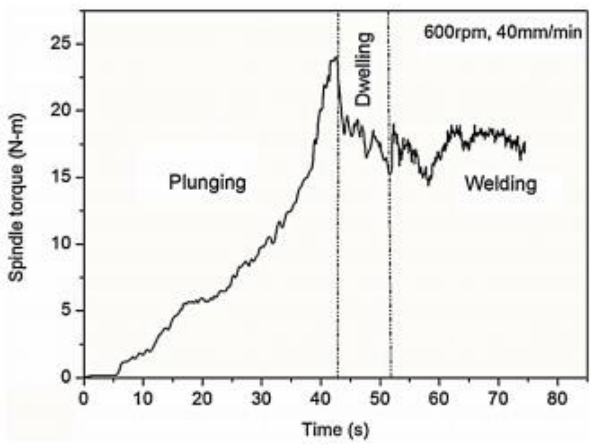

Fig.10. Evalution of spindle torque with time during FSW process [6]

1.2.4 Tool Geometry

K. Kumari et al. 2015[7], designed and fabricated a new counter-rotating twin tool fig.[11]. They analyze the effect of a single tool using double pass (ST-DP) and twin tool on pure aluminium alloy with different welding speed and tool rotation in a Friction stir welding. They found at 1800 rpm and 63 mm/min twin tool shows the higher hardness profile as compare to single tool double pass

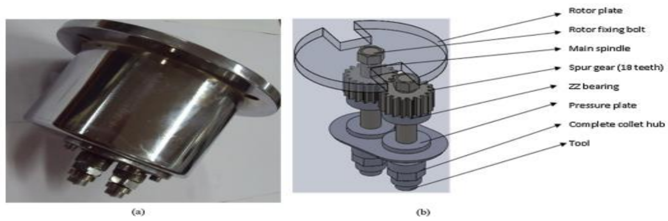

Fig.11 Twin tool attachment with schematic diagram [7]

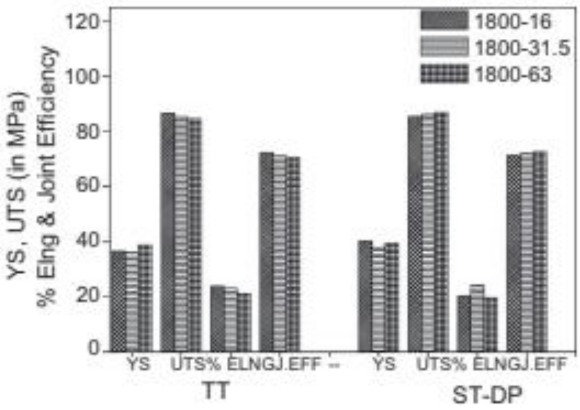

Fig.12 Effect of TT and ST-DP on YS, UTS, % elongation and joint efficiency of the welded samples at a constant rotational speed of 1800 rpm [7]

1.2.5 Tool Profile

One of the important parameters for friction stir welding is tool geometry as it influences material flow, Forces and other output responses. Jain et al. 2017[8] have observed different performances on two different pins, i.e., smooth conical and threaded conical by developing a thermomechanical model based on the lagrangian method.fig.[13] They found that higher slip rate and vertical flow are observed in threaded conical pin and its negligible for the smooth conical pin and axial and welding forces are lower in the threaded conical pin as compared to others.

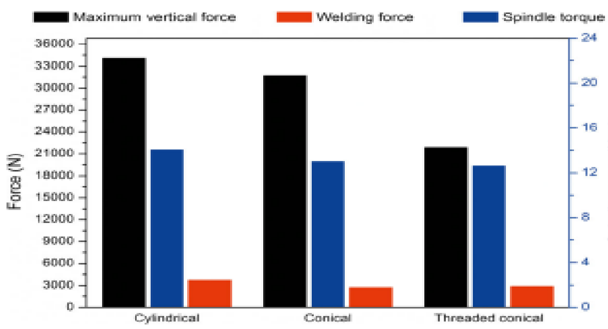

Fig.13 Effect of pin shape on forces and spindle torque for rotational speed of 800 rpm and 80-mm/min welding velocity [8]

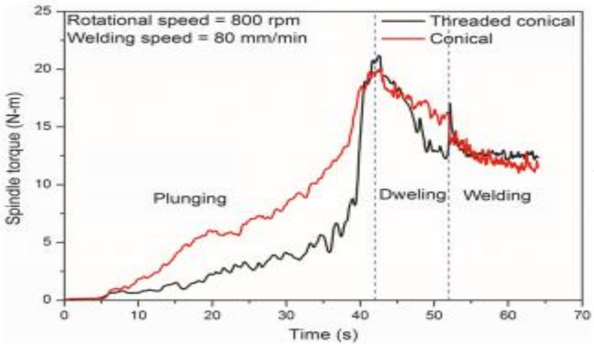

Fig.14 Evolution of spindle torque with time for conical and threaded conical pins [8]

1.2.6 Tool Parameter

Sahu et al. 2016[9] have done to see the effect of the Influence of plate position, tool offset and tool rotational speed on mechanical properties and microstructures of dissimilar Al/Cu friction stir welding joints. They found that high-quality weld joint maybe obtain by placing the copper plate the advancing side of the tool rotation. In addition to this under specific critical offset condition, higher mechanical properties and defect-free joint can be observed. Maximum ultimate tensile strength is achieved 95% with respect to the base plate where the bending angle was around 65^0 Fig.[15]. The hardness will be distributed from al to cu side and maximum hardness is obtained at the joint interface and at the bottom of the nugget zone which is observed by the vickers hardness test. However at nano-level broken grains were observed. XRD analysis shows that the weld joint are the same at the center of the joint and 2mm away from the joint center for al and cu. Following are the conclusion are made by the author

1.large volume defects are observed when Al plates are placed on the advancing side while Defect-free joint can be obtained, when the hard Cu plate is placed on the advancing side.

2. It was observed from these experiments that, to get appreciable quality in Al/Cu joint offset-ting the pin towards the softer material (Al plate) is needed.

3. Defect free joint and good mechanical properties can be obtained when pin offset is more than 1.5mm, rotation speed 1200 rpm, welding speed 30mm/mi,0.1 mm plunging depth.

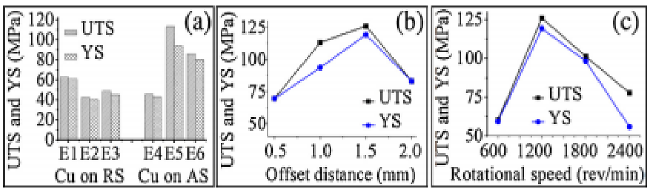

Fig.15 Variations of tensile strength with (a) position of the plate, (b) tool offset and (c) tool rotational speed.[9]

2. WELDING DEFECT IN FSW

2.1 Defect Identification

Ujjwal et al. 2015[10] have studied Defect identification in friction stir welding using discrete wavelet analysis to evaluate the transformation of Force and torque signal. For this purpose, aluminum alloy AA1100 are used whose specification was 200mm × 80mm × 2.5mm. The Defect can be analyzed in the form of change in force signal (Z-load). frequency vs. time with varying resolution can be obtained in Discrete wavelet transform. High frequency has shown the detail features whereas low frequency shows the original data. They have decomposed the filtered signal into three levels using mother wavelet of Daubechis of order 4 and the detail coefficient are studied. Defect free joint can be shown by a smooth force signal plot as shown in fig[14].

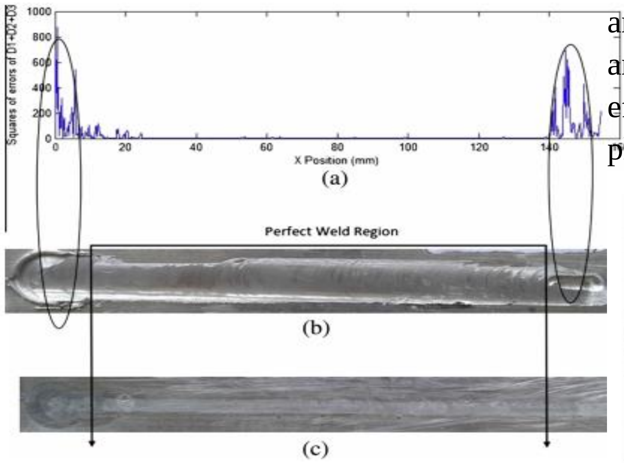

Fig.14 (a) Square of errors of sum of detail coefficients, (b) front side of the weld, and (c) rear side of the weld [10]

2.2 **Welding Defects**

Chauhan et al.[11] have developed a coupled Eulerian and Lagrangian method to studied the friction stir welding process. For this purpose to analyze the defects, the volume of fluid principle is used in addition to this they have successfully calculated spindle torque and axial force developed during FSW. They simulate different heights of a pin and optimum height is observed at 2.5mm and tilt angle is 2^0.

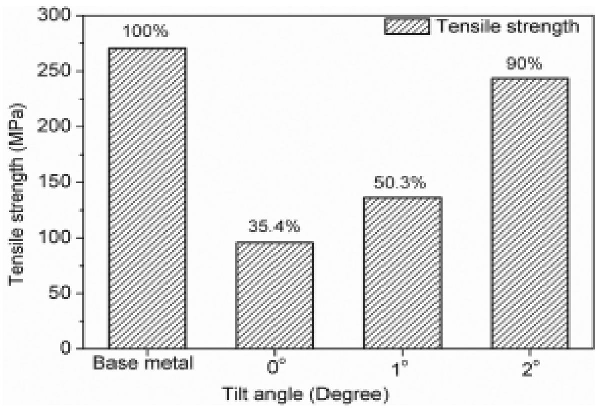

Fig. 15. Influence of tilt angle on experimental weld strength for a rotational speed of 900 rpm and welding speed of 60 mm/min.[11]

For defining the flow stress johnson cook material model is used and contact interaction is defined by coulombs law of friction. Experiment shows that tensile strength is directly proportional to effective plastic strain and welding efficiency of 90% are found for an effective plastic strain of 230 and weld efficiency of 65% are found for effective plastic strain 60.

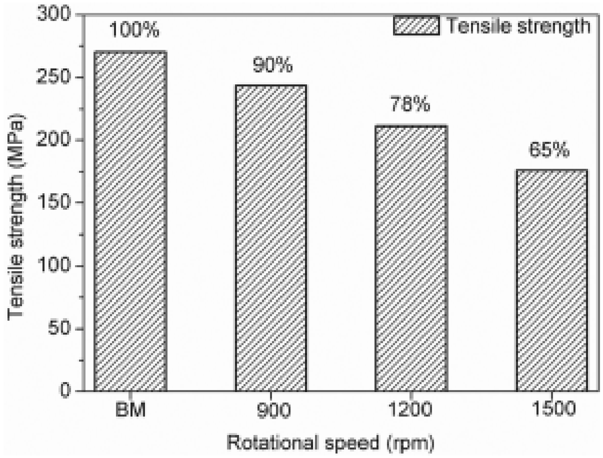

Fig.16 Influence of tilt angle on experimental weld strength for a rotational speed of 900 rpm and welding speed of 60 mm/min [11]

2.2.1 Surface defects

Ranjan et al. 2016[12] have studied for defect-free weld and mainly focused on surface defects during the FSW process. They have used digital image processing techniques to identify suraface defect using image pyramid and image reconstruction algorithms. These defects are classified as voids,grooves,rough surface textures in workpiece. Additionally, the area plot gives the density of all kinds of defects in a cross-section of the weld bead surface which can be used to analyze the percentage of good weld that occurred.

Conclusion

This review paper has discussed different aspects of FSW and recent research work, FSW having a capability to grows in different industries and solve issues related to aluminium which tending to form an oxidized layer during welding. The Different modifications will be suggested to obtain desire weld strength and to get sound weld.

Different methodologies are used to studied FSW where three types of process based on Langrangian approach, Eulerian approach, and coupled Lagrangian and Eulerian are used. Each of this method having an own advantages. Eulerian techniques take least times among them but cannot simulate plunging state. lagrangian technique used along with strong remeshing technique which are capable for predicting all the out-put responses, grain size and microstructure of the material. CEL method having an ability to predict volumetric defects and used for large deformation processes.

Conflict of interest

The author declares no conflict of interest.

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