Journal of Manufacturing Engineering, September, 2011, Vol. 6, Issue. 3, pp 172-176

EFFECT OF TOOL SHOULDER DIAMETERS ON TENSILE STRENGTH OF FRICTION STIR WELDED AA1100 ALUMINUM ALLOY JOINTS

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ABSTRACT

Recently, friction stir welding of AA 1100 aluminium alloys has received great attention in industry. This is due to its widespread application in marine cooking utensils, various architectural components, food and chemical handling and storage equipments, and welded assemblies. Friction stir welding process is an emerging solid state joining process in which the material that is being welded does not melt and recast. The friction-stir-welding (FSW) process and tool parameters play a major role in deciding the joint characteristics. Therefore, mechanical properties should be controlled to obtain good welded joints. This paper reports the effect of friction stir welding (FSW) tool shoulder diameters on the tensile strength of AA 1100 aluminium alloy joints. Five joints were fabricated using with the different combinations of tool shoulder diameter. The joint fabricated using shoulder diameter of 15mm exhibited higher tensile strength compared to other joints.

Key words: *Aluminum Alloy, Welding and Microstructure.*

1. Introduction

Friction stir welding (FSW) is a relatively new solid-state joining technique and has been extensively employed for aluminum alloys, as well as for magnesium, copper, titanium and steel. Compared to conventional fusion welding methods, the advantages of the FSW process include better mechanical properties, low residual stress and distortion, and reduced occurrence of defects [1&2]. This welding technique is being applied to the aerospace, automotive, and shipbuilding industries, and it is attracting an increasing amount of research interest. FSW technology requires a thorough understanding of the process and the consequent evaluation of weld mechanical properties are needed in order to use the FSW process for production of components in aerospace applications. For this reason, detailed research and qualification work is required [3]. Based on friction heating at the faying surfaces of two sheets to be joined, in the FSW process a special tool with a properly designed rotating probe travels down the thickness of contacting metal plates, producing a highly plastically deformed zone through the associated stirring action. The localized thermo mechanical affected zone is produced by friction between the tool shoulder and the plate top surface, as well as plastic deformation of the material in contact with the tool [4]. The probe is typically slightly shorter than the thickness of the work piece and its diameter is typically slight larger than the thickness of the work piece [5]. The microstructure evolution and the resulting mechanical properties depend strongly on the variation of the processing parameters leading to a wide range of possible performances [6].

The formation of FSP zone is affected by the material flow behavior under the action of rotating tool. However, the material flow behaviour is predominantly influenced by the material properties such as: yield strength, ductility and hardness of the base metal, tool design, and FSW process parameters. Compared to fusion welding techniques, friction stir welding strongly reduces the presence of distortions and residual stresses [7-9].

O.Hatamleh et al. [10] have reported the effect of shot-peened and laser peened on weld microstructure and mechanical properties of AA7075-T_6 aluminium alloy joints. The metallographic section show a classic weld nugget region and the stirring marks, commonly denoted as ‘‘onion rings,” typically found in this region of the weld. A more recent investigation by Cai et al. [11] revealed that the grains in the nugget zone are not 3d equiaxial but 2d rod-like. The grain structure in Thermo-Mechanical Affected Zone (TMAZ) region was elongated and distorted due to the mechanical action from the welding tool. The heat-affected zone was unaffected by the mechanical effects from the welding tool, and the grain structure in that region resembles the parent material grain structure.

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There have been lot of efforts to understand the effect of process parameters on material flow behaviour, microstructure formation and mechanical properties of friction stir welded joints. Finding the most effective parameters on properties of friction stir welds as well as realizing their influence on the weld properties has been major topics for researchers [12-13]. The influence of some of the important parameters such as axial tool pressure (*F*), rotational speed (*N*) and traverse speed (*S*), on weld properties have been investigated. The tool shoulder diameters on FSP formation and tensile strength are hitherto not reported. Hence, in this investigation an attempt has been made to understand the effect of tool shoulder diameters on FSP zone formation and related tensile strength of friction stir welded AA 1100 aluminium alloy joints.

2. Experimental Work

Rolled plates of 5 mm thick, AA 1100 aluminium alloy base metal, were cut to the required size (300 mm ×150 mm) by power hacksaw cutting and milling. Square butt joint configuration (300 mm × 300 mm) was prepared and the direction of welding was normal to the rolling direction of the base plates. The joint dimensions are shown in Fig.1. Single pass welding procedure was followed to fabricate the joints.

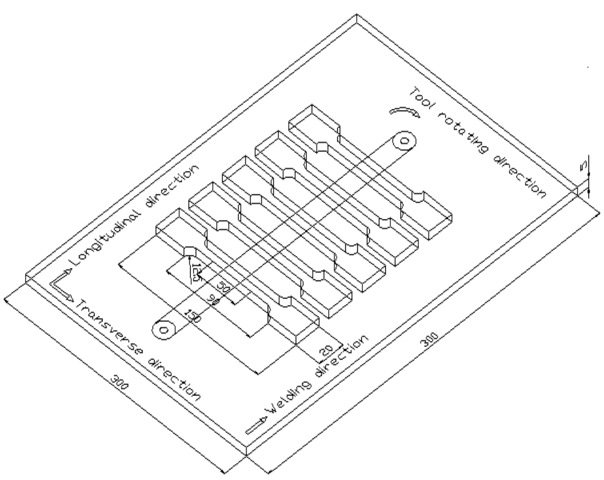


Fig. 1 Dimensions of Butt Joint Configurations in ('mm')

The chemical composition and mechanical properties of base metal are presented in Table 1 and Table 2. Non-consumable tools made of high carbon steels were used to fabricate the joints. Five different shoulder diameters were made to fabricate the joints and selected joints are displayed in Fig.2.

Fig.2 Fabricated Joints

An indigenously designed and developed computer numerical controlled FSW (22 kW; 4000 RPM; 6 Ton) machine was used to fabricate the joints. The welding condition and process parameters are presented in Table.3.

Table 1: Chemical Composition (wt %) Properties of Base Metal

Chemical composition						
Alloy	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Al**
AA1100	0	0.06	0	0.51	0.15	Bal

Table 2: Mechanical Properties of Base Metal

Mechanical Properties			
Yield strength (MPa)	**Ultimate tensile strength (MPa)**	**Elongation (%)**	**Hardness (0.05 kg @ 15 s) (HV)**
105	110	32	70

The welded joints were sliced using a power hacksaw and then machined to the required dimensions to get tensile specimens. The tensile specimens were prepared as per the ASTM E8M-04 guidelines [14] and it was shown in Fig.3. The tensile test was carried out in 100 kN, servo controlled universal testing machine (Make: FIE – BLUESTAR, INDIA, Model: UNITEK 94100) with a cross head speed of 0.5 mm/min at room temperature.

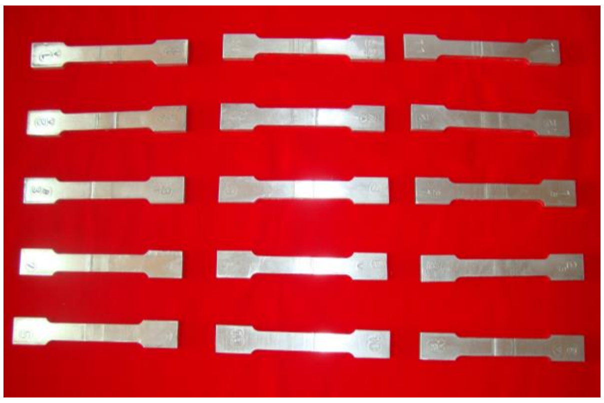


Fig. 3 Tensile specimens

Table 3: Process Parameters

Parameter (Unit)	Range
Tool rotational speed (rpm)	900
Welding speed (mm/min)	100
Tool shoulder diameter (mm)	9,12,15,18,21

The specimens for metallographic examination were sectioned to the required sizes from the joint comprising FSP zone, TMAZ, HAZ and base metal regions and then polished using different grades of emery papers. Final polishing was done using the diamond compound (1µm particle size) in the disc polishing machine. The polished samples were etched using 10% NaOH to show general flow structure of the alloy. A standard Keller's reagent made of 5ml HNO_3 (95% concentration), 2 ml HF, 3ml HCL, 190ml H_2O was used to reveal the microstructure of the welded joints. Macro and micro-structural analysis have been carried out using a light optical microscope (VERSAMET-3) incorporated with an image analyzing software (Clemex-Vision). The fractured surfaces of the tensile tested specimens were examined by a Scanning Electron Microscope (SEM) to reveal the fracture surface morphology.

3. Discussion

3.1 Effect of Tool Shoulder Diameter

The tool shoulder diameter is having directly proportional relationship with the heat generation due to friction [15-18]. It is reported that at the top surface of the FSP region, a material transport occurs due to the action of the rotating tool shoulder. Material near the top of the FSP region, approximately the upper one-third, moves under the influence of the shoulder rather than the profiles on the pin. The pin of the tool generates the heat and stirs the material being welded but the shoulder also plays an important part by providing additional frictional treatment as well as preventing the plasticized material from escaping from the weld region. The friction between the shoulder and work piece results in the biggest component of heating. From the heating aspect, the relative size of pin and shoulder is important. The shoulder also provides confinement for the heated volume of material. The second function of the tool shoulder is to 'stir' and 'move' the material. The uniformity of microstructure and properties as well as process loads is governed by the tool design. Fig.2 displays the effect of shoulder diameter on strength properties of FSW joints of AA 1100 aluminium alloy. Table 4 presents the effect of shoulder diameter on macrostructure, microstructures, and fracture surface morphology of FSW joints of AA 1100 aluminium alloy. From Fig.4 and Table 4, the following inferences can be obtained:

i. The larger tool shoulder diameter (21 mm) lead to wider contact area and resulted in wider TMAZ region and HAZ region and subsequently the tensile strength (80MPa) of the joints are deteriorated.

ii. The smaller tool shoulder diameter (9 mm) lead to narrow contact area and resulted in less frictional heat generation and hence the weld metal consolidation is not good in the FSP region and subsequently resulted in lowest tensile strength (78MPa).

iii. Of the five joints fabricated using different tool shoulder diameters, the joint fabricated using the tool with 15 mm shoulder diameter exhibited superior tensile strength (101MPa).

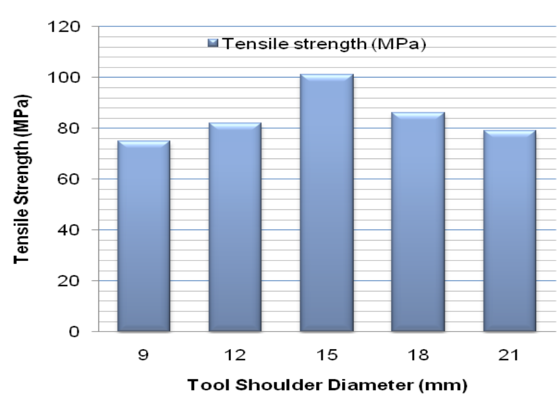
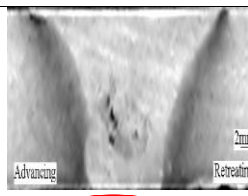
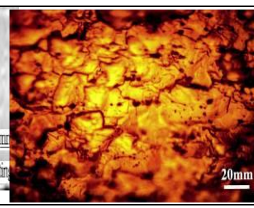
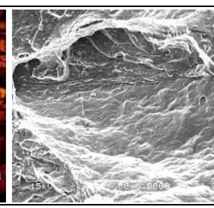
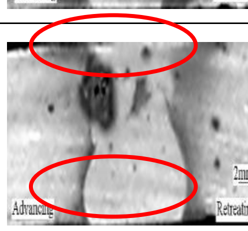
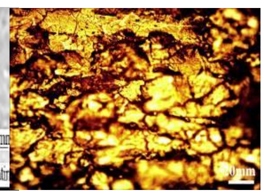
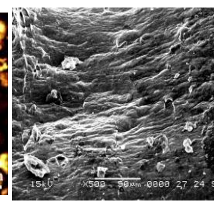
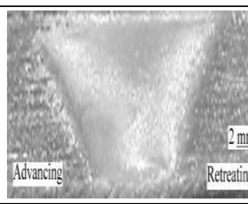
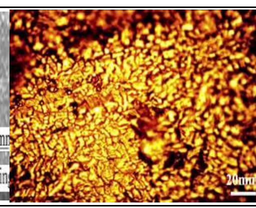
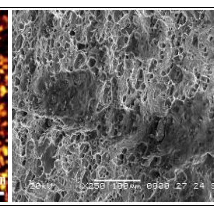
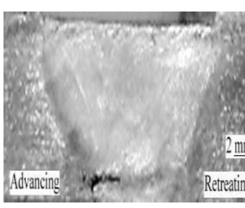
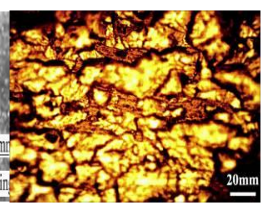
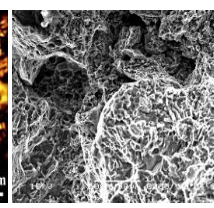
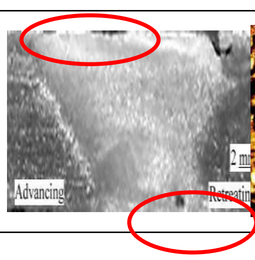
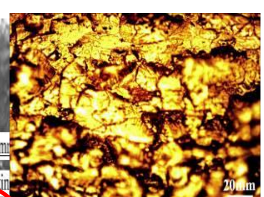
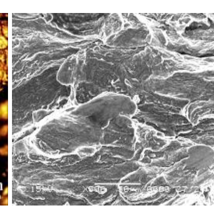


Fig. 4 Effect of Tool Shoulder Diameters on Tensile Strength

Table 4: Effect of Tool Shoulder Diameters on Joint Characteristics of AA 1100 Alloy (N-900rpm, S-100mm/min)

Shoulder diameter	Tensile Strength (MPa)	Macrograph of joint cross-section	Micrograph of FSP region	Factograph of fracture surface	Observations
8	TS= 78				(i)Name of the defect: Pin hole (ii)Location of the defect: Stir zone (iii)Reason for the defect: Insufficient heat input (iv)Location of failure: Along the weld (v)Average grain diameter: 42µm (vi)Fracture morphology: Quasi-cleavage
12	TS=82				(i)Name of the defect: Worm hole (ii)Location of the defect: Advancing side (iii)Reason for the defect: Insufficient Fitting surfaces (iv)Location of failure: TMAZ (v)Average grain diameter: 27µm (vi)Fracture morphology: Fine dimples
15	TS=101				(i)Name of the defect: Defect free (ii)Location of the defect: Nil (iii)Reason for the defect: Sufficient heat input (iv)Location of failure: TMAZ (v)Average grain diameter: 23µm (vi)Fracture morphology: Very fine dimples
18	TS=86				(i)Name of the defect: Pin hole (ii)Location of the defect: Advancing side (iii)Reason for the defect: More heat input (iv)Location of failure: TMAZ (v)Average grain diameter: 25µm (vi)Fracture morphology: Coarse dimples
21	TS=80				(i)Name of the defect: Pin hole (ii)Location of the defect: Retreating side (iii)Reason for the defect: Excessive heat input (iv)Location of failure: TMAZ (v)Average grain diameter: 36µm (vi)Fracture morphology: Quasi-cleavage

At larger shoulder diameter, may leads to wider contact area and resulted in wider TMAZ region and HAZ region and subsequently the tensile strength properties of the joints are deteriorated. As the shoulder diameter increased from 9 mm to15 mm both the strength and joint efficiency improved, reaching maximum before falling again at larger shoulder diameter (21 mm). Smaller shoulder diameter resulted in sufficient heat generation due to smaller contact area, cause's defects in FSP zone causes grain growth and severe clustering of precipitates in the SZ, which resultantly produced lower tensile strength. The fracture morphology of coarse dimples is also due to the above reasons. So, the combined effect of coarse grains, lower hardness and presence of defects deteriorated the tensile strength properties of the joint fabricated at a larger shoulder diameter of 21 mm compared to the joint fabricated at a shoulder diameter of 15 mm. The joint fabricated with a shoulder diameter of 15mm produced finer grains (17.36 µm) with uniformly distributed dimples in the FSP region, and this is one of the reasons for higher tensile strength (101MPa) of the joints.

4. Conclusions

i. Of the five joints fabricated using five tools having different shoulder diameter, the joint fabricated with a tool having tool shoulder of 15mm showed superior strength properties.

ii. Defect free fine grained microstructure of weld nugget and uniformly distributed finer $MgZn_2$ particles in the weld nugget are found to be the important factors responsible for the higher tensile strength of the above joint.

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Acknowledgement

The authors are grateful to the Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar, India for extending the facilities of Material Testing Laboratory to carry out this investigation. The authors wish to place their sincere thanks to Clean Technology Division of Ministry of Environment and Forest, Government of India, New Delhi for financial support rendered through a R&D Project No. MoEF1-9/2005- CT. Authors would like to thank Mr.E.Balamurugan, Post Graduate student, Manufacturing Engineering, Mr.S.Muthukumaran, Mr.N.Sairaman, Mr.John and Mr.A.K.Thillaiparaman of Project Assistants, Centre for Materials Joining and Research (CEMAJOR) for their help and support.

