www.ijemr.net ISSN (ONLINE): 2250-0758, ISSN (PRINT): 2394-6962

Vandana Publications
IJEMR

Volume-7, Issue-3, May-June 2017
International Journal of Engineering and Management Research
Page Number: 121-125

Defects Formation during Friction Stir Welding: A Review

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ABSTRACT

Friction stir welding (FSW) is an advanced solid state joining process for joining Aluminum, Magnesium alloys. In the recent years, it is gaining enormous applications in shipbuilding, aerospace, automotive, railway rolling stock, robotics, and personal computers etc. In this review article, authors are focused on the formation of different defects during friction stir welding. The defects were influence the quality of the weldment and also affect the micro structural and mechanical properties. The defects can be overcome by optimizing the process parameters along with suitable tool geometry. In particular, various difficulties and defects observed during dissimilar welding of the Al-Cu and Al-Steel are addressed.

***Keywords*--** Friction stir welding; Defects; FSW of dissimilar metals

I. INTRODUCTION

Now a day's challenge for researchers is developing an eco friendly process in manufacturing and this include Friction Stir Welding (FSW) and Processing (FSP). Friction Stir Welding (FSW) is a solid–state joining technique invented and patented by The Welding Institute (TWI) in 1991 for butt and lap welding of ferrous and non–ferrous metals and plastics. FSW is a continuous process that involves plunging a portion of a specially shaped rotating tool between the butting faces of the joint. The relative motion between the tool and the substrate generates frictional heat that creates a plasticized region around the immersed portion of the tool [1]. A non-consumable rotating tool consisting of a pin extending below the shoulder is used to carry out the friction stir welding process. The tool is forced between the adjacent mating edges of the workpiece as shown in Fig.1. Forging action, stirring action and heat input of the tool induces the plastic flow in material and forms a solid-state weld.

Tool design and selection of appropriate process parameters are the critical in producing the sound welds in FSW process. A basic and conventional design for a FSW tool is shown in Fig. 2 which consists of concave shoulder and threaded pin. FSW tools generally consist of three generic features including shoulder, probe or pin and external features on the probe. The diameter of the tool shoulder is important because it generates most of the heat and it establishes material flow field by gripping the plasticized material under it. Heat is generated from sticking and sliding action whereas material flow is caused only from sticking action. The shape of the tool pin influences the flow of the plasticized material and influences the weld properties [2].

II. DEFECTS IN FSW

Weld quality in friction stir welding is affected because of various defects produced during the welding process. In this review article, various defects produced during friction stir welding was addressed. The friction stir welding defects includes Tunnel, Flash, Kissing bond, Void/Wormhole, Cavity/Groove, Cracks defect.

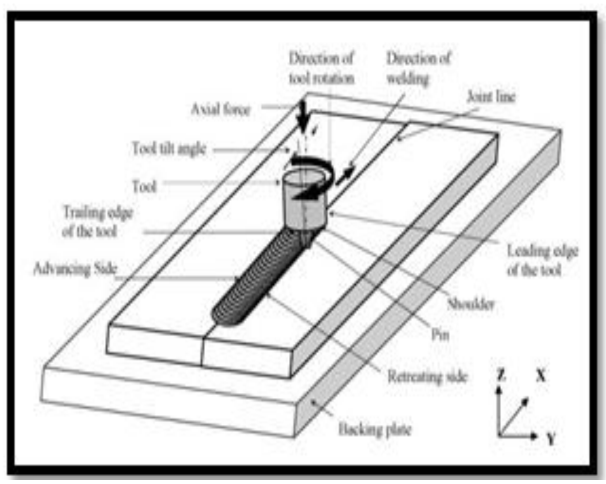

Figure.1 Schematic of friction stir process and terminology [1]

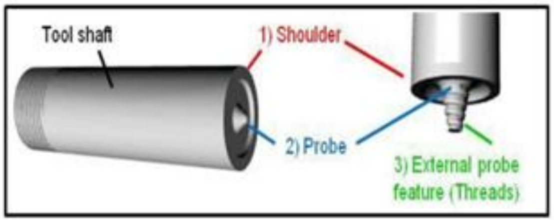

Figure .2 Schematic view of FSW tool [2]

2.1 TUNNEL DEFECT

Mainly tunnel defects are formed at the toe corners of the (T-lap, T-Butt and but joints) fillet zone. It generally occurs in the advancing side due to insufficient heat input and metal flow of the material. Xiaopeng et.al [4] investigated the effect of joint geometry on defects and mechanical properties of friction stir welded AA6061-T4 alloy joints. In case of T-joints flow of metal in vertical direction is needed to fill the fillets. Flow in vertical direction is not possible if insufficient heat input is given which leads to tunnel defect. Heat input and good flow pattern of the plastic material are the two main factors in eliminating tunnel defect. By reducing the traverse speed more heat input can be given, which improves the material flow and produces tunnel defect free joints [6].

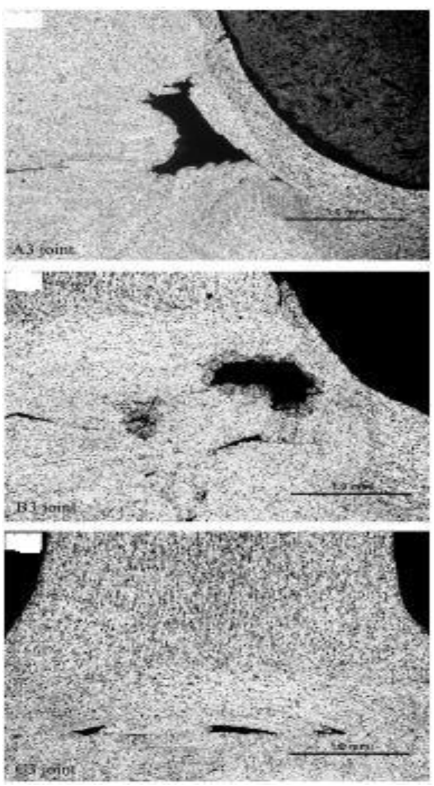

Figure.3 Macroscopic observation of tunnel defect [4]

If the processing conditions such as weld travel speed, tool rotation etc. fail to generate the required heat for bonding, inadequate material mixing and stirring occurs which leads to the formation of tunnel defects. Rapid dissipation of heat from the immediate deformation zone produces too cold welds. These too cold welds become macroscopically hard, and fracture can occur through the defect [8, 9]. Yong Zhao et.al [9] investigated tunnel and kissing bond defects in FSW 6063 Al alloy T-Joint. They reported that area of tunnel defect is increasing with increase of traverse speed. They have shown defect free T-Joint at 100mm/min tool traverse speed.

2.2 FLASH DEFECT

The workpiece experiences very hot processing conditions as the tool rotates at very high speeds. The generated heat thermally softens the material near the boundary of tool shoulder and expels the large volume of material in the form of flash. Excessive tool-shoulder frictional heat thermally softens the material which leads to the formation of flash, and high tool shoulder pressure ejects the excessive amount of flash. Surjya K. Pal [10] et al investigated surface defects formation in FSW. They identified surface defects using image processing techniques. Paul kah et.al [4] investigated the weld defects in friction stir welding of aluminum alloys.

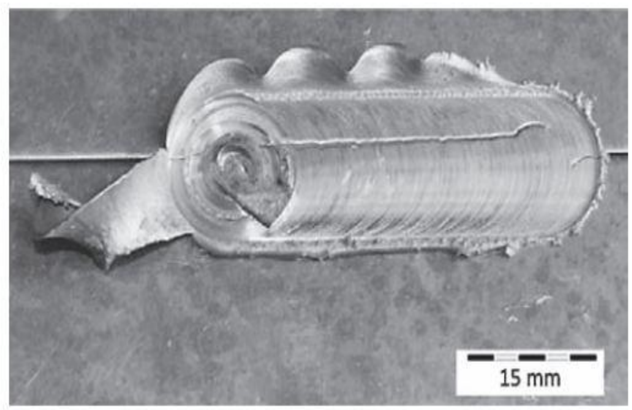

Fig. 4 Flash defect with surface groove [13]

Incorrect tool pin length relative to the workpiece thickness and change in penetration depth due to variation in plate thickness along the weld line leads to the formation of flash. When the pin plunge depth is high, the plastic material near the pin is extruded which leads to weld flash. Y.G. Kim et.al [5] has investigated the defects in friction stir welding. At higher rotational speed and lower welding speed material undergo sever plastic deformation which leads to the formation of excessive flash.

2.3 KISSING BOND DEFECT

At high welding speed and low rotary speeds Al_2O_3 oxide layer breaks partially due to insufficient stirring of the metal and low heat input, which leads to the reduced flowability of plastic material. This results in the inclusion of broken oxide particles in the form of zigzag line or a kissing bond defect [4].

Noor Zaman khan et.al [3] investigated tunneling and kissing bond defects in FSW of dissimilar aluminum alloys. Inadequate pressure and insufficient stirring of material leads to the formation of kissing bond defect. In such conditions if the oxide layers are not removed properly will lead the improper bonding between base metal. This defect usually occurs at the root of the weld or interface of the base material. Reasons for formation of kissing bond defect includes presence of oxide layer, lack of deposition of material and higher flow stress. Presence of kissing bond defect leads to the weak mechanical properties of the weld. This defect can be overcome by keeping proper offset during the friction stir welding of dissimilar materials.

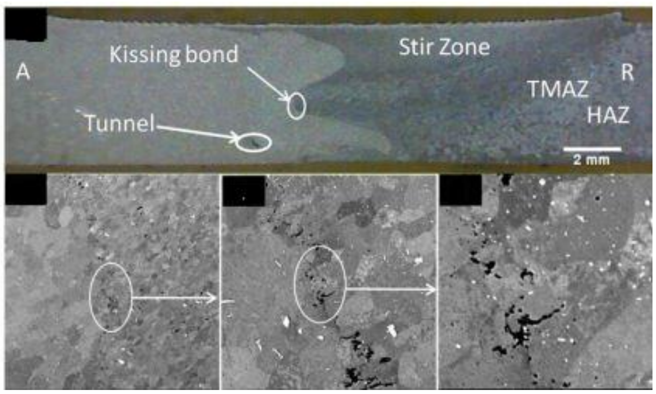

Figure.5 SEM Micrograph showing Kissing Bond defect [3]

Xinqi Yang et.al [6] investigated the formation mechanisms of defects in FSW of T-joints on AA6061-T4 sheets. They classified kissing bond as longitudinal (L) and traverse (T) kissing bond. The kissing bond defects exhibit more obvious drift tendencies toward the nugget zone with increasing traverse speed and the length and width of the kissing bond defects increase as well.

2.4 VOID/WORMHOLE DEFECT

High welding speeds promote more economical friction stir welds and higher productivity, too high welding speeds lead to the formation of voids beneath the top surface of the weld or on the advancing side at the edge of the weld nugget. Further increase in speed leads to the formation of bigger wormhole defects [15]. Ravi Ranjam et.al [10] investigated surface defects in friction stir welding using image processing approach. Voids are the defects having variable size and could be oriented at any angle. It does not have any particular feature which could be used for its classification. A J Leonard et.al [11] investigated flaws in friction stir welding of aluminum alloy. They have shown voids occur due to insufficient forging pressure and with faster welding speeds. Tool with flat shoulder produced voids along the length of the weld. The defect can be reduced by using sub shoulder tool.

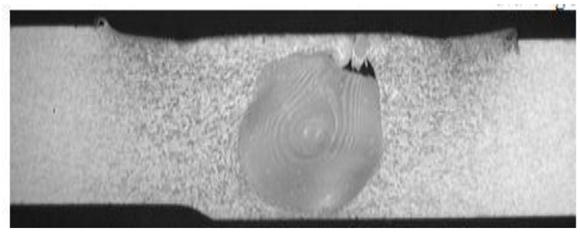

Figure. 6 A Void on advancing side of weld [11]

2.5 CAVITY OR GROOVE/CHANNEL LIKE DEFECT

The cavity or groove defect has significant influence on the mechanical properties of the joints. It is formed due to insufficient heat input. Insufficient heat input caused due to improper selection of process parameters [5, 13].

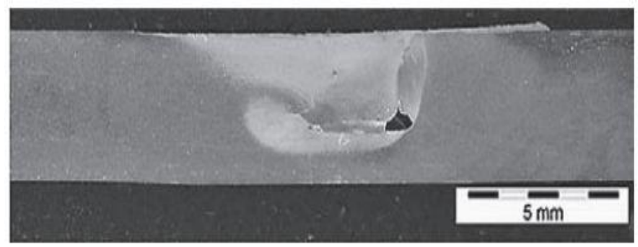

Figure.7 Cavity due to insufficient heat input [27]

Generally, grooves are longer and horizontal therefore, its classification was done using the length of major axis and its orientation (of the ellipse) formed around that blob. Hence, the defect blobs having quite a larger major axis length (≥35 pixels) as well as orientation in the range of -25° to 25° were classified as grooves.

Fig.5 Cavity due to insufficient heat input [13]

The groove defect that has a significant influence on the mechanical properties of the joints can be removed by friction stir repair welding, but different repair welding processes exhibit different repair results. The offset repair welding process is superior to the symmetrical repair welding process, and the tensile strength of the offset repair joint is equivalent to that of the good-quality initial joint and is up to 78% of that of the base metal [7].

2.6 CRACKS AND CRACK LINE ROOT DEFECT

Cracks are formed during friction stir welding of dissimilar materials beneath the tool shoulder. Sang Woo Song et.al [14] performed friction stir welding of dissimilar metals. They have shown that cracks are formed at 1500 rpm and at different welding speeds. Peak temperature was observed at the edge of the tool shoulder where liquation crack occurred. This is due to temperature developed here is high enough to cause reaction between precipitates and aluminum matrix.

Process parameters play important role in producing defect free weld during friction stir welding. Root defects developed due to insufficient heat input or due to incomplete breakup of surface oxide layers.

Inadequate pin plunge depth leads to the formation of groove defect at the advancing side. Insufficient pin length for the thickness of the workpiece leads to the formation of crack-line root defect. Insufficient downward forging of the plasticized metal at smaller tilt angles leads to the root groove from a lack of penetration. Therefore, very small tilt angles and very high tilt angles leads to the formation of root defects.

III. FSW OF DISSIMILAR METALS

3.1 Al-STEEL

Aluminum alloys with good conductivity, formability, high strength and weight saving being considered for ship building, railway cars and aerospace structures, etc. stainless steel with high static and dynamic strength, high toughness and excellent corrosion resistance is a promising structural material for vehicle and aerospace applications. To achieve the advantage of combined properties of aluminum alloys and stainless steel, it is required to develop reliable joints between aluminum alloys and stainless steel to consider the applications in variety of fields like nuclear reactor components, aerospace structures and household appliances etc. Welding of aluminum alloy to stainless steel is not easy as there is large difference in melting points. Variety of joining technologies were developed, among all friction stir welding is one of the most popular welding technique for joining dissimilar materials [3]. H. Uzun et al [8]
joined Al 6013-T4 to X5CrNi18-10 stainless steel. They concluded that the fatigue properties are approximately 30% lower than Al alloy base metal. T. Watanabe et al [15] butt welded aluminum alloy plate to steel plate by FSW. Maximum strength of the joint was obtained at 0.2mm offset distance towards the steel plate. There was an optimum rotation speed to make sound joint. Too low and too high rotation speed produces defective weld. K. Kimapong et al [16] butt welded SS400 mild steel to A5083 aluminum alloy. They have shown tensile strength of the joint was 86% of the aluminum alloy base metal.

3.2 Al- Cu

Production of aluminum/copper hybrid system will give new engineering solutions by combining copper's improved mechanical, thermal and electrical properties with aluminum's low specific weight and cost [12]. However, FSW of these metals not easy as they differ in physical and mechanical properties and their chemical affinity makes mandatory to optimize process parameters to provide proper material flow around the tool pin to produce defect free joint [17]. Bisadi *et al* [18] joined AA5083 and commercially pure copper using FSW. They have shown very low welding temperature led the channel defect near the sheet interface near to the copper sheet. Xue *et al* [19] welded AA1060 aluminum to commercially pure copper. At lower rotation speed of 400 rpm many defects in nugget zone were identified, whereas at higher rotation speeds of 800 and 1000 rpm, good metallurgical bonding between the Cu pieces and Al matrix was achieved. In summary defect, free weld of dissimilar materials can be produced by properly selecting process parameters and tool design.

IV. CONCLUSION

Review of defects formed during friction stir welding of Al, Al-Cu and Al-steel has been successfully addressed.

Tunnel defect formed due to insufficient heat input and metal flow.

Excessive tool shoulder frictional heat thermally softens the material which leads the formation of flash and high shoulder pressure ejects the excessive amount of flash.

Inadequate pressure and insufficient stirring of material leads to the formation of kissing bond defect.
Voids occur due insufficient forging pressure with faster welding speeds. Cavity or groove defect formed due to insufficient heat input.

Cracks formation is due to incomplete plastic flow of material because of inadequate heat input at lower speed.

As joining of dissimilar metals using FSW is in early stage, till now less research was done on defects formation during FSW of dissimilar metals. There is scope to carry out further studies on defect formation during FSW of dissimilar metals.

V. ACKNOWLEDGMENTS

The authors would like to thank the authorities of National Institute of Technology (NIT), Warangal, India, for providing the facilities to carry out this work. and also thank to DMRL and DRDL they provided such a great help for carry out this work.

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