ISSN:0971-1260
Vol-22-Issue-4-October-December-2019

Defect features in Friction Stir Welded joints

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Abstract— Friction stir welding (FSW) is nowadays used to join similar as well as dissimilar metals and their alloys. Defect formed during the FSW process can adversely affect weld quality. The present study gives an overview of the various defects formed in friction stir welded lap and butt joints. The welds were analyzed to understand the effect of process parameters, namely tool rotational speed and tool traverse speed, on defect formation. The formation and prevention of the main weld defects in friction stir welded joints, such as tunnel, channel, wormhole, kissing bond, hooking, cold lap, cracks and micro cracks, void, porosity, and flash is discussed. Further, the detrimental effects of the defects on weld performance are discussed.

Index Terms—*FSW, flash, kissing bond, hooking, cracks, pores, tunnel, voids, and wormhole*

I. INTRODUCTION

Friction stir welding (FSW) is one of popular a solid-state metal joining process invented by TWI, Cambridge, UK in 1991[1]–[3] for lap and butt welding of ferrous, nonferrous and plastic materials ,which is feasible technique used for joining aluminium and two dissimilar metal alloy which are difficult to join by fusion welding processes [2]. Due to more efforts of researchers are towards developing an eco-friendly metal joining process in manufacturing which includes Friction stir welding (FSW)[3]. Because of emerging application in petrochemical transportation, electronics industries, nuclear, aerospace and power generation for joining of dissimilar materials with the help of Friction stir welding (FSW) process.[4]–[7]. Every metal exhibit different physical and chemical properties, so it is difficult to join two dissimilar material rather than joining two similar material. However material joining processes with Friction stir welding (FSW) give rise problems not only from material properties but also formation of intermetallic and eutectics with lower melting points[7]. Various experimental, modeling analysis are done to find out different characterized zones formed in joint area like the heat affected zone (HAZ) which is common in conventional arc welding. From FSW processes nuggets and thermo mechanical affected zone (TMAZ), which forms complex weld characteristics [2], [8]. In friction stir lap or lap welding, a specially designed cylindrical tool is used. This tool is rotated and plunged into the joint line. The Tool has a small tool pin diameter and larger shoulder diameter. As the rotating probe come near and contacts the surface, frictional heat is produced which soften the column of material. As the probe penetrates deeper some part of metal extruded due to flash is created on the surface. Depth of penetration can be controlled by probe entry length and tool shoulder [1]. The best combination for dissimilar metal welding is aluminum alloy and AHSS. But welding of these two different metals is difficult because they have different mechanical and physical properties. Due to this dissimilarity, intermetallic compound formation takes place which are brittles in nature. [Ogura et al.2012] Aluminum is a different type of metal because it does not show solid-state phase transformation after cooling. So, during cooling, only solidification determines the microstructure of aluminum and properties. During the welding process, the higher temperature affects the microstructure of the aluminum, which directly affects the properties and behavior of the material [9].

II. DEFECTS FORMED IN FRICTION STIR WELDING

A. *Flash defects*

Flash defects in friction stir welding occur due to hot processing conditions as tool pin rotates at high speed [9]. During higher lower welding and high rotational speed, the material undergoes plastic deformation due to which xcessive flash is formed, as shown in figure 1 [3].

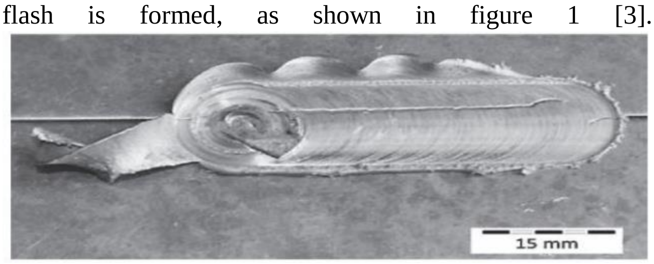

Figure 1. Flash defect with surface groove[3]

Incorrect tool geometry such as pin length and penetration depth for various plate thickness to the weld line results in flash formation [3]. Flash defects result in the generation of excessive heat in the work piece, which thermally softens

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ISSN:0971-1260
Vol-22-Issue-4-October-December-2019

material around the boundary around the tool and removes a large amount of material in the form of flash.[9]. Because of high pin plunge depth, plastically deformed material extrudes along the pin and results in weld flash [3].

B. Kissing bond

Main reasons for kissing bond formation are the presence of oxide layer, high flow stress, and material deposition [3]. At high welding speed and low rotational speeds, metals break partially due to the 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 metal particles in the form of a zigzag line or a kissing bond defect, as shown in figure 2 [9]. Providing proper offset in the friction stir welding process can reduce these defects in dissimilar metal welding [3]. This type of defect leads to weak mechanical welds and results in failure of workpiece [3] and further reduces fatigue performance, and these defects are hard to detect, which requires non-destructive testing [10].

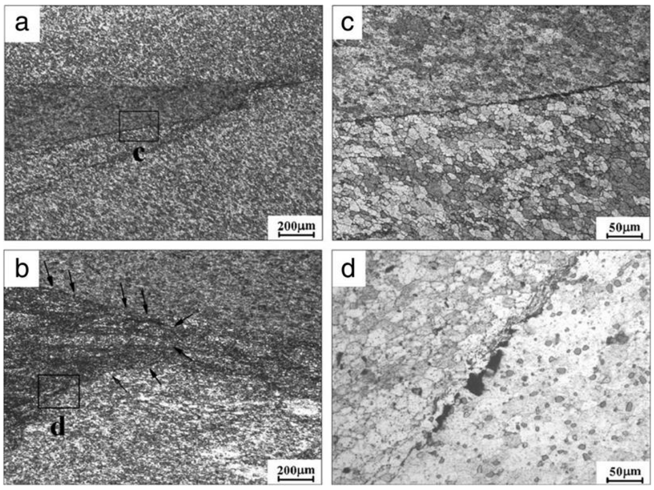

Figure 2. The microstructure of kiss-bond defects in the nugget zone[3]

C. Hooking Defect

Hooking defect generally occurs when the interface between Cu and Al is pulled to the top of the sheet. This defect can be seen in the lap joint at advancing side where higher temperature and material flow occurs in Thermo-Mechanical affected zone (TMAZ). Bisadi et al. [4] observed a similar phenomenon, which is visible at both advancing and retreating side. The Stir Zone (SZ) had the minimum grain size among the other weld areas due to the recrystallization because of experiencing high temperature and plastic deformation caused by the pin tool contrast. Salari et al. [12] observed hooking defect in TMAZ and weld nugget (WN). The origin of the hooking defect is related to material flow which is dependent on welding conditions and tool geometry; hence it is reasonable to assume that with the new tool geometry, better material mixing has occurred resulting in less unidirectional material movement from the joint interface towards the upper sheet and hence lower hook height occurred. Shirazi et al. [13]observed that changing the parameters such as welding speed or rotational speed affect the hooking shape and height, as shown in figure 4. At constant welding speed, both hooking height and shape changed because of the increased rotational speed. At the advancing side, by increasing the rotational speed, hooking which was quite sharp and perpendicular to the interface at low rotational speeds, was deflected with an angle of up to 45°. In contrast, at the retreating side, increasing the rotational speed resulted in a reduction in hooking deflection; so that, hooking was almost straight at higher rotational speeds. At constant rotational speeds, the height and direction of hooking changed with the increase of welding speed. At low rotational speeds (300 and 600 rpm), the increase in the welding speed resulted in a decrease of the hooking height on both advancing and retreating sides due to less vertical material flow. The schematic diagram of the cold lap and hook defect is shown in figure 3.

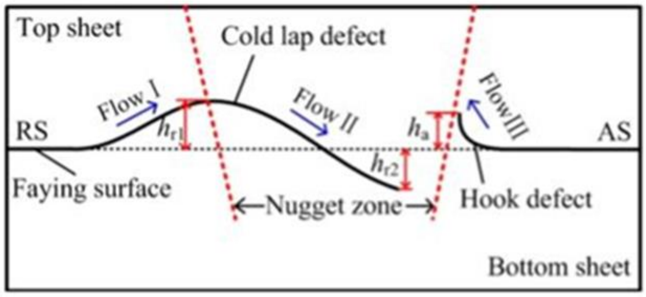

Figure 3. Schematic diagram of the cold lap and Hook defect [14]

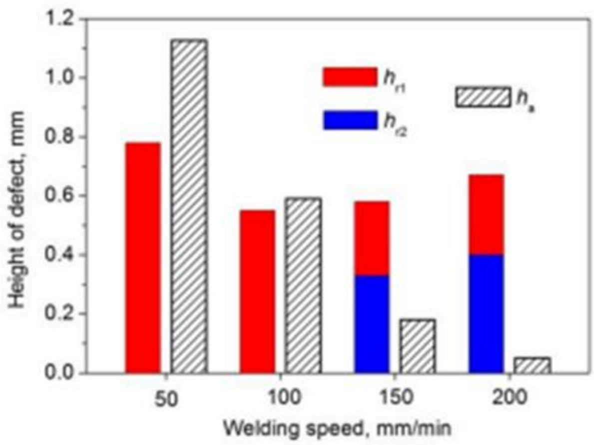

Figure 4. Height values of the hook and cold lap defects formed at different welding speeds; h_a refers to the height of the hook defect at AS, while h_{r1} and h_{r2} represent the heights of the cold lap defects in the top and bottom sheets at RS, respectively[14]

D. Cracks/Microcracks

Cracks are significant defects in any mechanical component. In welding also, this may lead to failure of the joint. These defects occur due to improper process parameters, lack of penetration of tool, poor control on process parameters. Sang-Woo Song et al.[15] performed welding of dissimilar metals and observed that the rotation speed of 1500 rpm and welding speed of 400 mm/min leads to a peak temperature of about 480 degree Celsius where

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ISSN:0971-1260
Vol-22-Issue-4-October-December-2019

liquation cracking occurs. Soni et al.[3]stated that 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 lead to the formation of root defects. Kuang et al.[16] used FSW to produce the Al/Cu joint and observed a thick inter-metallic layer which may lead to the weakening of joint. To reduce the inter-metallic layer thickness, welding of reactive metal is chosen. Although it was reported that the formation of a thin intermetallic layer along the Al/brass interface might increase the mechanical properties of the dissimilar welds, it is different to control the layer thickness, and an increase in the layer thickness will result in the crack formation, and the mechanical properties decrease significantly. The interface between the Cu plate and the interlayer and the crack disappears with the increase of rotation speed and the decrease of traverse speed [16] Mehta et al. [17] welded Al and Cu by FSW and reported various defects, as shown in figure 5 . Microcracks and macro cracks generally occur due to the formation of brittle IMCs which increase the weld hardness and may lead to large surface cracks. Poor metallurgical bonding between the Al matrix and large Cu particles was the leading cause of this defect. Improper tool design, offset tool pin, and material positioning is parameters which may also cause these defects.

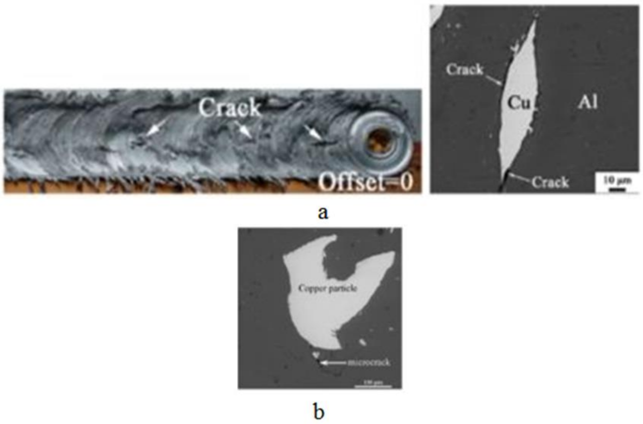


Figure 5. a. Crack and b. micro-crack [17]

E. Tunnel defects

Tunnel occurs due to insufficient heat input and metal flow of the material. If the processing conditions such as weld travel speed, tool rotational speed fail to generate the required heat for bonding, inadequate material mixing and stirring occurs which leads to the formation of tunnel defects[18]. Inappropriate design of tools and axial pressure are the main cause of the formation tunnel defect[17]. By reducing the traverse speed, more heat input can be provided, which improves the material flow and produces tunnel-defect free joints[19]. Increasing the shoulder diameter significantly increases the heat input volume, which directly improves the flowability of the weld metal into the cavities. Therefore, optimized heat input and good flow patterns of the plastic material are necessary to avoid very cold processing conditions and thus eliminate tunnel defects. Hence, a welding tool with a relatively large shoulder can help reduce the occurrence of tunnel defects [1]. The macroscopic observation of tunnel is shown in figure 6.

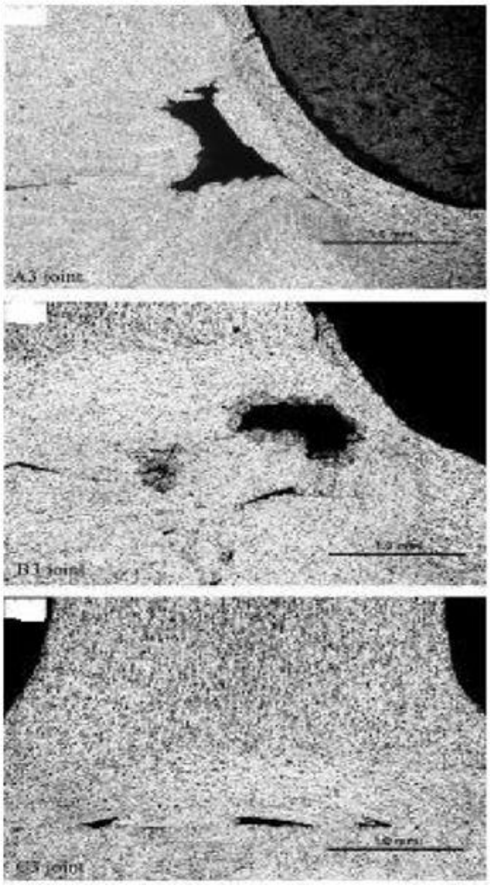
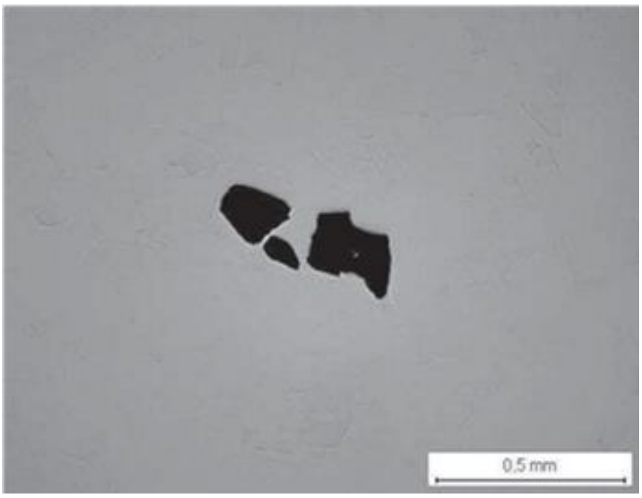


Figure 6. Macroscopic observation of tunnel [9]

F. Pores

Pores are generally found in the stir zone either single or in line form, which is 0.1–0.5 mm in diameter, and pore lines may be up to 9 mm in length. Incorrect welding parameters such as too small tool plunge depth cause this defect [20]. They also occur in stir zone due to the small tilt angle. Pores reduce the strength of the weld and increase the possibility of weld failure. The pores in the overlap zone of a 50 mm thick copper FSW weld are shown in figure 7.



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ISSN:0971-1260
Vol-22-Issue-4-October-December-2019

Figure 7. Pores in the overlap zone of a 50 mm thick copper FSW weld [21]

G. Voids and Wormhole Defect

Use of higher welding speed leads to higher productivity and economical welding production. However, this can increase the possibility of some part of weld to remain vacant, leading to the formation of a void in the weld. Further increase in welding speed leads to the formation of wormhole defect [22] Ranjan et al. [23] investigated the FSW surface defect using image processing approach and observed that voids could be of any size and oriented at any angle, which makes them difficult to classify. Leonard et al. [24] investigated the cause and prevention of void formation. The void on the advancing side is shown in figure 8.

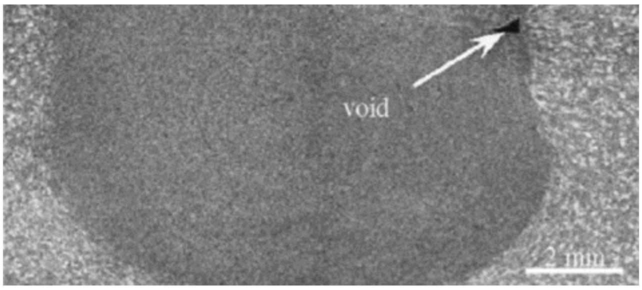

Figure 8. Void on the advancing side [24]

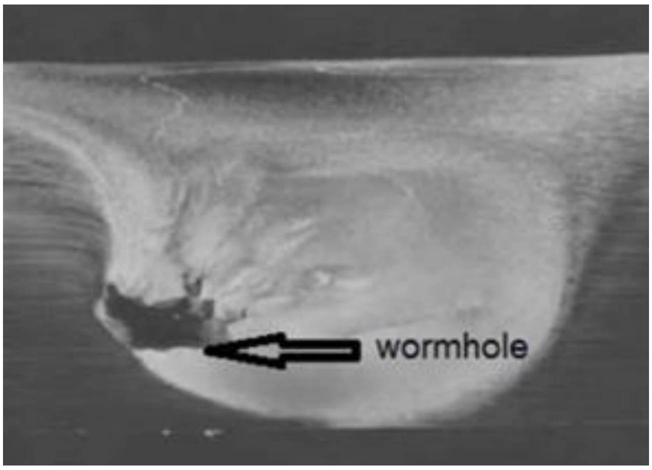

Figure 9. A wormhole defect [25]

Higher welding speed and insufficient forging pressure, and flat shoulder cause void formation, which can be reduced by using a sub shoulder. In FSW lap joints of AA5083 and SS400, it is observed that void formation increases with increase in tool tilt angle and tool pin diameter [26]. Surface defect and porosity are the common cause of Wormhole formation. Wormhole initiates at the bottom of the weld as the traverse speed increase at a constant rotational speed. As traverse speed increases, the wormhole increases because of inadequate flow of material at the bottom of weld [27]. Travel speed to rotational speed plays an essential role in the formation of wormhole defect. A higher ratio of travel speed and rotational speed increases the wormhole defect [28]. The probability of voids increases with an increase in traverse speed, but there is an alloy dependence, for example, defects dominated in AA 5083-O and AA 2024-T3 but not in the AA 6063-T6. There is a significant drop in hardness within TMAZ. On advancing side there is a tendency of defect formation because there is an abrupt microstructural transition from highly refined grains to the TMAZ, but on the retreating side, the transition is gradual, thereby reducing the tendency of defect formation on RS side [29].

CONCLUSION

Defect features, preventions, and their causes in friction stir welding of similar and dissimilar has been successfully studied. 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 the 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. In order to avoid such defects, the thermo-physical and mechanical properties of the welded material should be identified, and the processing temperature and processing rates manipulated accordingly. Tool rotary speed and tool traverse speed govern the peak temperature generated during FSW and the time required to weld the material. The manner in which temperature affects material properties varies significantly for different materials. Hence the friction stir welding process parameters are different for different materials. As joining of dissimilar metals using FSW is still in development stage, extensive research is yet to be carried out on defects formation during FSW of dissimilar metals.

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