

REVIEW

Macrostructural Analysis of Friction Stir Welding (FSW) Joints

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ABSTRACT

Friction Stir Welding (FSW) technology is increasingly used in aerospace, automotive, construction and other industries. It allows for safe, secure and long-lasting joining of materials that are difficult to weld or non-weldable with traditional methods. In engineering practice, these are primarily aluminium alloys.

This article discusses the basic issues related to the FSW technology. The macrostructure of a typical weld is presented. The influence of linear and rotational speed of the tool on the macrostructure of the weld was analyzed (cross-sectional shape, presence of defects). The process of "onion rings" formation in the weld nugget was characterized, taking into account the influence of technological parameters on their morphology.

1. Introduction

In modern technology, there is a significant need for an efficient, reliable and fast method of making high quality welds. This is particularly important in the case of materials whose welding with traditional methods entails significant technological difficulties (eg. aluminium, copper alloys, etc.). The Friction Stir Welding (FSW) technology, despite the relatively high costs, meets these criteria and is increasingly used in industry.

This article presents basic technological issues related to FSW, with particular emphasis on the impact of technological parameters on the weld macrostructure.

2. Friction Stir Welding Technology

Friction Stir Welding with displacement of the weld material was developed and patented in 1991 by W. M. Thomas at the Welding Institute in Cambridge, UK ^[1]. Ultimately, the method was to be used for joining aluminum alloys.

The FSW method is based on the transformation of kinetic energy into thermal energy generated by the friction of the non-consumable tool moving along the edge of contact line. Figure 1 illustrates the FSW process diagram. Friction causes heating and plasticizing of the material in the area of welding. At the beginning of the friction

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stir welding process, heating of the material is caused by the friction between the pin and the plastically deformed material of the joined elements. In the next step, when the resistance rim touches the surface of the material to be joined, most of the energy necessary to heat the material is obtained from the friction between the shoulder and the surface of the material being joined^[2]. During penetration, a cylindrical tool ended with a shoulder and a profiled pin rotates, introducing the plasticized material into a whirl movement^[3]. In this way, it is displaced in the direction of rotation of the tool, which can be either clockwise or counter-clockwise. As a result, we obtain an asymmetrical connector, which consists of the advancing side and the retreating side. The advancing side occurs in the place where the material flows in the direction of the moving tool, in the opposite situation we are talking about the retreating side. These sides differ from each other in terms of the size of their own stresses, strains and microstructure^[4].

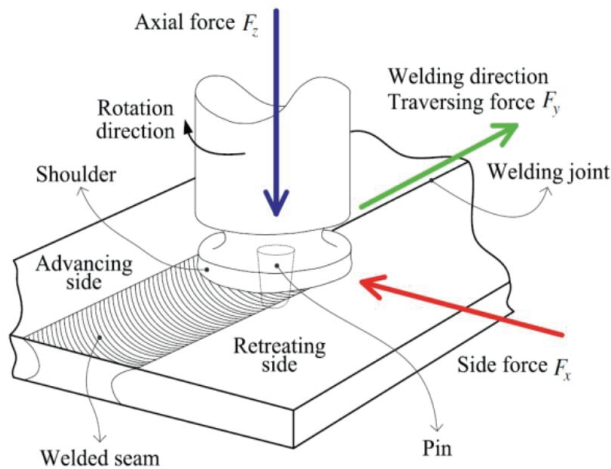


Figure 1. Scheme of the FSW process^[5]

The basic parameters of the friction welding process are: the shape of the mixing tool, the welding speed, the rotational speed of the tool, the angle of inclination of the tool to the welded surface and the pressure force^[3]. Among the above parameters, the shape of the tool is considered one of the most important factors in the process of friction stir welding. It affects the flow of material, and thus the quality of the weld obtained and the type of defects that may arise after the welding process. The FSW tool consists of a shoulder and a pin, and its detailed design may differ due to the shape, diameter and length of the pin and shape, the diameter of the shoulder surface^[6]. Figure 2 illustrates the FSW tool diagram. Due to the intensive development of FSW technologies in the last two decades, the impact of welding process parameters on the quality of the weld obtained was discussed in numerous publications^[7-10].

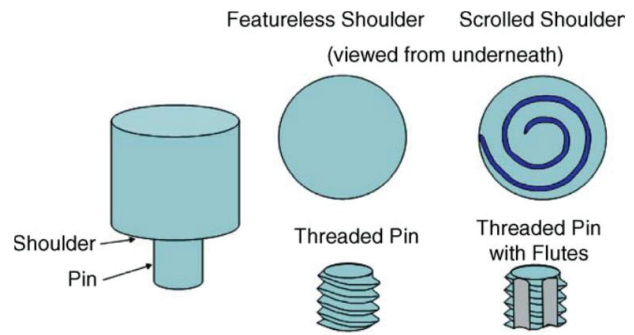


Figure 2. Scheme of FSW tool^[6]

Most often, the following factors are given as the advantages of friction stir welding with mixing of the weld material^[3,6]:

- a. high static and dynamic strength properties of the joints;
- b. favorable metallurgical properties: slight distortion of the working area, good microstructure, no cracks;
- c. dimensional stability and repeatability due to process automation;
- d. the method is ecological and safe, because it does not cause emission of welding gases and dusts, formation of magnetic fields and noise; does not require the use of solvents for surface degreasing and shielding gases;
- e. low consumption of materials and short process preparation time due to the lack of cleaning, grinding, brushing or surface pickling;
- f. the aesthetic look of the weld surface, often requiring no further processing;
- g. reduction of energy consumption due to the possibility of better use of combined materials.

However, the disadvantages of FSW methods are^[2]:

- h. dimensions of the welding device make it a stationary method;
- i. the need to use higher quality tool material, adapted to the material properties of the combined metals;
- g. the necessity of using rigid holders for fixing welded elements that prevent moving of the joined panels during the process;
- k. limitation of the tool life and its high cost.

3. Macrostructural Analysis of FSW Joint

3.1 Weld Structure^[6]

Similarly to conventional weld, in the FSW joint a few characteristic areas in the cross-section can be distinguished (Fig. 3):

- joint nugget,
- thermo-mechanically affected zone (TMAZ),
- heat-affected zone (HAZ).

The specific process of welding takes place in the nugget (or dynamically recrystallized zone - DXZ). Due to the plastic deformation and frictional heat the nugget zone undergoes recrystallization, i. e. formation of fine grains. The grain size changes in the weld cross-section. The biggest grains were observed in the upper area of the weld, whereas smaller grains were observed at the bottom ^[11]. The grain size distribution described above is believed to be the effect of temperature gradient during welding, i.e. higher temperature produced at the upper side of the weld by the tool results in the formation of larger grains. The welding tool motion produces the structure of the so called "onion ring" in this area (see Fig. 3). As indicated in many papers, for example ^[12-14], the motion of FSW tool causes the dissolution of the inclusions. As a result, fewer inclusions occur in the area of the weld nugget and they are smaller than in the parent material.

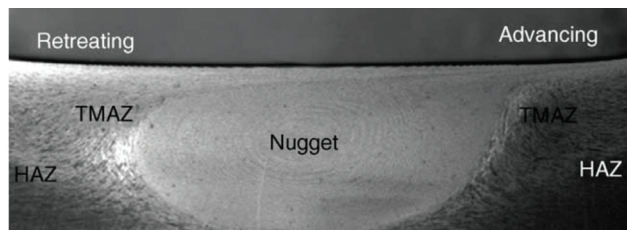


Figure 3. Typical FSW joint structure, according to ^[6]

Thermo-mechanically affected zone (TMAZ) plays the role of transition area between the nugget and heat-affected zone. Although this area is characterized by considerable deformation, the strain values are too low to cause grain recrystallization. On the other hand, a significant increase in temperature causes the dissolution of some precipitates, and thus the change in the microstructure of the material ^[15].

The heat affected zone (HAZ) is not subjected to significant plastic deformation, therefore the microstructure of the grains is similar to the native material. However, the elevated temperature results in a reduction in the amount and change in the structure of inclusions and precipitates.

3.2 Effect of Tool Travel and Rotation Speed on the Weld Macrostructure ^[16]

An interesting insight into the effect of FSW process parameters (rotation and travel speed) on the joint shape is presented in ^[16]. The authors analyzed friction stir welding of Al2195-T8 Al-Li alloy. During the experiment, plates with a thickness of 7.4 mm were welded together with the use of cone shape threaded pin and threaded surface of shoulder. Displacement controlled shoulder - to plate pressure was applied in order to provide shoulder contact with the material being processed.

Effect of travel speed on the FSW joint shape is demonstrated in Fig. 4 a-c. The welds illustrated in Fig. 4 were prepared at the fixed tool rotation speed 600 rpm. In each picture the left side of the photograph represents the advancing side, i.e. area, where tangential direction of rotation is consistent with the travel direction.



(a)



(b)



(c)

Figure 4. Effect of travel speed on the weld macrostructure: a) 120 mm/min, b) 300 mm/min, c) 420 mm/min (rotation speed 600rpm) ^[16]

As shown in Fig. 4, the weld boundary is sharper on the advancing side, while on the retreating side the border is indistinct. The results obtained by the authors of ^[16]

clearly confirm the effect of the tool linear speed on the shape of the weld cross-section. For the lowest speed of 120 mm/min (Fig. 4a), the shape of the bottom part of the joint is regular, close to the square. Increasing the speed of the tool causes irregular shape of the welds. At the top speed of 420 mm/min (Fig. 4c), on the advancing side macrodefects were observed. As the authors point out, the use of excessive speed of the tool may result in a tunnel effect, i.e. the formation of a linear defect along the weld. The authors of [16] performed the similar analysis for different tool rotational speeds (Fig. 5 a-c) and constant travel speed 240 mm/min. As before, the increase in the speed of the tool caused an irregular weld shape on the advancing side. The highest quality of the weld was obtained for the speed of 300 rpm. Increasing the tool rotation speed resulted in irregular shape of the weld, especially on the advancing side.

3.3 Effect of the Process Parameters on "Onion Rings" Formation in the Weld Nugget [17]

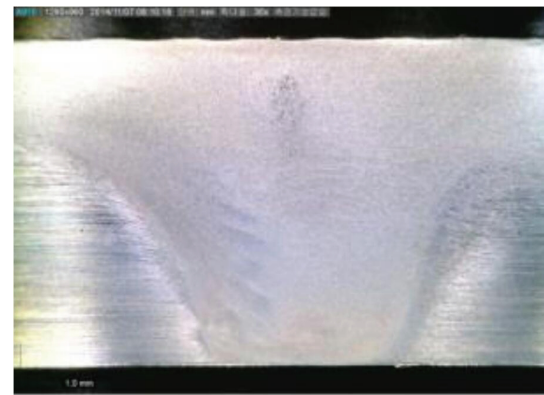
As mentioned, the characteristic feature of friction stir welding technology is the formation of the so-called "onion rings" in the weld nugget. Depending on the technological parameters of the process, the rings may have different structure.

The author of the paper [17] discussed the effect of rotational and travel speed of FSW tool on the macrostructure of the weld nugget.

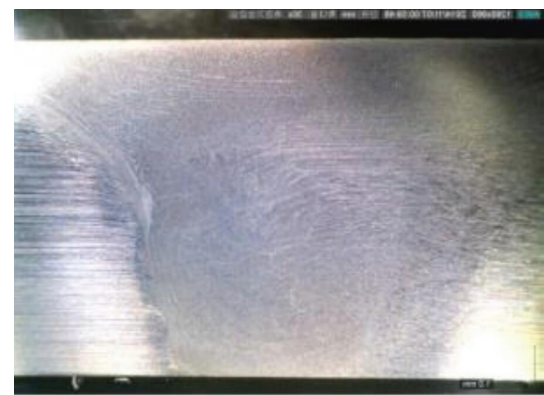
In order to analyze the FSW macrostructure, elements made of aluminium alloys 6061 and 7075 were welded together. Welds were prepared at the tool speeds of 400, 800 and 1440 rpm, while the welding speeds were 120 and 288 mm/min. The author has not provided information concerning the shape of FSW tool and the geometry of welded elements. In the next stage transversal and longitudinal sections of welds were prepared and then subjected to macrostructural observations.

Figure 6 presents an example of the structure of "onion rings" in the weld nugget. In the cross-section of the weld (Fig. 6a), characteristic ring structures are visible. The rings spacing is larger in the middle part of the weld, but decreases as it approaches its edges.

Figure 6b shows the longitudinal section of the weld. The rings from Figure 6a are in this case visible in the form of characteristic band structures. In the lower and middle parts of the weld, the bands are deflected in the direction opposite to the travel direction of the tool. In the upper part of the weld, the bands have a direction similar to vertical, which, according to the author of the work [17], results from the effect of the shoulder on the location of the mixed material. Figure 6c shows a three-dimensional



(a)



(b)

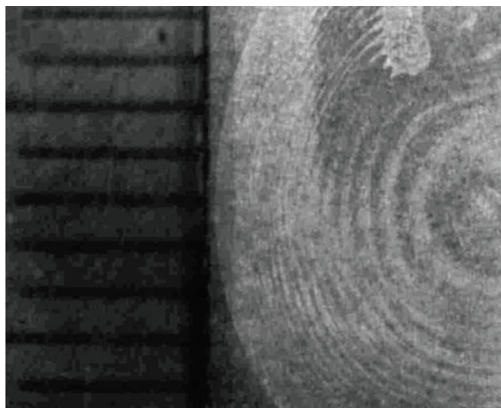


(c)

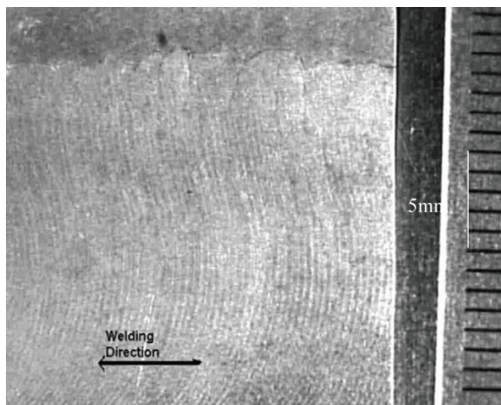
Figure 5. FSW weld macrostructures for different tool rotation speeds: a) 300 rpm, b) 600 rpm, c) 800 rpm, travel speed 240 mm/min [16]

visualization of the distribution of circles/bands in the weld nugget structure.

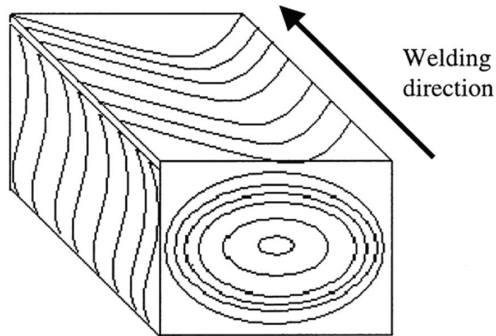
In Figure 6c, the characteristic semicircular structures on the upper surface of the weld are visible. Their presence results from the direction of material movement around the tool. The process starts with the material layer heating up due to the friction resulting from the rotary



(a)



(b)



(c)

Figure 6. Structure of "onion rings" in Al alloy weld nugget: a) weld cross section, b) weld longitudinal section, c) 3D view of weld nugget with "onion rings" pattern^[17]

movement of the tool. Then, the hot and plasticized material is passed over the tool, forming a weld and creating semi-cylindrical bands. As shown in^[17], the distance between bands is equal to the tool travel distance during its single rotation. In addition, the weld morphology (band structure) results from the fact that the material heating by friction is not an immediate process. It requires a certain

period of time, which results in periodic arrangement of the bands in the weld.

Figure 7, derived from^[17], illustrates the effect of linear and rotational velocity of the tool on the band spacing. As can be seen, the increase in rotational speed results in reduction in the band spacing, with the largest differences being observed in the rotational speed range below 1000 rpm. As expected, the increase in the linear speed of welding caused an increase in the spacing of bands in the weld. It should also be noted that, according to Figure 7, the use of different combinations of linear and rotational speed of the tool leads to the same spacing of bands in the joints.

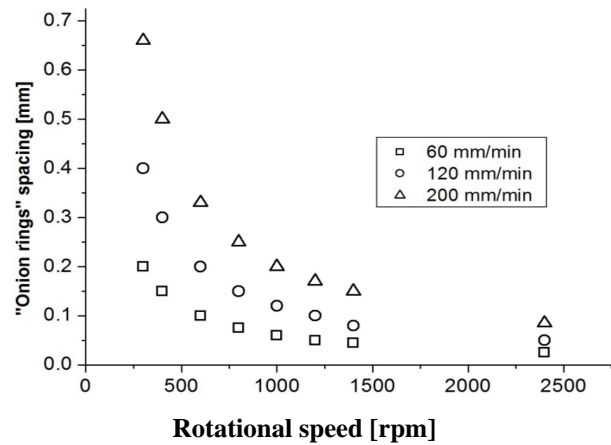


Figure 7. Effect of the FSW process parameters (tool travel and rotation speed) on "onion rings" spacing in the weld^[17]

3.4 Joint Defects as a Result of Process Parameters^[16]

It is to be expected that the method of forming a weld in the FSW process (extruding the heated material) can cause defects (voids) behind the tool, and thus in the prepared joint.

In the previously mentioned work^[16] an analysis of the influence of linear and rotational speed of the tool on the formation of weld defects (voids, discontinuities) was made. Welds, made in the manner described before, were used for this purpose. Finished welds were X-rayed. The results of the observations are presented in Figure 8.

The increase in the linear velocity, although it allows for a significant reduction in the weld time, in the whole analyzed range of rotational speeds resulted in the appearance of joint defects.

As it results from the graph analysis, the change in rotational speed in the range from 300 to 800 rpm did not cause the deterioration of the weld quality.

As shown in^[18], further increase in the rotational speed of the tool (over 1000rpm) was the cause of significant weld defects, affecting element strength.

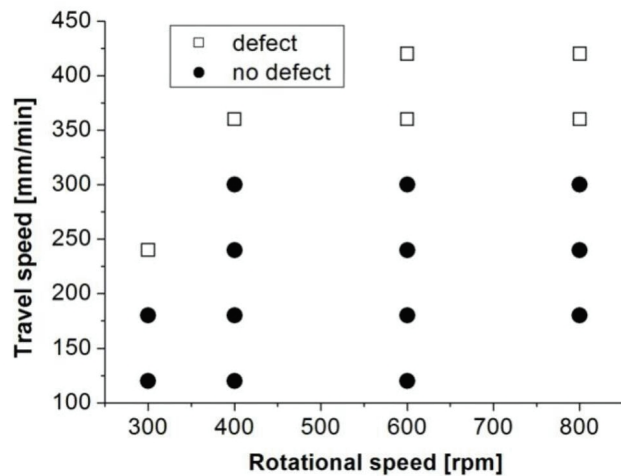


Figure 8. Joints quality depending on the tool travel and rotation speed, basing on ^[16]

4. Conclusion

The article presents basic issues related to FSW technology, with particular attention to the influence of tool rotational and linear speed on the macrostructure of the weld. The results obtained lead to the following conclusions:

- an increase in the welding speed above 300 mm/min results in an irregular cross-sectional edge of the weld and may result in its defects,

- increasing the tool rotational speed increases the risk of obtaining irregular shaped joints, especially on the advancing side; increasing the speed (in the analyzed range, i.e. up to about 800 rpm) did not significantly increase the risk of a defect,

- an increase in the rotational speed of the tool results in a reduction of the band spacing in the weld, a similar effect is caused by the reduction of the linear speed; the band spacing is equal to the distance traveled by the tool during its single rotation.

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