Two modes of metal flow phenomenon in friction stir welding process

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It has been widely recognised that the fundamental mechanism of weld formation in friction stir welding (FSW) is too complex, a phenomenon to be understood completely. In the present study two modes of metal transfer phenomenon in FSW have been discussed with the help of three FSW techniques. In the first technique a strip is welded to the plate by the process, in the second one the brass sheet is inserted perpendicular to the welding direction and in the third one the process is performed with tools having different pin lengths. The results suggest a strategy to model the process particularly for predicting welding tool performance.

Keywords: Friction stir welding, Metal flow, Tool pin length

Introduction

The friction stir welding (FSW) is a relatively recent welding process, patented in 1991 by Thomas *et al.*[1] This process is a low heat input solid state welding technology especially suitable to low melting point metals, such as Al and Mg.[1–3] The friction stir welding uses a rotating cylindrical tool with a shoulder to heat the metal by friction. The tool pin stirs the plasticised material and therefore joins two pieces together while it is moved along the weld line. This technique has many advantages, such as joining of materials that are difficult to fusion weld, low distortion and excellent mechanical properties.[4]

The metal flow in FSW is a complex phenomenon and only a few investigations have been carried out in this direction. Li *et al.*[5] inferred that a chaotic–dynamic mixing takes place in FSW by observing the microstructure of dissimilar metal welding. Colligan[6] studied the metal flow using embedded steel spheres placed along the weld centre line. It is also reported that chaotic mixing takes place at the top surface of the weld but given no proper explanation to establish this phenomenon. Reynolds *et al.*[7–9] and Seidel and Reynolds[8,9] analysed the metal flow of AA 2195-T8 in several friction stir welds using a marker insertion technique. Three-dimensional plot obtained from the deformed marker indicated no evidence of chaotic mixing of stirred material at the top layer. At lower level in the weld, where influence of shoulder is diminished, only a small amount of metal mixes on advancing side. This movement causes vertical mixing in the weld which may causes a complex circulation of metal around the longitudinal axis of the weld.[9] Xu *et al.*[10] performed finite element simulation of the material flow in FSW and reported that a particle directly in front of a rotating pin passes the pin and does not travel around the pin from both sides. It was also reported that the phenomenon is not matching with the experimental observations.[10] In the previous works it is clear that any conclusion about chaotic mixing and material moved by the pin yet has not been adequately established.

In the present work, two distinct modes of metal transfer in FSW are being proposed. In the first mode, the metal transfer is caused by the tool shoulder and in the second one caused by extrusion around the pin. Three experiments: strip welding, brass sheet insertion techniques and welding with short and normal pin length are performed to explain two modes of metal transfer, chaotic mixing and flow around the pin.

First mode of metal transfer

The first mode of metal transfer is performed by the tool shoulder. As the rotating shoulder touches the plates to be welded, the heat is generated owing to friction. When the pin advances, a small quantity of metal is moved from front to rear side via the retreating side for every rotation of the tool leading successive layers getting deposited one over the other. However, in weld involving a larger tool advance per rotation, the metal transfer by this mode decreases.

Second mode of metal transfer

The second mode of metal transfer takes place around the pin. As the metal reaches sufficient plasticity, it moves from the front to rear side by extrusion around the pin. The metal may get extruded at the retreating side or forwarding and retreating side as shown in Fig. 1.

Experimental details

Materials used

The material used in the present study is 6·3 mm thick 6063-T4 aluminium alloy with the chemical composition Al–Si0·4–Fe0·35–Cu0·1–Mn0·1–Mg0·7–Cr0·1–Zn0·1–Ti0·1. The plates are butt welded by FSW process.

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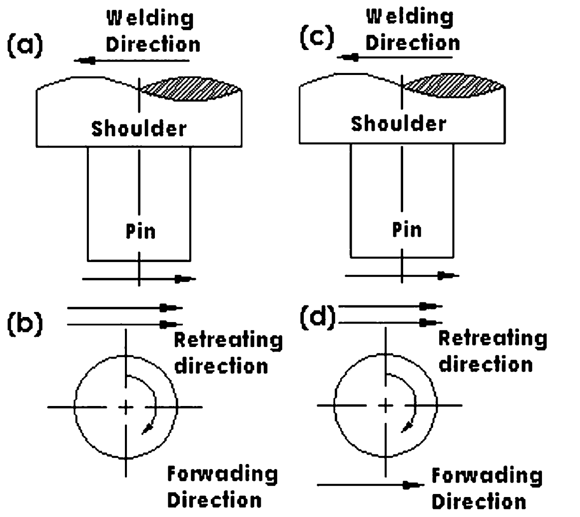


a side view and *b* top view in case 1: extrusion along the retreating side; *c* side view and *d* top view 2 in case 2: extrusion along the retreating and forwarding side

1 Metal extrusion in FSW process

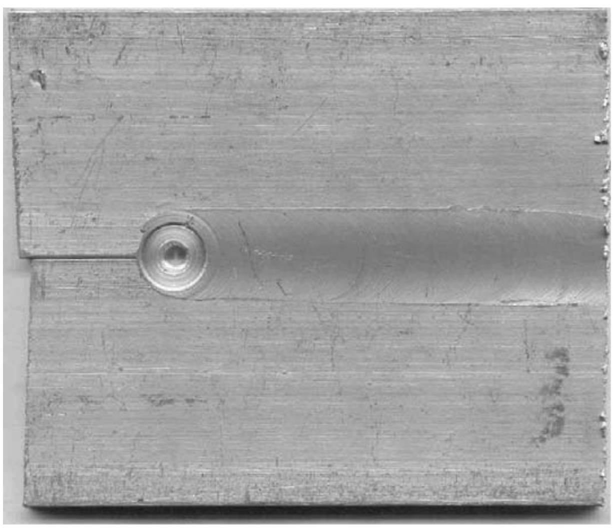
Instrumentation for FSW

A modified 2369-0 HMT universal milling machine is used for FSW. The FSW tool is made by tool steel with 16 mm shoulder diameter and a M6 threaded pin. The tool is provided with 1° rake angle for all the experiments. The friction stir welded plate obtained by the present experimental set-up is shown in Fig. 2.

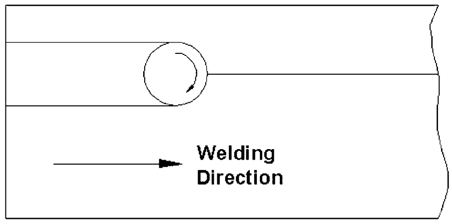
Verification of first and second mode of metal transfer

FSW of strip to plate

A plate of 25 mm width and 100 mm length is welded with a strip of 15 mm width and 100 mm length by the FSW process with suitable clamping arrangement shown in Fig. 3. The welding parameters adopted are 1120 rev min^{-1} tool rotation rate and 160 mm min^{-1} welding speed.



2 Friction stir welded aluminium plate



3 Friction stir welding of plates with uneven width

Thin brass sheet insertion technique

A thin brass sheet of 0·2 mm is inserted perpendicular to the welding direction. The schematic diagram of plate dimensions and the location of the brass sheet is shown in Fig. 4. The welding parameters adopted for this experiment are 1400 rev min^{-1} rotation rate, 125 mm min^{-1} tool travel speed and 5·3 mm pin length.

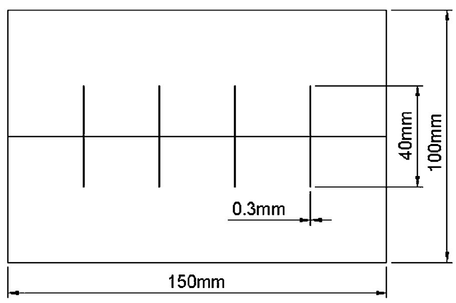
FSW with different pin lengths

Two friction stir welds are performed with pin lengths of 4 and 5·3 mm, as shown in Fig. 5. The rotation and travel speeds are 1120 rev min^{-1} and 160 mm min^{-1} respectively and other parameters adopted for shorter and normal pin length are the same in both cases. The specimens are prepared along the transverse direction, polished and etched by killer's reagent.

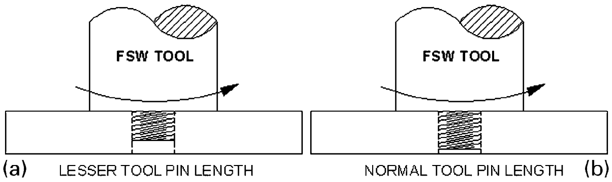
Results and discussions

The weld obtained from welding of a strip with a plate is shown in Fig. 6. Owing to residual stress, the welded plate along the strip side is found to get rolled similar to chip formation in machining process. The two modes of metal transfer are clearly seen in the weld (Fig. 6) where the top layer is the first mode of metal transfer and the bottom is the second of metal transfer.

A specimen is prepared from the weld obtained by brass strip insertion technique along the transverse direction. The two modes of metal transfer are clearly seen from the Fig. 7. The first mode of metal transfer takes place layer by layer near the tool shoulder and hence the width of the weld zone at the upper surface is more influenced by the shoulder diameter of the tool. In a 6·3 mm aluminium alloy weld, the weld temperature is in excess of 540°C at the weld zone and the tool axial force is ~10 kN (Ref. 11). Owing to such temperature and axial force, bonding between the layers may take place. More uniform flow pattern caused by the second mode obtained by extrusion is shown in Fig. 7. From the present study it is found that the first mode of metal transfer increases with decrease in tool forward motion

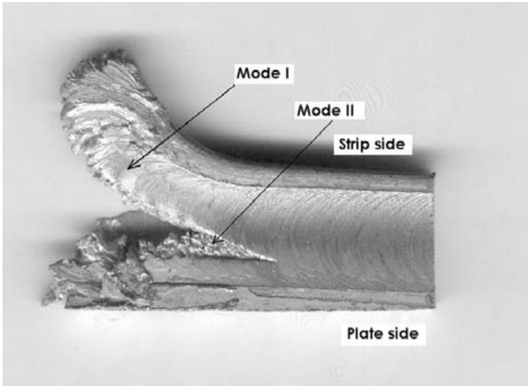


4 Aluminium plates inserted with brass sheet for flow analysis

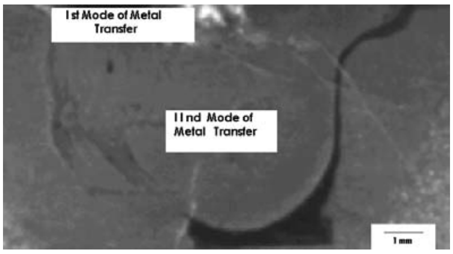


a shorter pin length; *b* normal pin length

5 Friction stir welding with different pin lengths



6 A part of top view of friction stir welded plate with uneven width

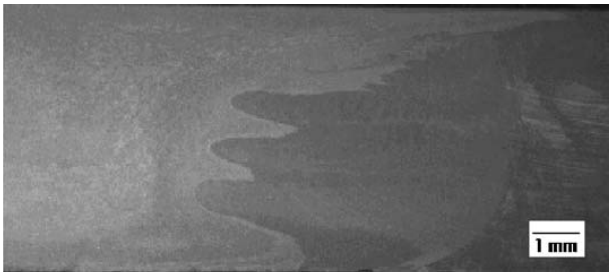


7 Macro structure obtained from friction stir welded aluminium plates with brass sheets along transverse direction

per rotation. However, detailed study have to be carried out to estimate the quantity of metal transfer by each mode with respect to welding parameters, tool dimensions and plate material characteristics and principles behind the phenomenon.

The chaotic mixing at top surface of the weld as proposed by Colligan[6] is attributed as first mode of metal transfer according to the present study. Seidel and Reynolds[9] adopted a 2·7 mm height, 1·8 mm thick marker for the flow study and reported that there is no chaotic mixing at the top of the weld. However, in the present study it is clear that a small quantity of metal is transferred by the shoulder and deposited as layer in the retreating side in every rotation. Hence the marker size and shape adopted by Seidel *et al.* may not reflect the first mode of metal transfer.

The macro structures of the welds obtained by tool pins of 4 mm and 5·3 mm are shown in Figs. 8 and 9 respectively. At lower pin length, the metal at the bottom of the pin is found to offer more resistance to metal flow and in the mean time the metal from the advancing side occupy the cavity created by the tool pin



8 Macro structure obtained from lesser tool pin length: metal flow takes place from both retreating and forwarding side

9 Macro structure obtained from normal tool length: metal flow takes place from retreating side only

and hence a distinct boundary is observed in the macro structure. The strength obtained by this weld is found to be 104 MPa and the onion like ring patterns are not observed in the weld zone. In the weld obtained from the pin length of 5·3 mm, complete flow of metal by extrusion from the retreating side towards forwarding side is observed. As the thickness of the metal below the tool pin is less in this case, it offers lesser resistance for metal flow. The strength obtained by this weld is found to be 137 MPa and onion like ring patterns are observed in the macro structure. Threadgill[4] also explained that the formation of onion like rings in FSW is associated with the flow pattern and affect the properties of the weld. From the flow model proposed it is observed that metal flow takes place from both retreating and forwarding side where as in marker insertion technique it indicated that the metal flow was only along retreating side.[7] However, in the present study it is clear that both the conditions are possible in FSW process.

Conclusions

Based upon the present study and results it is apparent that the shoulder moves the portion of the metal on the top surface and other portions are moved by simple extrusion. The following conclusions can be drawn from the present study.

1. The metal flow phenomenon in FSW from the front side of the tool to the rear side takes place by two modes.
2. The first mode of metal transfer takes place layer by layer and is caused by the tool shoulder.
3. The second mode of metal transfer is caused by the extrusion around the pin.
4. The flow across the pin may take place through retreating side or both retreating and forwarding side.

However, further adequate work needs to be carried out to understand the complete flow phenomenon in FSW.

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