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Analysis of first mode of metal transfer in friction stir welded plates by image processing technique

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ARTICLE INFO

Article history:
Received 16 May 2006
Received in revised form
29 May 2007
Accepted 5 June 2007

Keywords:
Friction stir welding
Image processing
Metal flow

ABSTRACT

The metal flow phenomenon in friction stir welding (FSW) comprised of two modes of metal transfer. The first mode of metal transfer taking place layer by layer and is caused by the shearing action of the tool shoulder, while the second mode is caused by the extrusion of the plasticized metal around the pin. The aim of the present study is to quantitatively determine the amount of metal transferred by the first mode and its effect on strength of the weld. The images of the fractured faces of the samples are captured and processed to identify and distinguish the two modes of metal transfer. Quantitative analysis of the fractured surface and reveals existence of a possible linear correlation between the first mode in the fractured surface and the ultimate tensile strength, which controls the presence of defect in the weld.

1. Introduction

The friction stir welding (FSW) is a solid state welding process in which a non consumable rotating welding tool is used to join two metal pieces by frictional heat. It is especially suitable to low melting point metals, such as Al and Mg (Thomas et al., 1991; Biallas et al., 1999). The rotating cylindrical tool used in FSW is provided with a shoulder and a threaded pin. The shoulder heats the metal by friction and the pin stirs the plasticized material to join the two metal pieces together. The principal advantages of FSW over conventional welding techniques are low distortion, absence of melt related defects, high joint strength and excellent mechanical properties (Bussu and Irving, 2003). Consequently there is less joint contamination, lesser heat affected zone and a very fine microstructure, which increases the tensile strength and fatigue life. Hence FSW is an energy efficient, environment friendly and versatile welding process.

The metal flow phenomenon in FSW is a complex process and various theories have been proposed to explain the formation of the weld. Colligan (1999) studied the metal flow using embedded steel spheres placed along the weld centre line and reported that chaotic mixing take place in the top surface of the weld. Xu et al. (2001) explained the flow phenomenon in FSW by performing finite element simulation. It was reported by them that the material flow takes place from retreating side.

However, it has been recently established experimentally by Muthukumaran and Mukherjee (2006) that the two modes of metal transfer is the fundamental mechanism that governs the weld formation in FSW (Muthukumaran and Mukherjee, 2006). According to the study the first mode of metal transfer occurs due to the frictional heat generated between the tool shoulder and the plate. It is characterized by layer-by-layer deposition of metal, one over the other. The second mode of metal transfer occurs by the extrusion of metal around the tool pin, when it reaches a state of sufficient plasticity. To

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doi:10.1016/j.jmatprotec.2007.06.013

establish this phenomenon two techniques were employed. In the first technique a strip was welded to the plate by the FSW process, while in the second technique a brass sheet was inserted perpendicular to the welding direction. In both the cases, the two modes of metal transfer could distinctly be seen from the welded specimens, thereby firmly establishing the concept of two modes of metal transfer. Also it was proved that metal extrusion could take place from either the retreating side towards the forwarding side, or it could also occur from both retreating and forwarding sides (Muthukumaran and Mukherjee, 2006).

Cavaliere et al. (2006a,b) performed FSW on dissimilar 2024 and 7075 Al alloy sheets, in the T3 and T6 conditions, respectively. They examined fatigue and tensile fractured specimen surfaces for microscopic morphology and defect analysis. Elangovan and Balasubramanian (2007) observed that the square pin profiled tool gives defect free joint with better tensile property.

The present work investigates the correlation between the quantity of first mode of metal transfer and the tensile strength of the friction stir welded specimens. The boundary between the two modes of metal transfer is not distinct in the macro structure of some welds. However when the fracture occurs in the weld they are distinct. Hence in the present work an attempt is made to correlate the tensile strength with the first mode with the help of fractured surfaces. Specimen are prepared from friction stir welded aluminium plates and fractured by tensile load. The images of these fractured specimens are analyzed using image processing techniques to quantitatively determine the first mode of metal transfer.

The macrostructure of a friction stir welded plate having two distinct modes of metal transfer is shown in Fig. 1. The layers of metal deposited at the top represent the first mode of metal transfer while the layers below represents the second mode, where definite ring patterns can be observed. In general, friction stir welded macrostructure has four zones. The first and second zones are unaffected base metal and heat affected zone (HAZ), respectively. In HAZ the material does not undergo any plastic deformation but is influenced by the heat of the welding, leading to some changes in the macrostructure. The third is the thermo-mechanically affected zone (TMAZ), where the material is deformed as well as influenced by heat. The fourth zone is the nugget, which is the recrystallized region of the TMAZ (Cavaliere et al., 2006a,b; Prangnell and Heason, 2005).

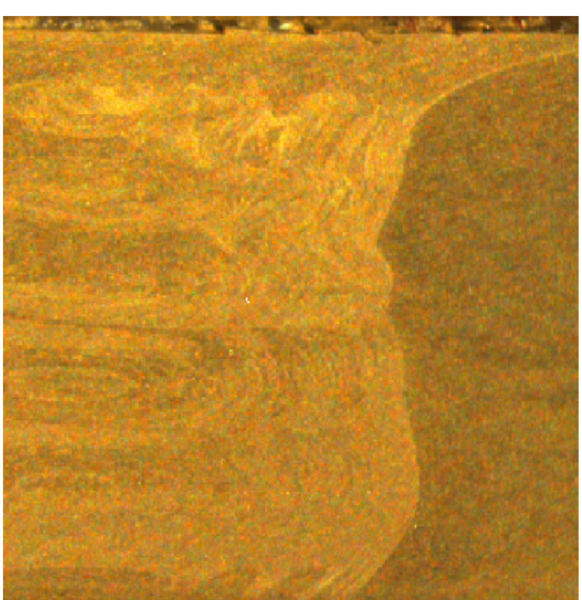

Fig. 1 – Macrostructure showing distinct first and second mode of metal transfer.

2. Experimental work

Friction stir welding tools with threaded pins are employed to butt weld 6.3 mm plates of 6063-T4 aluminium alloy. The FSW is carried with a modified 2369-0 HMT Universal Milling machine. The tool material used is 'tool steel' and the tool has a 16 mm shoulder diameter and a M6 threaded pin. The rake angle provided for all the experiments is 1°. The rotating speed of the tool and its traverse speed are varied between the ranges of 900–1120 rpm and 100–200 mm/min, respectively. The tensile specimens are prepared as per ASTM standard and tested in the hydraulic tensile testing machine.

The principle parameters in the FSW process are the rotational tool speed, tool travel speed and the pin length. A variation in these parameters affects the quantity of metal transferred by the first mode as well as the second mode, thus affecting the tensile strength.

3. Image processing and analysis

The captured images of the fractured samples are analysed in MATLAB by implementing the following steps:

(1) The preliminary pre processing stage consists of applying filtering techniques to eliminate the noise from the acquired images, thereby sharpening the image.
(2) Next a portion of the original image is cropped to select the region of interest.
(3) Then the cropped image is converted to an 8-bit grayscale intensity image for further analysis.
(4) The graylevel image is equalised to improve its contrast by histogram equalisation techniques.

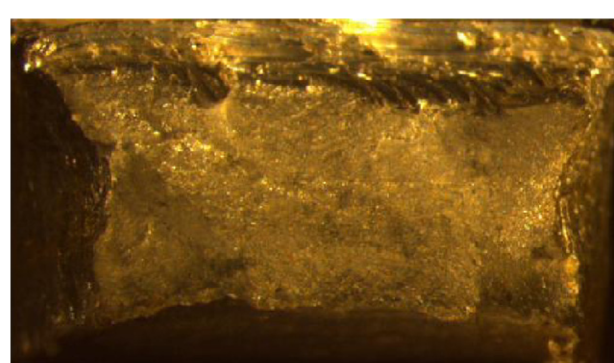

Fig. 2 – Fractured weld face of specimen 1 having tensile strength of 129 MPa.

Table 1 – Welding parameters adopted and tensile strength

Specimen no.	Tool speed (rpm)	Traverse speed (mm/min)	Pin length (mm)	Tensile strength (MPa)
1	900	160	5.2	129
2	1120	200	4.7	119
3	900	160	4.7	108
4	1120	160	5.8	118
5	900	100	5.8	124

(5) Finally the contouring of the graylevel image is done to display a contour plot of the data and extract prominent features from the image. A contour is defined as a path in an image along which the image intensity values are equal to a constant. Based on this contour plot, the region representing the first and second modes of metal transfer can be identified.

(6) Grids are made on the processed images to facilitate quantitative measurement of the first mode of metal transfer.

The fractured surfaces of five welded specimens are analysed using the image processing techniques. Three of them are shown through Fig. 2 and Fig. 10. The welds are prepared as per the ASTM Standard. The welding parameters adopted for the five different welds and their respective strength values are shown in Table 1.

In each case, the ratio of the amount of metal transferred by the first mode to the total cross sectional area is computed. The contour plot of the fractured face is useful in distinguishing the first mode from the second mode. The contours for specimens 1, 2 and 3 are shown in Figs. 3, 6 and 9, respectively.

4. Results and discussion

The fractured weld face of specimen 1 having fairly good tensile strength of 129 MPa is shown in Fig. 2. As discussed above, various image processing techniques are implemented to obtain the contour plot of the fractured face (Fig. 3). From the contour, the region representing the first mode of metal transfer was identified. The hatched area represents the first mode (Fig. 4) and the ratio of the amount of metal transferred by the first mode to the total cross sectional area is found to be 17.85%.

Similarly the image of the tensile fractured surface of specimen 2 is shown in Fig. 5. Subsequently as discussed above various image processing techniques are implemented to analyse the fractured face. Image contouring is done to discern between the first and second modes, as shown in Fig. 6. The region representing the first mode of metal transfer is

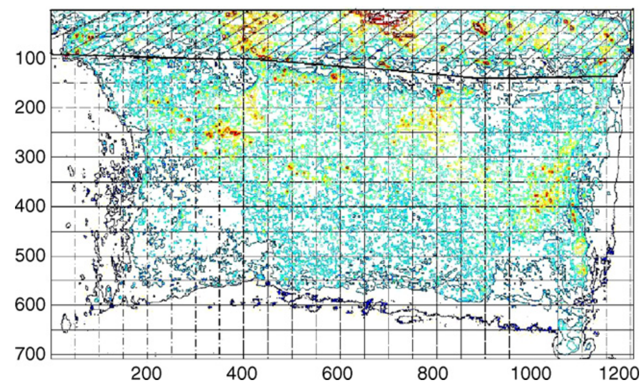

Fig. 4 – Hatched area represents the first mode of metal transfer in specimen 1.

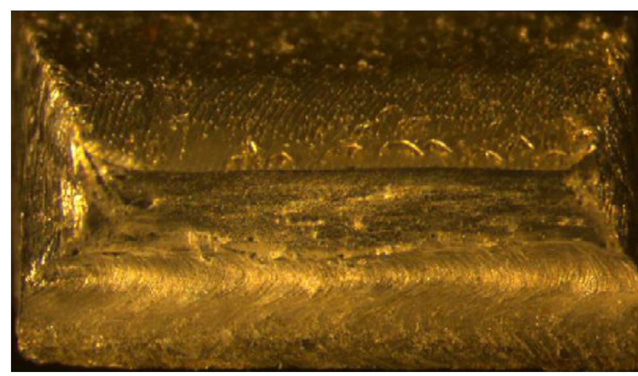

Fig. 5 – Fractured face of specimen 2 having tensile strength of 119 MPa.

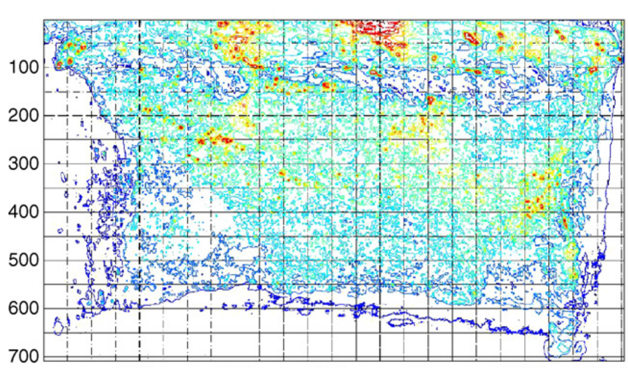

Fig. 3 – Contour plot of specimen 1.

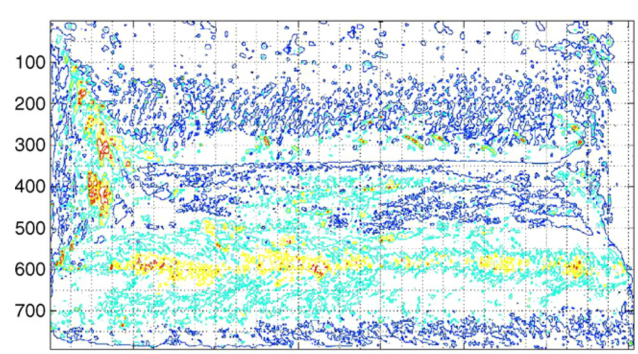

Fig. 6 – Contour plot of the fractured face of specimen 2.

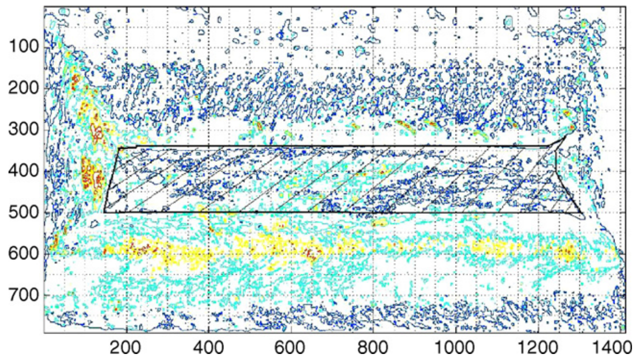

Fig. 7 – Hatched area represents the first mode of metal transfer in specimen 2.

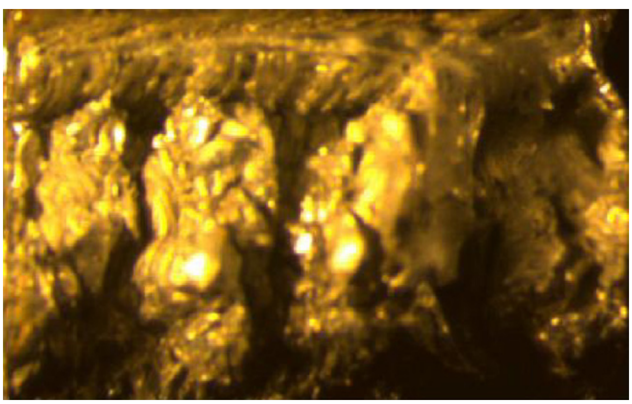

Fig. 8 – Fractured face of specimen 3 having poor tensile strength of 108 MPa.

hatched, as shown in Fig. 7. The percentage of the metal transferred by first mode is calculated and found to be 12.7%.

Fig. 8 shows the image of specimen 3. The contour plot generated to help in identifying the two modes is shown in Fig. 9. The area representing the first mode is again hatched, as shown in Fig. 10. It is found that in this case a very small amount of metal is transferred by the first mode. The ratio of the first mode to the total cross sectional area is only 6.63%. This indicates very poor bonding between the first and second modes of metal transfer. Similar analysis is performed for specimens 4 and 5; and the results are shown in Table 2.

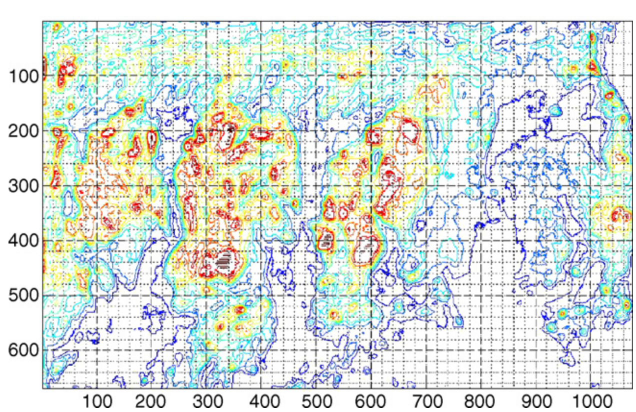

Fig. 9 – Contour plot of fractured face of specimen 3.

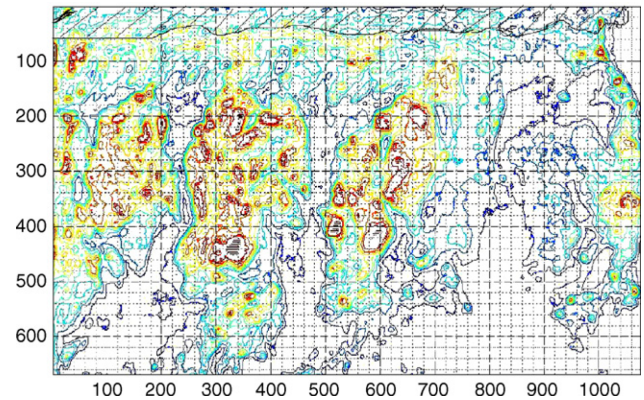

Fig. 10 – Hatched area represents first mode of metal transfer in specimen 3.

Table 2 – Tensile strength and percentage of first mode in fractured surface

Specimen no.	Tensile strength (MPa)	Percentage of first mode
1	129	17.85
2	119	12.7
3	108	6.63
4	118	12.02
5	124	15.2

Table 2 shows the tensile strength and the percentage of first mode of metal transfer for the five specimens. From Table 2, it can be concluded that in general, friction stir welds that exhibit better tensile strength are characterized by a higher percentage of metal transfer by first mode. The above phenomenon can be explained on the basis of bonding between the first and second modes. The first mode of metal transfer takes place on the extruded metal by the pin. It offers better compactness to the weld and hence increase in the first

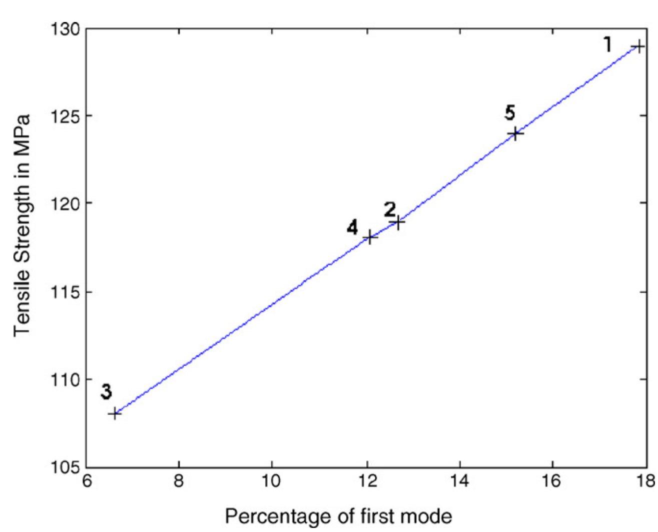

Fig. 11 – A straight-line profile between the first mode of metal transfer and the tensile strength.

mode is found to improve the tensile property of the weld, thereby resulting in defect free weld with better strength. This improvement in tensile property is explained due to the compressive load offered by the first mode on the metal extruded around the pin. There exists a linear relationship between the first mode of metal transfer and the tensile strength as shown in Fig. 11.

Cavaliere et al. (2006a,b) performed FSW by employing rotational speeds of 500, 800 and 1000 rpm and traverse speeds of 40, 56 and 80 mm/min, respectively. They observed that the highest tensile strength is reached in correspondence of the highest rotation speed, at the highest traverse speed. However, from the results obtained in Table 2, it is clear that excessive or lesser pin length may adversely decrease the tensile strength.

Process parameter variations, such as changes in tool rotation or traverse speed, will produce different thermal profiles (Kamp et al., 2006). The volume fraction of the bands of new nugget scale grains rises with strain and temperature (Prangnell and Heason, 2005). Hence, change in the process parameters causes changes in the weld properties and the two modes of metal transfer, thereby affecting tensile strength.

5. Conclusion

In the present study, FSW of 6063 aluminium alloys have been carried out at different process parameters. The tensile specimens are prepared from the welded plate as per the standard and tested. The fractured faces are analysed using image processing techniques and the following conclusions can be drawn:

1. The two modes of metal transfer are distinct in the fractured surfaces.
2. The first mode increases the compactness of the weld and eliminates defects. Hence, an increase in the first mode of metal transfer improves the tensile properties.
3. There exists a linear correlation between the percentage of first mode in the fractured surface and the ultimate tensile strength.
4. All the three parameters considered in the present study; tool rotation speed, traverse speed and pin length are found to affect the first mode of metal transfer.

However, this work is a preliminary attempt to investigate the quantity of metal transferred by the two modes and further study needs to be done to understand the influence of the individual process parameters on the two modes of metal transfer.

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