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STICKING AND SLIDING HEAT GENERATION DURING FRICTION STIR WELDING OF AN ALUMINIUM ALLOY

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ABSTRACT

The material flow, microstructure, and mechanical properties of the friction stir welded plates are influenced by the heat generation during the process. This paper proposes a model for predicting heat generation due to friction, deformation, shoulder and pin during the friction stir welding of AA 6061 aluminium alloy. This model also predicts the heat flux generated around the pin for different rotational speeds. The frictional, deformation, shoulder and pin heat generation as a function of temperature and volume heat flux around the pin as function of temperature and rotational speed have been discussed. The result shows that the heat generation due to pin, shoulder and heat flux are inversely proportional to temperature.

Keywords: *Friction stir welding, microstructure, heat generation and shear deformation.*

1. Introduction

Friction stir welding (FSW) is a solid state joining process in which a specially designed non consumable rotating tool is used to weld the plates together. The tool employed in FSW has a larger diameter shoulder and a smaller diameter pin as shown in Fig.1. FSW offers several advantages over fusion welding processes such as excellent mechanical properties, low distortion, no consumables, and little porosity and is environment friendly [4]. It has the potential for applications in many industries like aerospace, automotive and ship building [9,10]. FSW process is found suitable for welding materials such as aluminium alloys, metal matrix composites, stainless steel [12] etc. The heat generated in friction stir welding process is primarily by friction between tool and workpiece and the plastic deformation of the workpiece material. It influences the material flow, microstructure, and mechanical properties of the weld zone [3].

Prasanna *et al.* [7] presented a thermal model to predict the temperature distribution of FSW process of 304L stainless steel considering only frictional heat source as a function of radius. Nandan *et al.* [6] presented a three dimensional heat and material flow model considering heat generation due to both friction and plastic deformation of FSW to predict the thermal history. Zhang *et al.* [11] presented a thermo-mechanical model of FSW process assuming a slip factor as a function of velocity difference between tool and workpiece material to predict the thermal cycle. Hamilton *et al.* [2,1] developed a thermal model of friction stir welding of aluminium alloy utilizing a slip factor based on the energy per unit length of weld to predict the temperature distribution and thermal history. Three dimensional thermal model for friction stir welding considering energy due to friction and plastic deformation is developed by Samir and Ali [8] to predict the temperature distribution and thermal cycle.

Most of the present literature on thermal modeling of FSW used to predict the temperature distribution and thermal cycle. In this paper, an attempt has been made to predict the heat generation due to friction and shear deformation and heat generation at the pin as a functin of temperature.

2. Thermal model

2.1 Mathematical model

This part of the paper describes the mathematical expressions involved in the heat calculation during friction stir welding at different parts of the tool.

2.1.1 Heat generated at shoulder

Heat generated due to friction at the shoulder

$$Q_{sh-fr} = \frac{2\pi}{3}\mu\, p_n\, \omega\,(r_s^3 - r_1^3) \quad (1)$$

Axial pressure, $p_n = \dfrac{F_n}{\pi\, r_s^2}$ (2)

Angular velocity of tool, $\omega = \dfrac{2\,\pi\,N}{60}$ (3)

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where μ is the friction coefficient. The friction coefficient is assumed to be linearly varying from 0.5 to 0.4 between the room and solidus temperature [6].

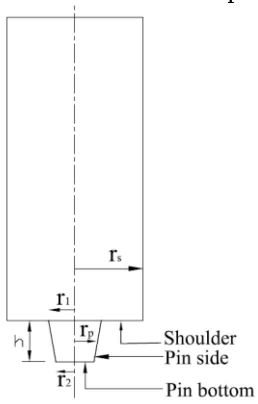

Fig. 1 FSW tool dimensions

Heat generated due to shear deformation at the shoulder

$$P_{sh-pl} = \frac{2\pi}{3} \tau \, \omega \, (r_s^3 - r_1^3) \qquad (4)$$

Shear stress, $\tau = \dfrac{\sigma_y}{\sqrt{3}}$ (5)

where σ_y is the yield stress as shown in Table 2.

Table 1. Properties of 6061-T6 aluminium alloy [5]

Temperature (°C)	**25**	**37.8**	**93.3**	**148**	**204**
Yield strength (MPa)	276	274	264	248	218
Density (kg/m^3)	2700	2685	2685	2667	2657
Thermal con. (W/m °C)	167	170	177	184	192
Heat capacity (J/kg °C)	896	920	978	1004	1028
Temperature (°C)	**260**	**315**	**371**	**426**	
Yield strength (MPa)	159	66.2	34.5	17.9	
Density (kg/m^3)	2657	2630	2620	2602	
Thermal con. (W/m °C)	201	207	217	223	
Heat capacity (J/kg °C)	1052	1078	1104	1133	

Heat generated at the shoulder

$$Q_{sh} = \delta . Q_{sh-pl} + (1-\delta) Q_{sh-fr} \qquad (6)$$

2.1.2 Total heat generated

Similarly heat generated at the pin side Q_{ps} and pin bottom Q_{pb} are calculated

Heat generated at the pin,

$$Q_{pin} = Q_{ps} + Q_{pb} \qquad (7)$$

Total Heat generated, $Q_T = Q_{sh} + Q_{ps} + Q_{pb}$ (8)

2.1.3 Heat flux

The heat flux at the shoulder area

$$q_{sh} = 0.9 \times \frac{3 Q_{sh} \, r}{2 \pi (r_s^3 - r_p^3)} \quad \text{for} \quad r_p \le r \le r_s \qquad (9)$$

The cylindrical heat flux of pin

$$q_{pin} = 0.9 \times \frac{Q_{pin}}{\pi [(r_p + 2)^2 - r_p^2] h} \qquad (10)$$

2.2 Finite element model

The finite element model is shown in Fig.2. The finite element simulation was carried out based on the boundary conditions given in the model.

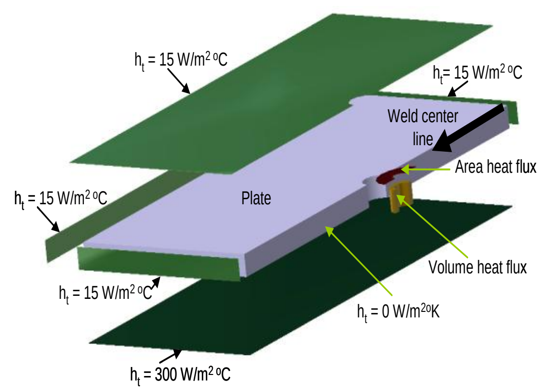

Fig. 2 Finite element model with heat inputs and boundary conditions

3. Result and discussion

In this part, the heat generation at the shoulder, pin, friction and shear deformation and heat flux around the pin have been discussed.

3.1 Heat generation at shoulder and pin

The heat generation due to rubbing of shoulder and pin against the workpiece material is shown in Fig. 3. The heat generation is calculated based on the mathematical expressions derived for the friction stir welding process as discussed in the section 2. The shoulder contact with the material looks similar to the type of contact occur in plate clutches. The tool and material are in solid state at the beginning of friction stir welding process. It is similar to the clutch contact mechanism. But during the friction stir welding, it not only sliding between the surface, because the material is in plasticized stage. Hence sliding and deformation both take place. The heat generation due to friction is calculated just like clutch. In case of shear deformation, the shear stress was considered while calculating the heat generation. The combined heat generation due to sliding and deformation at shoulder, pin and total is shown in Fig.3. It shows that heat generation reduces as temperature increases for shoulder, pin and total. This due to the reduction in shear stress as temperature increases. As temperature increases, shear stress of the material decreases and hence power required to over come the frictional and shear resistance is reduced. This lead to reduction in heat generation.

Table 2. Shoulder and pin heat generation for 900 rpm

Temp. in ^{o}c	30	130	210	310	390	490	570
Shoulder heat in W	3993	3848	3732	3586	3470	1778	28
Pin heat in W	977	941	913	877	849	434	7
Total heat in W	4970	4789	4645	4464	4319	2213	34

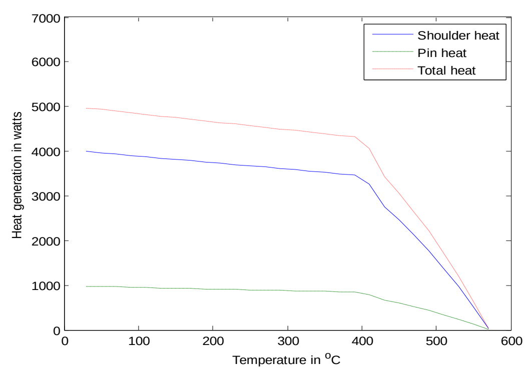

Fig. 3 Heat generation at shoulder, pin and total as a function of temperature for 900 rpm

3.2 Heat generation due to friction and deformation

During the friction stir welding process, the interface between the tool and shoulder subjected to friction and shear deformation of material. Fig.4 shows the heat generated due to friction, shear deformation and total during the process for 900 rpm. The heat generation due to friction reduces slowly till temperature is 400 ^{o}C, after that reduces steeply. The reason is that the tool and material are in solid stage upto 400 ^{o}c and the shear deformation is negligible. Hence the heat is generated due to friction alone. But after 400 ^{o}C, shear deformation increases and friction reduces drastically. So the heat generation due to friction reduces drastically. In contrast, The heat generation due to shear deformation is zero due to negligible shear deformation up to 400 ^{o}C and heat generation due to shear deformation appears after 400^{o}C due to the shear deformation of the material.

Table 3. Frictional and deformation heat generation for 900 rpm

Temperature in ^{o}c	30	130	210	310	390	490	570
Friction heat in W	0	0	0	0	0	595	13
Deformation heat in W	4970	4789	4645	4464	4319	1618	21
Total heat in W	4970	4789	4645	4464	4319	2213	34

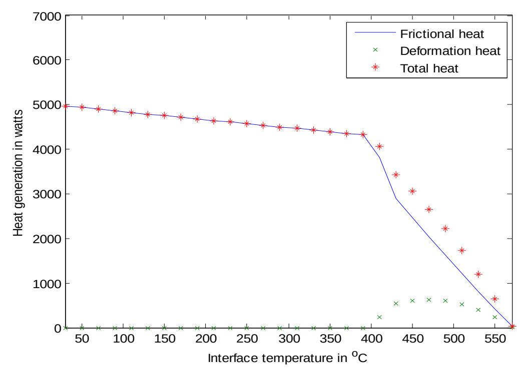

Fig. 4 Heat generation due to friction, deformation and total as a function of temperature for 900 rpm

3.3 Volume heat flux at the pin

The volume heat flux generated around the pin for different rotational speed 600, 900 and 1200 rpm against temperature is show in Fig.5. It shows that the heat flux decreases as temperature increase. The heat flux reduces due to the reduction in shear stress due to the rise in temperature. It also shows that the heat flux increases with rotational speed increases due to the increases rubbing velocity of the pin with material.

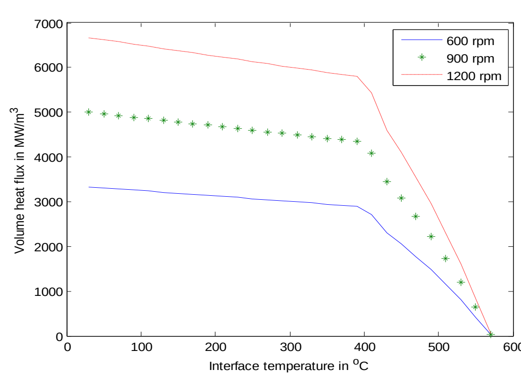

Fig. 5 Volume heat flux at the pin for 600, 900 and 1200 rpm

Table 4. Heat flux around the pin (MW/m3) for different rotational speeds

Temperature in ^{o}c	30	130	210	310	390	490	570
600 rpm	3334	3212	3115	2994	2897	1482	23
900 rpm	5000	4819	4673	4491	4346	2222	35
1200 rpm	6667	6425	6231	5988	5794	2963	46

4. Conclusions

A model for predicting heat generation due to friction, deformation, shoulder and pin during the friction stir welding of AA 6061 aluminium alloy have been proposed. Utilizing the model heat generations were predicted, the results are

1. The predicted heat generation at the shoulder and pin shows that heat generation is inversely proportional to interface temperature.

2. The frictional and shear deformation heat generation have been predicted. It shows that the frictional heat generation is inversely proportional to temperature and shear deformation heat does not exist up to 400 oc and exist after 400^{o}c.

3. The predicted heat flux at the pin shows that heat flux at the pin is inversely proportional to temperature.

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