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ENERGY MODELLING ON CYLINDRICAL TOOL GEOMETRY OF ALUMINUM ALLOYS USING "C" PROGRAM

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Abstract

Friction stir welding is competing technology used in many engineering applications. Many researchers showed their interest on developing numerical modelling on friction stri welding. The friction stir welding process is dependent mainly by controlling the major weld parameters. The major weld parameters are rotational speed, transverse speed and axial load.In this study,a energy model for taper tool geometry is developed numerically using these weld parameters which estimates the energy generated due to friction and plastic deformation. The generated energy model is programmed using "C" program. By using the program we can reduce the time of calculating the effective energy and maximum temperature using the developed numerical equations.

Keywords: Friction Stir Welding, C-Program, Energy, Temperature model.

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1. Introduction

Friction Stir Welding (FSW) is a process of joining two similar and dis-similar metals by the non-consumable tool. The major weld parameters involved are rotational speed, transverse speed and axial load. The joining of two metals is made by bonding the two similar and dis-similar metals. The creation of bond develops energy in between two metals by the application of direct heat. The major sources for direct heat is from friction and chemical reaction between group of atoms while colliding and cohesion. The atomic mechanism and chemical reactions are neglected for the simplicity on the creation of numerical equations.

Friction-stir welding (FSW) enables welding similar and dissimilar metals such as high-strength aluminum alloys. Friction-stir welding was developed and patented by The Welding Institute (TWI) in 1991 [1].

Friction-stir welding is carried out using a rotating tool that is attached to a shoulder piece and the whole unit is translating over the line of welding. The rotation and translation of the pin within and on top of the line of welding generates heat, which is used to weld the workpieces. Heat is generated due to plastic deformation of the workpiece and the effect of the friction between the surfaces of the tool and the workpiece [2,3]. Figure 1 is a schematic of the friction stir welding process.

Y. K. Yousif et al., shows the possibility of the use of neural networks for the calculation of the mechanical properties of welded Al plates using FSW. The Levenberg – Marquardt algorithm shows better performance than gradient descent[4].

M Selvaraj et al., developed a temperature dependent slip factor based on three-dimensional thermal model for friction stir welding with capability of predicting thermal cycle, temperature distribution, power required and heat generated per unit length for friction stir welding of stainless steel[5].

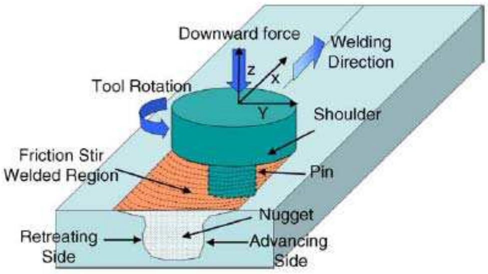


Figure 1. Schematic illustration of Friction Stir Welding

Samir A. Emam et al., created a simple model that estimates the energy generated in friction-stir welding is presented. The model accounts for the heat generated due to friction between the weld tool and the surface of the workpiece and heat generated due to plastic deformation. The heat due to plastic deformation is found to have a significant effect on the resulting temperature especially at low-energy levels[6].

Darko M. VELJI et al., is developed a 3-D finite element model in the commercial code ABAQUS/Explicit using the arbitrary Lagrangian-Eulerian formulation. Through the numerical modelling he found that the amounts of heat generated by friction and plastic deformation suddenly increase after contact between the workpiece and the tool shoulder is established. Also found that the heat generated by friction between the workpiece and the tool can account for the largest percentage of the generated heat[7].

S. Sulaiman et al., studied a heat input equation for FSW and found the main factors in heat generation and heat input issues as rotational and traveling speeds. If the heat input is too low, suitable plastic conditions will be prevented and will cause voids during welding and eventually, in extreme cases, the tool may break[8].

P. Edwards et al., proposed a energy model, energy input values below 1.4 kW lead to ‘cold’ welding conditions, while values greater than 2.5 kW produce ‘hot’ welding conditions. Optimal processing conditions were found to have energy input values between 1.4 and 2.5 kW for the given material thickness and tooling configuration[9].

Yuh J. Chao et al., studied the numercal equation that determines the heat flux from the friction which is applied at the lower end of the tool . Only about 5% of the heat generated by the friction process flows to the tool and the rest flows to the workpiece. The ‘‘heat efficiency’’ in FSW is thus 95%, which is very high relative to the traditional fusion welding where the heat efficiency is typically 60 to 80%[10].

With the proposed analytical approach of Vijay Shivaji Gadakh et al., one can directly see the peak temperature for respective taper probe angle under given process conditions which will be helpful for predicting the mechanical properties for that Al alloy and hence elimination of post weld testing cost and time[11].

Binnur Goren Kiral et al., used the moving heatb resource model and found the maximum temperature near the weld increases as the tool holding time and rotational speed are increased[12].

Muruganandam et al. used Tauguchi technique for the identification of rotational speed for higher strength using cylindrical and taper model[13]. In the present work, a simple energy-based model for the friction stir weld is proposed for taper pin. The model aims at estimating the heat generated due to plastic deformation within the work pieces and friction between the tool surfaces and the work pieces. This generated energy and the associated maximum temperature are compared to the results available in the literature to verify the proposed model.

2. Proposed Energy Model

Previous studies [14] assume that heat generated due to friction of the pin shoulder on the workpiece surface is dominant and the heat generated due to the plastic deformation within the workpiece and the friction of the pin of the material is negligible. However, other authors e.g. Heurtier et al. [14] and Hamilton et al. [15] consider the heat generated from both the friction of the pin shoulder and plastic flow. In fact, the energy due to plastic deformation and friction of the shoulder with the surface of the workpiece are related and competing each other. As the heat generated by the shoulder is low, the flow stress is higher and hence the resulting plastic deformation energy increases. On the other hand, as the heat generated by the shoulder is high, the flow stress reduces and as a result the plastic strain contribution decreases. In this work, heat is modeled to be generated by the friction of the shoulder and plastic deformation.

Figure 2 presents a cylindrical geometry of the friction-stir welding tool. It is assumed that the tool rotates with an angular speed of ω and transversely translates along the line of welding with a speed of vo . The tool is acted upon by a compressive force F.

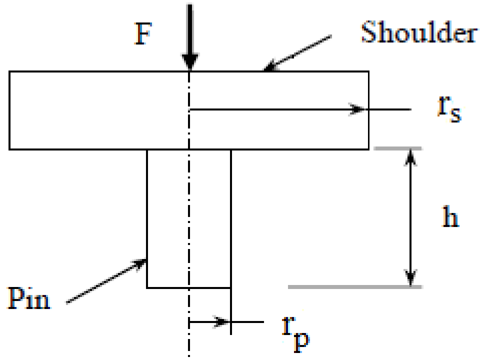


Figure 2. Geometry of the FSW tool

Following, Hamilton et al. [15], the energy generated per unit length of the weld E is given by

$$E_f = P_f / v_o \qquad (1)$$

where P is the total power generated by friction. Assuming that the total torque due to friction of the pin, shoulder, and pin circumference with the workpiece surfaces is Tf , the frictional power is then given by

$$P_f = T_f \, \omega \qquad (2)$$

where ω is the pin angular speed. To find an expression for the total frictional torque Tf , we let

$$T_f = T_s + T_p \qquad (3)$$

where Ts is the torque generated by the shoulder and Tp is torque generated by the pin. Assuming that a uniform shear stress τ occurs during welding, we obtain

$$\int_{r_p}^{r_s} \tau(2\pi r) r dr + \int_0^{r_p} \tau(2\pi r) r dr + 2\pi r_p{}^2 h \tau \qquad (4)$$

where rs is the radius of the shoulder, r_p is the radius of the pin, and h is the height of the pin, as shown in Fig. 2. Equation 3 reduces to

$$T_f = 2\,\pi\tau\, r_s{}^2 \left[\frac{1}{3} r_s + \frac{r_p^2}{r_s^2} h\right] \tag{5}$$

Assuming a coefficient of friction is μ , the total friction force Ff due to the compressive force F is given by

Ff = μF (6)

Noting that $\pi\tau\, r_s{}^2$ is the total friction force, Eq. 3 yields

$$T_f = 2\,\mu F \left[\frac{1}{3} r_s + \frac{r_p^2}{r_s^2} h\right] \tag{7}$$

Substituting Eq. 5 into Eqs. 1 and 2, we obtain

$$E_f = 2\,\mu F \left[\frac{1}{3} r_s + \frac{r_p^2}{r_s^2} h\right] \frac{\omega}{v_o} \tag{8}$$

Equation (8) defines the energy per unit length of the weld due to friction between the tool and the workpiece. For a given tool geometry, tool speed, and workpiece material, this energy can be easily identified. As can be noted from Eqn. (1), the power generated due to friction is given by

$$P_f = 2\,\mu F \left[\frac{1}{3} r_s + \frac{r_p^2}{r_s^2} h\right] \omega \tag{9}$$

The other source of heat is due to the plastic deformation within the workpiece. Provided that the plastic deformation within the workpiece is totally transformed into heat, the heat generated due to plastic deformation per unit weld length can be expressed as follows:

Ep =σε V (10)

where σ and ε are the stress and strain, respectively, V = is the volume per unit length of the base material. The stress σ is given by

$$\sigma = K\, \varepsilon^n \exp\left(\frac{mQ}{R_G T}\right) \tag{11}$$

where K is the strength coefficient, n is the strain hardening exponent, m is the strain rate sensitivity, Q is the apparent activation energy, RG is a constant equals 8.32 J mol-1K−1, and T is the absolute temperature. As a result, the energy generated due to plastic deformation per unit length of the weld is expressed as follows:

$$E = K\, \varepsilon^{n+1}\ blh \exp\left(\frac{mQ}{R_G T}\right) \tag{12}$$

The stress-strain relationship in the room temperature for AA2024, AA7075 and AA 6061 are shown in this figure 3.

Because the temperature is already unknown, the accurate calculation of the plastic strain energy needs an iterative process. Since the effect of the energy due to plastic deformation is much smaller than that due to friction, a simple model was proposed as follows:

Ep =σeεe ^{blh} (13)

where σe is the equivalent (effective) stress and εe is the effective strain. Using the finite element method, Heurtier et al. [3] found that the effective strain is around six. In this case, the effective stress is assumed to be constant, and hence the area under the curve becomes a rectangle. The power generated due to the plastic deformation is given by

$$Pp = \sigma e \varepsilon e\, blh\, vo \qquad (14)$$

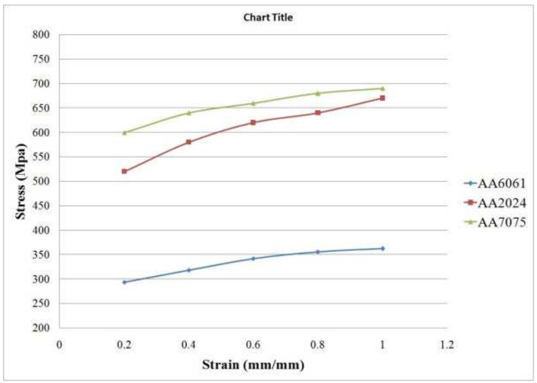


Figure 3. True-stress true-strain curve for AA 2024,AA7075 and AA6061.

The total energy generated per unit length of the wild is the sum of the energy generated due to friction between the tool and the workpiece surface and the plastic deformation within the workpiece.

The term effective energy is introduced to take into account the case where the height of the FSW tool pin h is different from the thickness of the workpiece t. The effective energy is defined as follows:

$$E_{eff} = \frac{h}{t} E = \beta E \qquad (15)$$

where β is the coefficient of transfer efficiency.

3. Result and discussion

The energy model proposed in the previous section accounts for both the frictional heating and the heating results from the plastic deformation. In order to validate the model, the total energy presented in taper model is adopted into the empirical formula developed by Hamilton et al. The formula is obtained from the experimental results available in the literature. The empirical formula is given by

$$\frac{T_{max}}{T_s} = 1.56 \ X \ 10^{-4} \ E_{eff+0.54} \qquad (16)$$

where Tmax is the maximum temperature generated within the weld, Ts is the solidus temperature in Kelvin, Eeff is the effective energy generated per unit length of weld in J/mm as given in Eq. (18). The non dimensionlized maximum temperature is obtained so that the deduced formula can serve for the AA6000 and AA7000 series considered in the study.

A good agreement is obtained except in the low-energy level region. The reason is that Hamilton et al. neglected the energy generated by the plastic deformation, which is significant when the frictional heating is low. In the present taper model, the heating due to plastic deformation has been taken into consideration through the scaling factor as given by Eq. (15). To validate this taper model, we find the total energy generated for given welding parameters and solved for the maximum temperature. The obtained maximum temperature is then compared to both the cylindrical model and the taper model. It is found out that considering the heat due to plastic deformation enabled this model to better fits the experimental results at all energy levels[16].

Three aluminum alloys are considered using different welding parameters such as tool geometry and welding speed. Table 1 presents the three alloys with the material characteristics and tool geometry used for each case.

Welding parameters including the tool rotational speed, tool translational speed, and the acting normal force are given in Table 2.

A comparison between the heat energy obtained by cylindrical model and the heat energy obtained using the proposed taper model in this study is given in Table 3. Investigating these results, one notes that at low-energy levels, the model of plastic deformation estimates the generated energy. This is expected since the plastic deformation is significant in this region, which is ignored in the model at higher energy level due to scaling factor close to zero.

Table 1.Material characteristics and tool geometry of the aluminum Alloys used

Aluminium alloy		6061 - T6	2024 - T6	7075 - T6
Ref.		L1	L2	L3
t (mm)		6	6	6
ρ (kg/m3)		2700	2780	2810
Cp (J/Kg K)		896	875	960
K (W/m K)		167	177	130
α (x 10-6 cm/cm/C)		23.4	22.8	23.2
Ts (K)		855	910	748
Tool geometry	ri (mm)	12.0	12.0	12.0
	ro(mm)	9.5	9.5	9.5
	h (mm)	6.0	6.0	6.0

On the other hand, the energy predicted using present taper model seems much greater than the cylindrical model, which reflects the enhancement of the model by including the plastic deformation. Moreover, in the high energy level, up to 2000 J/mm, the results are very close.

The graphs (Fig.5 and Fig.6) are plotted between the rotational speed and effective energy for both the cylindrical and taper model. By data interpretation it is clear that the change in tool geometry from cylindrical shape to taper shape increases the effective energy. However, the model is mainly based on geometry so the change in material is not much effected the effective energy.

Table 2:Welding rotational and translational speeds and the applied normal force.

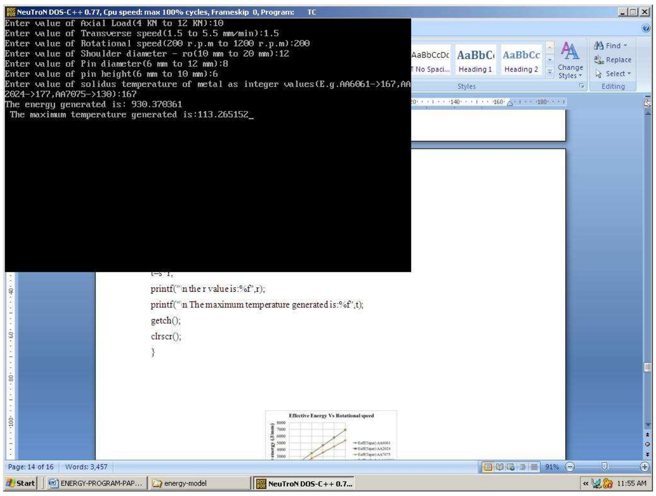
Alloy	Case	R.P.M.	v_0 (mm/s)	F (KN)
AA 6061 – T6	1	200	1.5	10
	2	400	1.5	10
	3	600	1.5	10
	4	800	1.5	10
	5	1000	1.5	10
	6	1200	1.5	10
AA 2024 – T6	7	200	1.5	10
	8	400	1.5	10
	9	600	1.5	10
	10	800	1.5	10
	11	1000	1.5	10
	12	1200	1.5	10
AA 7075 – T6	13	200	1.5	10
	14	400	1.5	10
	15	600	1.5	10
	16	800	1.5	10
	17	1000	1.5	10
	18	1200	1.5	10

“C” Program for cylidrical model:

```
#include<stdio.h>
#include<conio.h>
void main()
{
int F,w,ro,ri,h,s;
float v,Hs,i,j,k,l,m,n,o,p,q,r,t;
printf("Enter value of Axial Load(4 KN to 12 KN):");
scanf("%d",&F);
printf("Enter value of Transverse speed(1.5 to 5.5 mm/min):");
scanf("%f",&v);
```

```
printf("Enter value of Rotational speed(200 r.p.m to 1200 r.p.m):");
scanf("%d",&w);
printf("Enter value of Shoulder diameter - ro(10 mm to 20 mm):");
scanf("%d",&ro);
printf("Enter value of Pin diameter(6 mm to 12 mm):");
scanf("%d",&ri);
printf("Enter value of pin height(6 mm to 10 mm):");
scanf("%d",&h);
printf("Enter value of solidus temperature of metal as integer values(E.g.AA6061->167,AA2024-
>177,AA7075->130):");
scanf("%d",&s);
Hs=(ro/3);
i=ri*ri;
j=ro*ro;
k=(i/j)*h;
l=k+Hs;
m=2*0.5*F;
n=((2*(3.14/60))*w);
o=n/v;
p=m*l*o;
printf("The energy generated is: %f",p);
q=(5.7/6)*p;
r=0.54+((1.564/10000)*q);
t=s*r;
printf("\n the r value is:%f",r);
printf("\n The maximum temperature generated is:%f",t);
getch();
clrscr();
}
```

Output: Output of the program is shown in Figure.4



```
Enter value of Axial Load(4 KN to 12 KN):10
Enter value of Transverse speed(1.5 to 5.5 mm/min):1.5
Enter value of Rotational speed(200 r.p.m to 1200 r.p.m):200
Enter value of Shoulder diameter - ro(10 mm to 20 mm):12
Enter value of Pin diameter(6 mm to 12 mm):8
Enter value of pin height(6 mm to 10 mm):6
Enter value of solidus temperature of metal as integer values(E.g.AA6061->167,AA
2024->177,AA7075->130):167
The energy generated is: 930.370361
 The maximum temperature generated is:113.265152_
```

```
printf("\n the r value is:%f",r);
printf("\n The maximum temperature generated is:%f",t);
getch();
clrscr();
}
```

Figure 4. Calculated values of energy generated and maximum temperture from the “C” program for the given weld parameters

Table 3. Energy and maximum temperature obtained using taper Model and cylindrical model[16]

Case #	E (J/mm) – Cylindrical model	E (J/mm) – Taper model	Tmax – cylindrical model	Tmax – Taper model
1	975	1574	114	129
2	1881	2467	137	150
3	2824	3703	160	181
4	3760	4932	183	211
5	4702	6168	207	241
6	5643	7401	230	271
7	988	1587	121	137
8	1883	2469	145	159
9	2826	3705	170	191
10	3772	4944	195	223
11	4716	6181	220	255
12	5659	7418	244	287
13	1019	1618	90	101
14	1894	2480	107	117
15	2835	3714	125	141
16	3778	4950	143	164
17	4718	6184	161	188
18	5659	7417	179	211

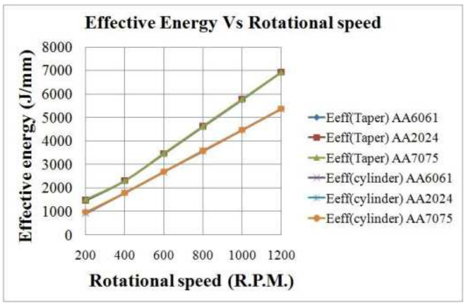


Figure 5. Variation of the effective energy with rotational speed for cylindrical and taper model

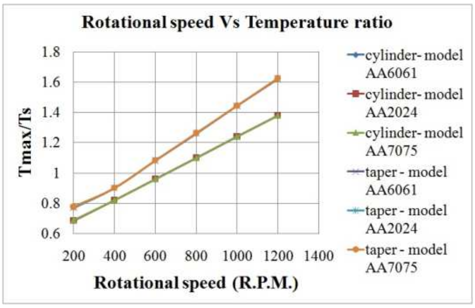


Figure 6. Variation of the temperature ratio with rotational speed for cylindrical and taper model

The present work is focussed on writing “C” program for cylindrical model. It is evident from the manual calculations that scaling factor consideration have less effect except the low energy levels. So it is neglected in “C’ programming and the coding is written for the identification of energy generated and maximum temperature for the known parameters.

4. Conclusions

In this study, a simple cylindrical model that estimates the energy and maximum temperature generated in friction-stir welding is identified using “C” programing. The usage of “C” program is minimised to calculate the number of equation substitution and solving.

The model accounts for the heat generated due to friction between the weld tool and the surface of the workpiece and heat generated due to plastic deformation. However the scaling factor is neglected as it have the effects only at minor energy levels. This model can be enhanced by considering an accurate model for the plastic deformation that will automatically predicts the heat generation due to plastic deformation at different energy levels. An accurate thermal model that simulates the heat transfer within and around the weld tool could be used.

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