

Mathematical modelling of joint temperature during linear friction welding of dissimilar Ti-6.5Al-3.5Mo-1.5Zr-0.3Si and Ti-5Al-2Sn-2Zr-4Mo-4Cr alloys

G-D. Wen¹, T-J. Ma¹, W-Y. Li¹, X. Li¹, J-L. Li¹, T. Chen², R. Wen², J. Niu² and H-Z. Guo¹

¹State Key Laboratory of Solidification Processing, Shaanxi Key Laboratory of Friction Welding Technologies, Northwestern Polytechnical University, Xi'an 710072, Shaanxi, PR China

²Xi'an Aero-Engine (Group) LTD, Xi'an 710021, Shaanxi, PR China

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Abstract

The linear friction welding (LFW) of dissimilar titanium alloys Ti-6.5Al-3.5Mo-1.5Zr-0.3Si (Ti11) and Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti17) was studied. Combined with experimentally recorded temperature of the specimen, the thermal history of the joint during LFW was calculated based on the equation of heat conduction. The calculated temperatures are comparable to those in experiment indicating that the proposed mathematic calculation method is appropriate to use for LFW. The highest temperature of the interface was about 1280°C and the time spent above the b transus temperature being about 4.5s in Ti17 side and 3.8s in Ti11 side, respectively. The highest temperatures of the TMAZs in Ti17 and Ti11 sides are about 1100°C and 1110°C, respectively. The cooling rate is about 250°C/s and 400°C/s in the interface and TMAZs. Fine equiaxed grains are present in the WZ, and numerous elongated grains are present in the TMAZs in both sides except a small number of fine recrystallized grains.

Keywords: Linear friction welding; Dissimilar titanium alloys; Mathematical calculation; Temperature field

1. Introduction

Linear friction welding (LFW) is a solid state welding process which has played a key role in manufacturing and repairing of aeroengine blisks, due to its high quality, high efficiency and energy conservation features it possess [1]. In particular, it is being used to weld titanium alloys which are widely used in the aviation and aerospace industries for their outstanding properties such as high specific strength, good mechanical properties at elevated temperatures and relatively ease in welding, when compared to other metal alloys that could be used in similar applications. In previous works LFW of titanium alloys has been studied. Karadge et al [2] studied the texture development in LFW of Ti-6Al-4V and observed a very fine martensite microstructure in the weld zone. Ma et al [3] studied LFW of Ti-6Al-4V and revealed that the weld zone consists of superfine a+b structure, which is associated with rapid heating and cooling processes.

However, as a relatively new and promising welding technique, there are a number of unresolved issues with LFW as it is difficult to be studied experimentally. For example due to specimen oscillation during the process the temperature at the weld interface cannot be measured accurately. With the advance of computer technology and

numerical techniques, the finite element method has become a powerful and reliable technique for the prediction of temperature and stress fields in the welded parts. In addition to these techniques, mathematical modelling can also be used to predict the temperature of the weld interface in LFW.

Vairis and Frost [4] established a numerical model and analyzed the thermo-mechanically coupled relationship to obtain temperature history in the initial stage of LFW. Sorina-Müller et al. [1] developed a 3D thermo-mechanical model for LFW of Ti-6Al-2Sn-4Cr-6Mo using the ANSYS finite element software to explore temperature distribution at the rubbing interface. Turner et al. [5] formulated a 2D finite element model for LFW of Ti-6Al-4V based on the FORGE software. They found that the simulated temperature corresponds to the measured one and that the highest temperature reached at the interface was about 1100°C. Tao et al. [6] developed a thermo-mechanically coupled model using the DEFORM software for LFW of Ti-6Al-4V. They found that the highest temperature reached of about 1340°C appears at the centre of the specimen, which corresponds to experiments. In our previous work [7], a 2D thermo-mechanically coupled model for LFW of Ti-6Al-4V was formulated using ABAQUS. The effects of processing parameters were examined and temperature contours in the specimen at different friction times were estimated. However, the calculated interface temperatures were not

* E-mail address: matiejun@nwpu.edu.cn

validated experimentally.

Therefore, in this study, in order to accurately predict the interface temperature, a mathematic model was developed to calculate the temperature history of LFW of dissimilar titanium alloys Ti11 (Ti-6.5Al-3.5Mo-1.5Zr-0.3Si) and Ti17 (Ti-5Al-2Sn-2Zr-4Mo-4Cr) based on recorded temperatures with thermocouples.

2. Mathematical prediction model

2.1 The following assumptions have been made in the calculation

- Temperature of the weld interface is uniform, therefore reducing the problem to a one dimensional one;
- Model describes the viscoplastic zone and the elastic zone where there is only thermal conduction. The thickness of the viscoplastic zone is ignored and therefore all heat produced by plastic deformation is assumed to be also negligible;
- Under steady state sticking friction condition during LFW, the viscoplastic zone of the specimen is continuously extruded as flash along the oscillating direction under the axial force applied. At the same time metal in the elastic zone enters the viscoplastic zone at a constant speed, i.e. the specimen axial shortening speed is constant;
- Radiation and convection losses to the environment from the elastic zone are ignored;
- Thermal conductivity, heat capacity, density and thermal diffusivity properties of material are constant, i.e. independent of temperature.

2.2 Foundation of mathematical model

Based on these assumptions, the temperature distribution along the moving interface is shown in Fig. 1, with the interface being the x axis origin. The interface temperature (at $x=0$) is T_i , temperatures at x_1 and x_2 in the elastic zone are T_{x1} and T_{x2} , respectively, and ambient temperature is T_0 . The interface moves with time, as shown in Fig. 1, due to axial shortening with a speed which denotes the transitional speed of temperature distribution during the steady state phase. The speed satisfies the Fourier heat conduction equation:

$$\kappa \frac{d^2T}{dx^2} - v \frac{dT}{dx} = 0 \quad (1)$$

where thermal diffusivity $\kappa = \lambda / (\rho c)$, λ , c and ρ are thermal conductivity, heat capacity and density, respectively; v is the shortening speed.

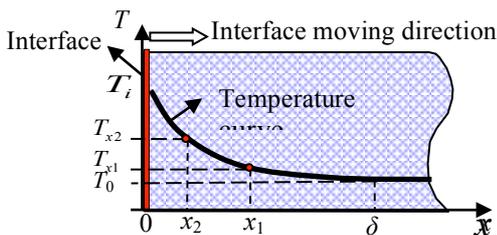


Fig. 1. Temperature distribution for the moving interface used in the mathematical model.

solving Eq. 1:

$$T = \frac{\kappa}{v} K_1 \exp\left(\frac{v}{\kappa} x\right) + K_2 \quad (2)$$

where K_1, K_2 are constants.

Temperatures T_{x1} and T_{x2} are at distances x_1 and x_2 on the moving specimen (Ti17). Substituting $x = x_1, T = T_{x1}; x = x_2, T = T_{x2}$ into Eq. 2, K_1 and K_2 can be obtained as:

$$K_1 = \frac{v}{\kappa} \frac{(T_{x1} - T_{x2})}{\left[\exp\left(-\frac{v}{\kappa} x_1\right) - \exp\left(-\frac{v}{\kappa} x_2\right) \right]} \quad (3)$$

$$K_2 = T_{x1} - \frac{T_{x1} - T_{x2}}{\left[1 - \exp\left(\frac{v}{\kappa} (x_1 - x_2)\right) \right]} \quad (4)$$

At the welding zone (WZ), $x=0$ (Thickness of the WZ is ignored), temperature is:

$$T_{WZ} = \frac{\kappa}{v} K_1 + K_2 \quad (5)$$

Assuming the thickness of the thermomechanically affected zone (TMAZ) being $x=L$ mm (on Ti17 side), the temperature can be expressed as:

$$T_{TMAZ-Ti17} = \frac{\kappa}{v} K_1 \exp\left(L \frac{v}{\kappa}\right) + K_2 \quad (6)$$

For the oscillating specimen (Ti11), temperature at δ mm from the interface is the surrounding temperature T_0 . Substituting $x = \delta, T = T_0$ into Eq. 2, constants K_1 and K_2 can be solved as:

$$K_1 = \frac{v}{\kappa} \frac{(T_i - T_0)}{\left[\exp\left(-\frac{v}{\kappa} \delta\right) - 1 \right]} \quad (7)$$

$$K_2 = T_0 - \frac{T_0 - T_i}{1 - \exp\left(-\frac{v}{\kappa} \delta\right)} \quad (8)$$

At TMAZ, if $x=H$ mm (on Ti11 side), temperature can be expressed as:

$$T_{TMAZ-Ti11} = \frac{\kappa}{v} K_1 \exp\left(H \frac{v}{\kappa}\right) + K_2 \quad (9)$$

3 Experiments

3.1 Materials and experimental procedure

Forged Ti11 and Ti17 titanium alloys were LFWed using the

Northwestern Polytechnical University's XMH-160 machine. As shown in Fig. 2 (a) and 2 (b), the microstructure of Ti11 parent metal is equiaxed $\alpha+\beta$ structure and the microstructure of Ti17 is a Widmanstatten structure. Specimens were machined to blocks with dimensions of 70'18'11mm (the weld interface had dimensions of 18'11mm – 11mm is the thickness and 18mm is the length along oscillation). Welding process parameters were set as: amplitude of oscillation 3.5mm, frequency of oscillation 40Hz, friction time 4s and friction pressure 45MPa.

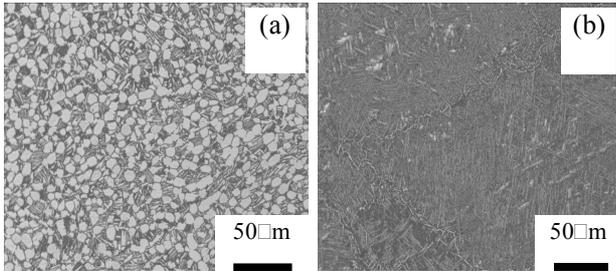


Fig. 2. OM micrographs of parent materials: (a) Ti11 and (b) Ti17.

3.2 Temperature measurement

Temperature was recorded using an infrared thermal imaging system (Infra Tec, VarioCAMahr head-HS) and thermocouples (nickel-chromium and nickel-silicon K-type, 1mm.). The sampling frequency of infrared thermometer was set at 50 Hz, emissivity for the WZ at 0.95 and emissivity for parent materials at 0.2 [8]. Thermocouples were placed at 4 mm and 6 mm away from the welding interface before welding, and had moved to 2 mm and 4 mm away from the welding interface, respectively, at the end of welding, as shown in Fig. 3.

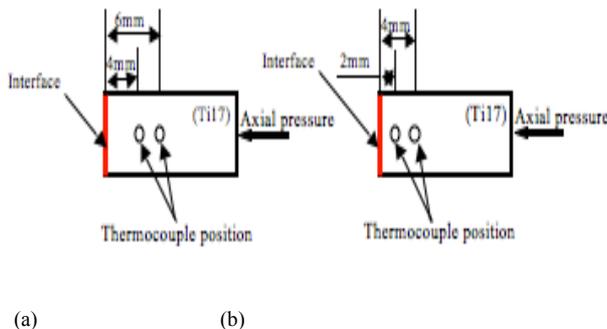


Fig. 3. Thermocouple placement during LFW: (a) before welding and (b) after welding.

Using temperatures recorded by thermocouples, K_1 and K_2 for the mathematical model were obtained from Eq. 3 and Eq. 4, so as to calculate temperatures at the weld interface $x=0$ using Eq. 5. The thicknesses of the TMAZs in Ti11 and Ti17 sides are determined to be $x=1.0\text{mm}$ and $x=1.2\text{mm}$, from optical micrographs of the joint cross-section as shown in Fig. 4. Then, the temperatures of TMAZs of Ti17 and Ti11 were calculated using Eq. 6 and Eq. 9 respectively. According to [9], in the temperature range of 900°C - 1300°C , the thermo-physical parameters of Ti11 are $\lambda=22.8\text{ W}\times\text{m}^{-1}\times\text{K}^{-1}$, $c=890\text{ J}\times\text{Kg}^{-1}\times\text{K}^{-1}$, and $\rho=4480\text{ kg}/\text{m}^3$, while those of Ti17 are $\lambda=21.7\text{ W}\times\text{m}^{-1}\times\text{K}^{-1}$, $c=720\text{ J}\times\text{kg}^{-1}\times\text{K}^{-1}$, $\rho=4650\text{ kg}/\text{m}^3$, $v=2\text{ mm}/\text{s}$. The thermal cycles of the weld interface and TMAZs can be calculated.

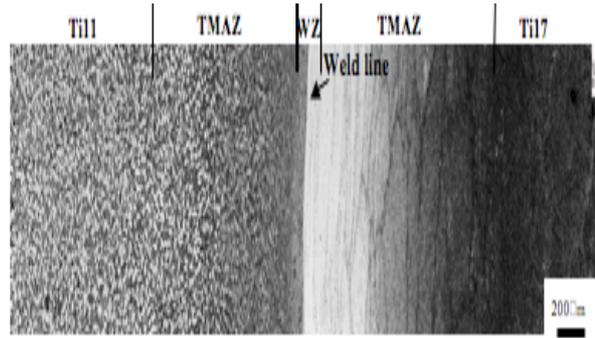


Fig. 4. OM micrograph of joint cross-section.

4 Results and discussion

4.1 Microstructure of joint

From the OM micrographs of the joint cross-section as shown in Fig. 4, the joint can be divided into three microstructural zones, which are the WZ (welding zone), TMAZ (thermomechanically affected zone) and the base metal. The microstructures of the two sides differ widely as they are of dissimilar materials. The microstructure of WZ shows fine equiaxed grains. In the TMAZ, clearly streamlined band structures are present. The direction of the streamlined structures shows the flow and deformation direction of plastic material during welding. These microstructure characteristics can be attributed to different thermal histories as discussed next.

4.2 Temperature model validation

Fig. 5 shows the thermal histories at different positions of LFW of dissimilar Ti11 and Ti17 joint. The two lowest curves in Fig. 5 (a) show temperature history at 2 mm and 4 mm away from the weld interface, as measured by thermocouples. The top curve is the calculated temperature history of the WZ, and under this is the temperature history curve of the WZ as measured by infrared thermometer. It can be seen that the calculated and the measured curves of the WZ have a similar profile, with calculated values being a little higher than measured ones, as the temperature obtained by the infrared thermometer is the flash surface temperature and not that of the weld interface. Nevertheless, calculated temperature is comparable to recorded values validating the proposed mathematical model. With this model, it is found that the highest temperature reached at the interface is 1280°C as shown in Fig. 5. According to literature [9], the b transus temperatures of Ti11 and Ti17 are $1000 \pm 20^\circ\text{C}$ and $890 \pm 15^\circ\text{C}$ respectively. The time during which b transus temperatures are exceeded is short, about 4.5s for the Ti17 side and 3.8s for the Ti11 side. The curve in the middle of Fig. 5 (a) is the calculated temperature history curve of the TMAZ of Ti17. Using the same mathematical model, the TMAZ temperature in the Ti11 side can be obtained, see Fig. 5 (b) (top curve is the same as in the top curve of Fig. 5 (a)). It can be seen that the highest temperatures reached at the TMAZs in Ti17 and Ti11 are 1100°C and 1110°C respectively. The times where the b transus temperature was exceeded in TMAZs are also short, at about 3.2s for the Ti17 side and 2s for the Ti11 side. During cooling, the heat loss rate of WZ is about $250^\circ\text{C}/\text{s}$ while that of the TMAZs in both specimen sides reaches $400^\circ\text{C}/\text{s}$. However, these cooling rates tend to become uniform (to about $29^\circ\text{C}/\text{s}$) when temperatures drop below 800°C .

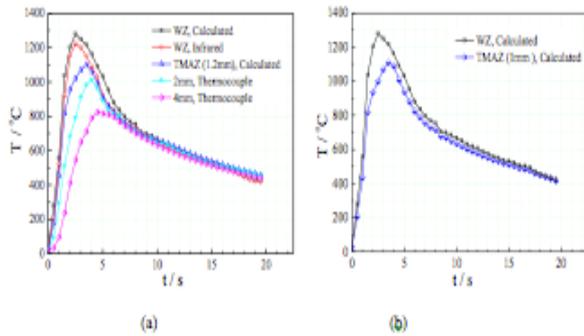


Fig. 5. Temperature history at different positions: (a) Ti17 side and (b) Ti11 side.

From these, the microstructure evolution of the joint can be assessed. As high temperature exposure is short and cooling rate is high, the growth of recrystallized grains is inadequate with fine equiaxed grains being present in the WZ. In the TMAZ high temperature exposure is even shorter and the cooling rate is higher than WZ, with temperatures of the TMAZs in both Ti17 and Ti11 being lower than WZ, producing therefore numerous elongated grains, except for a small number of fine recrystallized grains.

5 Conclusions

The following conclusions can be drawn :

(1) Using the Fourier heat conduction equation, a mathematical model to estimate the temperature history of

the joint during linear friction welding was developed. Calculated temperature history of dissimilar Ti17 and Ti11 welds at the interface and TMAZs are comparable with experimental curves, validating the mathematical model.

(2) The highest temperature reached at the weld interface was 1280°C and the time where the b transus temperature was exceeded was about 4.5s for the Ti17 side and 3.8s for the Ti11 side. The highest temperatures reached in the TMAZ for the Ti17 and Ti11 sides are 1100°C and 1110°C. The times where the b transus temperature was exceeded in the TMAZs are about 3.2s for the Ti17 side and 2s for the Ti11 side. During cooling, the temperature drop rate of WZ is about 250°C/s and that of TMAZs for both materials was 400°C/s.

(3) As exposure to high temperatures is short during LFW of dissimilar Ti17 and Ti11 alloys and the cooling rate is fast, fine equiaxed grains develop in the WZ, while numerous elongated grains appear in the TMAZs of both sides except for a small number of fine recrystallized grains.

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