Original Article

Finite element modelling for temperature, stresses and strains calculation in linear friction welding of TB9 titanium alloy

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Article history:
Received 19 July 2019
Accepted 17 August 2019
Available online 5 September 2019

Keywords:
Finite element method
Linear friction welding
TB9 titanium alloy
Johnson-Cook
Temperature fields
Microstructure

ABSTRACT

In the present paper, finite element method (FEM) simulation of linear friction welding (LFW) TB9 titanium alloy was carried out using ABAQUS software. The constitutive model of TB9 alloy was established using Johnson-Cook constitutive equations, and then a two-dimensional (2D) coupled thermo-mechanical model was established to simulate the temperature, the Mises stress and the equivalent plastic strain fields of TB9 during LFW process. The axial shortening and macroscopic morphology of the linear friction welded joint were obtained by simulation results and verified by experiments. Finally, by consideration of the temperature fields of the simulated welded joint, the authors experimentally investigated the microstructure of the actual welded joint.

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1. Introduction

Titanium and its alloys have been widely used in varied industries such as aerospace, automobile, marine, chemical, medical due to their high strength, corrosion resistance and toughness [1–4]. The metastable β titanium alloy TB9 (Ti-3Al-8V-6Cr-4Mo-4Zr) is characterized by an excellent corrosion resistance and reasonable room temperature formability and it can offers exceptional ductility in the sole solution heat-treated and a high ultimate tensile strength of 1500MPa in the solution heat-treated and aged condition [5–7]. In recent years, the development of a new joining technology, linear friction welding (LFW), which can be applied for the manufacture and repair of a wide range of aerospace components [8]. LFW, an efficient solid phase joining working process, is able to join two components through the relative reciprocating motion of the two components under a force [9,10]. The friction between the two components surfaces coupled with the strong applied pressure heats up the materials. And then materials in the contact zone between the two components are softened. A forging force is applied when sufficient plastically deformed material has occurred.

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https://doi.org/10.1016/j.jmrt.2019.08.026
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LFW has a bright future for the development and application in recent years, especially in the last ten years. It is currently mainly used to manufacture aircraft engines [11]. The blades and disks of aircraft-engine were manufactured separately, and then these two parts were joined using LFW. LFW has been applied successfully in many materials, such as titanium alloys [12–18], steels [11,19], superalloys [20–23] and so on. The temperatures and stresses distributions during the LFW process can influence the evolution of material deformation and the behavior of metal flow. And they were investigated by many researchers using experimental methods. With the development of computer technology, numerical analysis has become an effective method to predict temperature and stress fields in welding process. Many research groups have used finite element simulation to study the LFW process [15,24–27]. A full structural-thermal coupled transient 3D-analysis for LFW process was selected to investigate the temperature fields and axial shortening of Ti6Al2Sn4Cr6Mo alloy during welding process [24]. A 2D fully-coupled thermo-mechanical FEM model with semi-automatic re-meshing method was selected to investigate the residual stresses distribution in the LFW pieces [25]. A 2D model of ABAQUS/Explicit was selected to investigate the effects of processing parameters on the temperature evolution and axial shortening of LFW TC4 alloy joints [15,26]. In the publication [27], temperature distributions and axial shortening of A285 steel specimens during LFW process were investigated using a 3D model.

Although numerical analysis can play an important role in understanding the complex LFW process, both the constitutive equations for LFW numerical simulation and the quantitative characterization of temperature and strain fields of LFW joint are not clear. In addition, the relationship between the temperature field and the microstructure of LFW joint is not investigated in detail so far. The purpose of this paper is to create an accurate constitutive equation of TB9 alloy and to establish FEM model of this alloy during LFW process. The authors want to investigate the temperature fields, Mises stress and equivalent plastic strain fields during LFW process. The simulated axial shortening was validated by experimental observations. Finally, through the analysis of the temperature fields on the simulated joint, the microstructures in different regions of the actual welded joint were observed.

### 2. Experimental procedures

#### 2.1. Hot compression test procedures

In this paper, commercial TB9 titanium alloy was selected as the raw material. The chemical composition (wt.%) of this alloy in the present investigation are given in Table 1 [28]. The microstructure of the TB9 alloy base metal is shown in Fig. 1. Cylindrical compression samples of 12 mm in height and 8 mm in diameter were machined from the rod. All the isothermal compression tests were carried out on a Gleeble-3800 thermo-mechanical simulator. The hot temperature compression test parameters are shown in Table 2. The parameter of temperature range, from 25 °C to 1100 °C, is wide enough to cover the temperature variation of the joint during the whole linear friction welding process. The reason to select the parameter of strain rate is consistent with the temperature selection. The friction between the specimen and the die was reduced by using a lubricant mixed with graphite and machine oil. Prior to compression test, the samples were preheated at deformation temperature for 120 s and the deformation was continued up to the engineering compressive strain of 60%. At the end of straining, the specimens were immediately quenched in water.

#### 2.2. LFW experimental procedures

Fig. 2 shows the LFW machine. Fig. 2(a) shows the whole LFW system. Fig. 2(b) shows the locating and clamping devices of LFW machine. Fig. 2(c) shows the detail of the locating and clamping devices. Specimen is a block of 12 × 20 × 60 mm³ (H × W × L) and the welding surface is 12 × 20 mm² (H × W), as shown in Fig. 2(c). The vibration direction is parallel to width direction. The welding parameters of experiment are vibration frequency, 30 Hz, amplitude, 2.5 mm, frictional pressure, 70 MPa and freedom length of sample, 10 mm. This paper is mainly based on numerical simulation and supplemented by

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**Table 1 – The chemical composition of TB9 titanium alloy [28].**

<table>
<thead>
<tr>
<th>Ti</th>
<th>Al</th>
<th>V</th>
<th>Cr</th>
<th>Zr</th>
<th>Mo</th>
<th>Fe</th>
<th>Si</th>
<th>C</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bal</td>
<td>3.28</td>
<td>8.18</td>
<td>5.86</td>
<td>4.20</td>
<td>4.10</td>
<td>0.068</td>
<td>0.028</td>
<td>0.014</td>
<td>0.0825</td>
</tr>
</tbody>
</table>

**Fig. 1 – Microstructure of the TB9 parent material.**

**Table 2 – Hot temperature compression test parameters.**

<table>
<thead>
<tr>
<th>Dimensions of sample (mm)</th>
<th>Φ8 × 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain rate (s⁻¹)</td>
<td>0.001, 0.01, 0.1, 1, 10</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>25, 75, 150, 250, 400, 600, 750, 800, 850, 900, 950, 1000, 1050, 1100</td>
</tr>
<tr>
<td>Deformation extent (%)</td>
<td>60%</td>
</tr>
</tbody>
</table>
Fig. 2 – Shows the LFW machine and the locating and clamping devices of machine.
(a) LFW machine; (b) locating and clamping devices; (c) locating and clamping devices in details
experimental tests. So, one set of the values is selected for experiment while a large number of parameters are selected for numerical simulation study. The parameters of simulation study are described in part 4.

3. FEM model of LFW process and constitutive model of TB9 alloy

3.1. FEM model

In this paper, the FEM based on ABAQUS is applied to simulate LFW process of TB9 alloy blocks. Two-dimensional (2D) model of FEM simulation is shown in Fig. 3. In our published paper [23], we justify why the assumption of 2D analysis is valid. As shown in Fig. 3, the specimen was divided into three parts, the upper region (10 mm in length), the middle region (10 mm in length) and the lower region (40 mm in length). In this model, the linear quadrilateral elements of type CPE4RT and linear triangular elements of type CPE3T were adopted in ABAQUS software. The thermo-mechanical coupling method was adopted in the simulation of LFW process. The gradient meshes were adopted considering the computation efficiency and accuracy.

The LFW process typical parameters used in simulation are shown as follows: amplitude of 2.5 mm, oscillation frequency of 30 Hz, friction pressure of 70 MPa, time of 5 s and free end length of 10 mm. The initial temperature of the specimen was set at 25 °C. As shown in Fig. 3, the external boundary of the middle and the lower regions was constrained in x-direction, freed in y-direction. The type of interaction of the rigid surface and the top surface of the specimen was surface to surface contact. The rigid surface was only allowed to move along x-direction in a linear motion with a sinusoidal mode. The materials undergo intense deformation in the actual LFW process. So, the numerical simulation of LFW process often needs to deal with the strong deformation of materials. The arbitrary Lagrangian-Eulerian (ALE) adaptive meshing is used to maintain a high-quality mesh throughout an analysis [29]. The arbitrary Lagrangian-Eulerian (ALE) adaptive meshing, which is applied in the present paper, allows you to maintain a high-quality mesh throughout an analysis, even when large deformations or losses of material occur, by allowing the mesh to move independently of the material [29]. “ALE Adaptive Mesh Controls” is set in the “Step” module of ABAQUS software. In the “Edit ALE Adaptive Mesh Controls”, we maintain default settings. The ALE adaptive meshing is used with a remeshing frequency of 1 and remeshing sweeps of 50 per increment. In this paper, computational efficiency and time are not the main considerations because of the FEM modeling with simple 2D model and basic mesh generation. Surface to surface contact interaction between specimen and rigid was defined in the Interaction module of ABAQUS software. The tangential behavior was adopted in the contact property options. The friction formulation of tangential behavior was selected as penalty.

In the LFW process, the joint temperature increases rapidly due to friction and plastic working. The heat transfer analysis is conducted to calculate the temperature field of the welded joint. The heat conduction equation is described as [23,32]

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i} \left( k \frac{\partial T}{\partial x_i} \right) + \rho C_p \frac{\partial T}{\partial x_i} + \dot{S}$$  \hspace{1cm} (1)

where \(\rho, T, C_p, k\) and \(t\) are density, temperature, specific heat capacity, thermal conductivity and time, respectively. \(x_i (i = 1, 2 \text{ and } 3)\) stands for \(x, y \text{ and } z\) directions, respectively. \(\mu\) is shortening velocity of specimen during LFW process. \(\dot{S},\) heat generation rate, is described as [23,32]:

$$\dot{S} = \alpha \dot{\varepsilon}$$ \hspace{1cm} (2)

where \(\alpha\) is thermal efficiency of plastic deformation, which is defined to be 0.9-0.95 [23,32]. \(\varepsilon\) and \(\tilde{T}\) are effective stress and
Fig. 5 – True stress and true strain curves of TB9 titanium alloy during different strain rates. (a) 0.001 s\(^{-1}\), (b) 0.01 s\(^{-1}\), (c) 0.1 s\(^{-1}\), (d) 1 s\(^{-1}\), (e) 10 s\(^{-1}\).

effective strain rate, respectively. Inelastic heat fraction in the present model was set as 0.9.

The boundary condition is expressed by

\[ q = h_k(T_w - T_c) + h_s(T_w^4 - T_c^4) = h(T_w - T_c) \]  

where \( q \), \( h_k \), \( h_s \), \( h \) are heat flux, convection coefficient, radiation coefficient and total heat transfer coefficient, respectively. \( T_w \) and \( T_c \) are temperatures of boundary and ambience, respectively.

According to the literatures [15,24,30,31], in order to simplify the calculation, the heat transfer coefficient is set to a
fixed value of 30 W/(m²·K). The contact heat conduction coefficient between specimen and clamp is set to 1000 W/(m²·K).

The initial condition at time \( t = 0 \) is expressed by

\[
T_{t=0} = T_0(x, y, z)
\]

where \( T_0(x, y, z) \) is initial temperature function. The initial temperature of the specimen was set as room temperature, \( 25^\circ C \).

The total strain increment \( \Delta \varepsilon \) can be additively decomposed into five components. And it can be expressed as

\[
\Delta \varepsilon = \Delta \varepsilon^e + \Delta \varepsilon^p + \Delta \varepsilon^{th} + \Delta \varepsilon^{vol} + \Delta \varepsilon^{tr}
\]

where \( \Delta \varepsilon^e, \Delta \varepsilon^p, \Delta \varepsilon^{th}, \Delta \varepsilon^{vol} \) and \( \Delta \varepsilon^{tr} \) are elastic strain increment, plastic strain increment, thermal plastic strain increment, volumetric strain increment and transformation induced plastic strain increment, respectively. The authors set \( \Delta \varepsilon^{tr} \) value to zero.

3.2. Constitutive model of TB9 alloy

The constitutive behavior of materials is usually expressed by a non-linear equation, which is a relationship among flow stress, strain rate and temperature. Johnson and Cook (1983) have developed an empirical constitutive equation (Eq. 6) for metals over a wide range of strains and temperatures in which the flow stress is assumed to be a function of temperature, strain rate and plastic strain as follows.

\[
\sigma = (A + B\varepsilon^n) \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - (T^*)^m \right]
\]

where \( \varepsilon \) is the strain, \( \dot{\varepsilon} \) is the actual plastic deformation strain rate, \( \dot{\varepsilon}_0 \) is the reference strain rate, \( A \) is the yield stress at reference temperature and strain rate, \( B \) is the strain hardening coefficient, \( n \) is the exponent of strain hardening, \( C \) and \( m \) are the material constants that represent the coefficient of strain rate hardening and the thermal softening exponent, respectively. \( T^* \) (\( T^* = (T-T_r)/(T_m-T_r) \)) is the homologous temperature. \( T_r \) and \( T_m \) are the reference temperature and melting point temperature, respectively.

4. Results and discussion

4.1. True stress-true strain curves of the TB9 alloy

Fig. 4 shows the pictures of the initial and deformed specimens of TB9 alloy. It can be seen from Fig. 4 that there is no crack on the surface of the deformed sample. Fig. 5 shows true stress-true strain curves of the TB9 alloy for a wide range of deformation temperatures (750, 800, 850, 900, 950, 1000, 1050 and 1100) and strain rates (0.001 s⁻¹, 0.01 s⁻¹, 0.1 s⁻¹, 1 s⁻¹ and 10 s⁻¹) conditions. As shown in Fig. 5, the flow stress depends on strain rate, deformation temperature and strain, and the general trend is that the flow stress increases with the increase of strain rates and/or with the decrease of experimental temperatures. At the initial stage, the stress increases rapidly with increasing strain due to the work hardening. Following to strain increase, stress reaches to a peak value and then decreases gradually into a steady state stress. As shown in Fig. 5(e), at the highest strain rate (10 s⁻¹) and the four lower deformation temperatures (750, 800, 850 and 900), the TB9 alloy shows an obvious peak stress, and then a sharply decreasing trend occurs. As shown in Fig. 5(a) and (b), at the two lower strain rates (0.001 s⁻¹ and 0.01 s⁻¹) and the two higher deformation temperatures (1100 and 1150), no evident peak stress appears in stress-strain curves.

4.2. Establishment and verification of Johnson-Cook constitutive equations

4.2.1. Establishment of johnson-cook constitutive equations

In the JC equation (Eq. 6), the first bracket is applied to describe the work-hardening effect, the second one for the strain-rate effect and the last one for the temperature effect. In order to predict the flow behavior of TB9 alloy by JC model, the reference temperature (\( T_r \)) and the strain rate (\( \dot{\varepsilon}_0 \)) were selected as 25\(^\circ\)C and 0.001 s⁻¹, respectively. According to the literature [33], the modulus of elasticity and the melting temperature of TB9 alloy are 114 GPa and 1649\(^\circ\)C, respectively. The heat conduction and the specific heat capacity of TB9 alloy are calculated by the JMatPro software. Fig. 6 shows the temperature-dependent properties (heat conduction and specific heat capacity) of TB9. At the reference temperature and strain rate, Eq. (6) would be transformed to the following equation.

\[
\sigma = A + B\varepsilon^n
\]

A is related to the yield stress of the reference condition, and it is equal to the value of stress at true strain of 0.002. The yield stress of the reference condition of TB9 alloy is 830 MPa obtained from the stress-strain curves. That is, \( A \) is 830 MPa. Eq. (8) can respectively derived by taking natural logarithm of Eq. (7).

\[
\ln (\sigma - A) = \ln B + \ln \varepsilon
\]
ues of $n$ and $\ln B$, respectively. Thus, the following can be calculated as $B = 645.5$ MPa and $n = 0.47$.

When the deformation temperature is $T = T_r = 25 \degree C$, Eq. (6) can be simplified as:

$$\frac{\sigma}{A + Br^n} = C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) + 1$$  \hspace{1cm} (9)

Using the flow stress data for a fixed strain at various strain rates, $C$ is obtained from the slope of $[\sigma/(A + Br^n)]$ vs. $\ln(\dot{\varepsilon}/\dot{\varepsilon}_0)$ plot. At reference temperature $25 \degree C$ and at five different strain rates of 0.001 s$^{-1}$, 0.01 s$^{-1}$, 0.1 s$^{-1}$, 1 s$^{-1}$, 10 s$^{-1}$, the stress values corresponding to 0.1 strain value were selected. Substitute these data into Eq. (4), draw $[\sigma/(A + Br^n)]$ vs. $\ln(\dot{\varepsilon}/\dot{\varepsilon}_0)$ curve, and carry out linear fitting, as shown in Fig. 8. The slope of the fitting curve is the value of $C = 0.012$.

When the strain rate is $\dot{\varepsilon}_0 = 0.001$ s$^{-1}$, Eq. (6) can be simplified as

$$\sigma = (A + Br^n) (1 - T^m)$$  \hspace{1cm} (10)

Rearrange Eq. (10) it to the following form:

$$1 - \frac{\sigma}{(A + Br^n)} = T^m$$  \hspace{1cm} (11)

Taking natural logarithm on both sides of Eq. (6), one obtains:

$$\ln \left[ 1 - \frac{\sigma}{A + Br^n} \right] = m \ln T^*$$  \hspace{1cm} (12)

Using the flow stress data for a particular strain at different temperatures (25, 75, 150, 250, 400, 600, 750, 800, 850, 900, 950, 1000, 1050 and 1100 \degree C), the graph of $\ln \left[ 1 - \frac{\sigma}{A + Br^n} \right]$ vs. $\ln T^*$ is plotted. The material constant $m$ is obtained from the slope of this graph. As shown in Fig. 9, $m = 0.89$. Therefore, the relation among stress, strain, deformation rate and deformation temperature was established according to the JC model, and the parameters of JC model are list as Table 3.

### Table 3 - Johnson-Cook constitutive model parameters under low temperatures

<table>
<thead>
<tr>
<th>$A$(MPa)</th>
<th>$B$(MPa)</th>
<th>n</th>
<th>C</th>
<th>$\dot{\varepsilon}_0$(s$^{-1}$)</th>
<th>m</th>
<th>$T_r$(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>830</td>
<td>645.5</td>
<td>0.47</td>
<td>0.012</td>
<td>0.001</td>
<td>0.89</td>
<td>25</td>
</tr>
</tbody>
</table>

4.2.2. Verification of Johnson-Cook constitutive equations

In order to verify the accuracy of the JC model of TB9 alloy established in this paper, comparison between the predicted flow stress and the experimental data was conducted, shown as Fig. 10. As shown in Fig. 10(a), when the experimental were conducted in the conditions of lower temperatures (75, 150 and 250 \degree C), the experimental results agree well with the calculation values obtained from JC constitutive equation. The mean relative error between calculated data and experimental values maintains at approximately 6%. But, when the experimental were conducted in the conditions of the higher temperature 750\degree C (Fig. 10(b)), the experimental results are very different from the calculation values obtained from JC constitutive equation. So, when the $\dot{\varepsilon}_0$, $T_r$ and $T_m$ are respectively selected as 0.001 s$^{-1}$, 25\degree C and 1649\degree C, the JC constitutive equation cannot be suitable for the description of the plastic deformation behavior of TB9 alloy at the higher temperatures, while can well describe the plastic deformation behavior of TB9 alloy at the lower temperatures. Therefore, the constitutive model is called the lower temperature JC constitutive model.

As the LFW process belongs to a high temperature deformation process, so the plastic deformation behavior of TB9
Fig. 10 – Comparison of flow stress between experimental data and calculated results at JC model parameters of $\dot{\varepsilon}_0, 0.001 \text{s}^{-1}$, $T_r$, $25 ^\circ \text{C}$ and $T_m$, $1649 ^\circ \text{C}$. (a) low temperature, (b) medium-high temperature.

| Table 4 – JC constitutive model parameters under middle/high temperatures. |
|---------------------------------|-------|-------|-------|-------|-------|-------|
| Parameter                   | Value |
| $A$ (MPa)                    | 436.14 |
| $B$ (MPa)                    | 90 |
| $n$                           | 0.48 |
| $C$                           | 0.1052 |
| $\dot{\varepsilon}_0$ (s$^{-1}$) | 1 |
| $m$                           | 0.552 |
| $T_r$ ($^\circ \text{C}$)    | 750 |

alloy at middle/high temperatures must be described. Here $\dot{\varepsilon}_0$, $T_r$, and $T_m$ are selected as $1 \text{s}^{-1}$, $750 ^\circ \text{C}$ and $1649 ^\circ \text{C}$, respectively. Using true stress-true strain curves data from $750 ^\circ \text{C}$ to $1100 ^\circ \text{C}$ and according to the previous method of establishing constitutive model, the JC constitutive model under middle/high temperatures was established. The JC constitutive model parameters under middle/high temperatures are shown in Table 4.

Comparison between the predicted flow stress obtained from JC model and the experimental data was conducted, shown as Fig. 11. As shown in Fig. 11(a), when the experimental were conducted in the conditions of lower temperatures (75, 150 and 250 $^\circ \text{C}$), the experimental results are very different from the calculation values obtained from JC constitutive equation. But when the experimental were conducted in the conditions of the higher temperature 750 $^\circ \text{C}$, the experimental results agree well with the calculation values obtained from JC constitutive equation. So, when the $\dot{\varepsilon}_0$, $T_r$, and $T_m$ are respectively selected as $1 \text{s}^{-1}$, $750 ^\circ \text{C}$ and $1649 ^\circ \text{C}$, the JC constitutive equation cannot be suitable for the description of the plastic deformation behavior of TB9 alloy at the lower temperatures, while can well describe the plastic deformation behavior of TB9 alloy at the higher temperatures. Therefore, the constitutive model is called the higher temperature JC constitutive model.

4.3. Simulation for the LFW process

4.3.1. Temperature fields results

The numerical simulation of LFW was carried out using the higher temperature JC constitutive model established by the above section. Here the typical process parameters (amplitude of 2.5 mm, vibration frequency of 30 Hz, friction pressure of 70 MPa, time of 5 s and free end length of 10 mm) were selected for the numerical simulation. Fig. 12 shows the temperature evolutions at different welding times (1 s, 2 s, 3 s, 3.5 s, 4 s and 5 s) during the welding process. As shown in Fig. 12, in the

Fig. 11 – Comparison of flow stress between experimental data and calculated results at JC model parameters of $\dot{\varepsilon}_0, 1 \text{s}^{-1}$, $T_r$, $750 ^\circ \text{C}$ and $T_m, 1649 ^\circ \text{C}$. (a) low temperature. (b) medium-high temperature.
Fig. 12 – Temperature evolutions at different welding times during the welding phase.
(a) Welding time = 1 s; (b) Welding time = 2 s; (c) Welding time = 3 s;
(d) Welding time = 3.5 s; (e) Welding time = 4 s; (f) Welding time = 5 s

initial stage of friction welding process, the temperature of the welded joint interface metal increases rapidly under the action of friction shear stress. With the increase of the welding time, the interface with high temperature zone is continuously expanded from the center of the interface. As shown in Fig. 12(a) and (b), when the time is in the range of 0–2 s, the joint is not sufficient to produce a sufficient amount of viscoplastic metal to be extruded to form a flash. When the time is in the range of 2–3 s (Fig. 12(b) and (c)), although part of the metal on the interface undergoes plastic deformation, it is not enough to produce a significant flash. When the time is over 3 s (Fig. 12(d), (e) and (f)), the joint is sufficient to produce a sufficient amount of viscoplastic metal to be extruded to form a flash.

Fig. 13 shows the change of the interfacial center temperature with the friction time under the typical process conditions. Based on the curve in Fig. 13, when the welding time is in the range of 0–1 s, the ability of the joint metal to resist plastic deformation is strong because the welding interface temperature is not enough. When the welding time is in the range of 1–1.5 s, the interfacial center temperature of joint increase rapidly with the increase of the welding time, and the increasing trend decrease evidently when the welding time is over 1.5 s. When the welding time is over 2 s, the interfacial center temperature of joint is basically maintain the same with the increase of the welding time.

Fig. 14 shows the temperature distributions along five characteristic paths of linear friction welded (LFWed) TB9 alloy. The schematic of these five paths is shown in Fig. 14(a). As shown in Fig. 14(b), the maximum temperature along path 1 appears in the central position of the curve. In other words, the maximum temperature along path 1 appears in the central position
of the interface. While along path 2, path 3, path 4 or path 5, the minimum temperature appears in the central position of the curve. In other words, the minimum temperature appears in the center region of the specimen. If the region is closer to the interface, the temperature uniformity in this region is better. Here, we should note that the more uniform temperature distributions are, the more uniform the microstructure of the welded joint is.

The five curves in Fig. 14(b) can be expressed using mathematical equations. They are described as:

\[
T = 1186.4750 + 2.4278x - 1.1628x^2 - 0.0064x^3 + 0.0014x^4
\] (13)

\[
T = 927.6100 - 2.2216x + 0.9214x^2 + 0.0214x^3 - 0.0045x^4
\] (14)

\[
T = 712.5782 - 4.9842x + 2.6950x^2 + 0.0379x^3 - 0.0153x^4
\] (15)

\[
T = 456.8922 + 0.7505x + 3.2850x^2 - 0.0586x^3 - 0.0159x^4
\] (16)

\[
T = 185.6406 + 0.3266x + 3.0741x^2 + 0.0280x^3 - 0.0183x^4
\] (17)

**Fig. 15** shows the temperature distributions at different times (1 s, 5 s, 10 s, 30 s, 50 s and 100 s) during the cooling phase. As shown in Fig. 15, the joint interface temperature decreases rapidly as the cooling time decreases. The maximum temperature of joint interface is 1200 °C at the end of welding process (Fig. 12(f)), while it is less than 1000 °C when the cooling time is 1 s (Fig. 15(a)). When the cooling time is 50 s, the maximum temperature of joint interface is 281 °C (Fig. 15(e)). When the cooling time is 100 s, the maximum temperature of joint interface is 150 °C (Fig. 15(f)). In order to further study the joint cooling process, five characteristic points were selected to research the law of temperature changes with time, and the distances from these points to the center of the joint interface are respectively 0 mm, 3 mm, 5 mm, 7 mm and 9 mm (Fig. 16). As shown in Fig. 16, the temperatures in points A and B decrease rapidly with the increase of the cooling time during the initial stage of the cooling process. As for the points C, D and E, the temperatures in these points increase firstly and then decrease with the increase of the cooling time. This is due to the high temperature gradient of the joint during the cooling process. The temperature of the position near the welding interface is very high while the temperature of the position far away from the welding interface is relatively low. The friction heat disappears when the welding process finished, so the dynamic equilibrium of the joint temperature field cannot be maintained. Under the action of heat conduction, the closer the distance between the position and the interface is, the faster the temperature drops. The cooling trend of the central position A of interface is larger than that of the position B. When the cooling time is 0 s, the temperature in the central position A of interface is 1170 °C, while the time is 0.5 s, the temperature is 934 °C.

The corresponding times for the temperature peak values of positions C, D and E are, respectively, 0.4, 1.25 and 3.4 s. And the temperature peak values are respectively 737, 595 and 495 °C. When the cooling time is 10 s, the temperatures of positions A, B, C, D and E are respectively 552, 539, 520, 494 and 460 °C. When the cooling time is over 40 s, the temperature difference between the different positions (A, B, C, D and E) of the joint gradually decreases as the cooling time increases.

**Fig. 14** – Temperature distributions in characteristic paths after welding process (a) schematic of five paths, (b) temperature distributions in paths 1-5.
4.3.2. Stress and strain fields evolution under typical process parameters

Fig. 17 shows Mises stress of the weld center during the welding process. Here the typical process parameters (amplitude of 2.5 mm, vibration frequency of 30 Hz, friction pressure of 70 MPa, time of 5 s and free length of 10 mm) were selected. As shown in Fig. 17, the Mises stress of the weld joint center shows a fluctuation phenomenon with the increase of the welding time. The Mises stress of the weld joint center decreases with the increase of the welding time. When the welding time is in the range of 0–1 s, the Mises stress of the weld joint center keeps a high value. When the welding time is in the range of 1–3 s, the Mises stress of the weld joint center decreases sharply with the increase of the welding time. When the welding time is over 3 s, the Mises stress of the weld joint center remains at a low value and basically no longer changes. This also indicates that the quasi-steady state of the welding process occurs when the welding time is over 3 s. And at this condition, the interface temperature remains stable.

Fig. 15 – Temperature distributions at different times during the cooling phase.
(a) Cooling time = 1 s; (b) Cooling time = 5 s; (c) Cooling time = 10 s;
(d) Cooling time = 30 s; (e) Cooling time = 50 s; (f) Cooling time = 100 s

Fig. 16 – The cooling curves of different points along the axial centre line.
Fig. 17 – Mises stress of the weld joint center during the welding process.

Fig. 18 reveals the PEEQ (equivalent plastic strain) distribution during LFW of TB9 alloy. In Fig. 18, note that $t=0$ indicates the beginning of the welding process. The PEEQ in ABAQUS is defined as [21]

$$\text{PEEQ} = \bar{\varepsilon}^p|_0 + \int_0^t \dot{\bar{\varepsilon}}^p \, dt \quad (18)$$

where $\bar{\varepsilon}^p|_0$ is the initial equivalent plastic strain, the definition of $\dot{\bar{\varepsilon}}^p$ depends on the materials model. For classical metal (Mises) plasticity,

$$\dot{\bar{\varepsilon}}^p = \sqrt{\frac{2}{3} \dot{\varepsilon}^{pl} : \dot{\varepsilon}^{pl}} \quad (19)$$

It can be seen from Fig. 18 that the PEEQ distributions are nonuniform. The maximum PEEQ appears in the interface. From the interface and along the $y$-axis negative direction of

Fig. 18 – PEEQ contour of joint at different welding times.
(a) Welding time = 1 s; (b) Welding time = 2 s; (c) Welding time = 3 s;
(d) Welding time = 3.5 s; (e) Welding time = 4 s; (f) Welding time = 5 s
the specimen, the PEEQ sharply decreases with the increase of the distance between the interface and the selected region.

Fig. 19 shows the PEEQ distributions along the characteristic paths after welding process. As shown in Fig. 19(b), the PEEQ in interface region is evidently larger than that in the other regions. PEEQ in the center of the interface shows a big fluctuation, while in the sides of the interface, it exhibits a stable state. If the region is closer to the path 5, the PEEQ in this region is lower. If the region is closer to the interface (path 1), the PEEQ in this region is higher. As shown in Fig. 19(b) and (c), the PEEQ uniformity along the path 1 is the worst of all paths. While in the two paths (path 4 and path 5), it is better. Here, we should note that the more uniform PEEQ distribution is, the more uniform the microstructure of the welded joint is.

4.4. Influence of welding parameters on LFW process

In order to further study the influence of different process parameters on the temperature field and axial shortening of LFW of TB9 alloy, the FEM model established in this paper was applied for the simulation of LFW of TB9 alloy under four sets of process parameters. Table 5 shows the four sets of process parameters of LFW of TB9 alloy. In these four sets of process parameters, the welding time is 5 s. The selection of the four sets of parameters is based on the typical parameters (vibration frequency 30 Hz, amplitude 2.5 mm, friction pressure 70 MPa, welding time 5 s and free end length 10 mm). As shown in Table 5, under the first set parameters conditions, the simulation was performed using different frequencies (25 Hz, 30 Hz and 35 Hz). Under the second set parameters conditions, the simulation was performed using different amplitudes (2 mm, 2.5 mm and 3 mm). Under the third set parameters conditions, the simulation was performed using different friction pressures (65 MPa, 70 MPa and 75 MPa). Under the fourth set parameters conditions, the simulation was performed using different free end lengths (8 mm, 10 mm and 12 mm).

Fig. 20 shows the simulation results about the temperature contours and the morphology of joint under four sets of process parameters. As shown in Fig. 20, when the amplitude is 2.5 mm, the friction pressure is 70 MPa and the free end length is 10 mm, the amount of the extruded flash increases evidently with the increase of the frequency. As for the frequencies 25 Hz, 30 Hz and 35 Hz, the maximum temperatures of joint interface are respectively 1171 °C, 1178 °C and 1172 °C. When the frequency is 30 Hz, the friction pressure is 70 MPa and the free end length is 10 mm, the amount of the extruded flash increases evidently with the increase of the amplitude. As for the amplitudes 2 mm, 2.5 mm and 3 mm, the maximum temperatures of joint interface are respectively 1201 °C, 1178 °C and 1229 °C. When the frequency is 30 Hz, the amplitude is 2.5 mm
<table>
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<th>Parameters</th>
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<td></td>
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<td></td>
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Fig. 20 – Temperature contours and macrostructure of joint using FEM under four sets of process parameters.

and the free end length is 10 mm, the amount of the extruded flash increases evidently with the increase of the friction pressure. As for the friction pressures 65 MPa, 70 MPa and 75 MPa, the maximum temperatures of joint interface are respectively 1188°, 1178° and 1195°. When the frequency is 30Hz, the amplitude is 2.5 mm and the friction pressure is 70 MPa, for
free end lengths 8 mm, 10 mm and 12 mm, there is not much difference in the amount of the extruded flash, and the maximum temperatures of joint interface are respectively 1184°C, 1178°C and 1171°C.

Fig. 21 shows temperature-time curves of the joint interface center under different parameters. Fig. 21(a) shows temperature-time curves of the joint interface center under different frequencies (25 Hz, 30 Hz and 35 Hz) and at amplitude 2.5 mm, friction pressure 70 MPa and free end length 10 mm. As shown in Fig. 21(a), the joint interface center temperature of these three frequencies all increases evidently with the increase of the welding time at the initial stage of the welding process, and then the increasing trend was slowing down, finally the temperature value tends to be stable. It can be seen from Fig. 21(a) that the curve of frequency 35 Hz is clearly above the curve of frequency 30 Hz and the curve of frequency 30 Hz is also clearly above the curve of frequency 25 Hz. It is seen from Fig. 21(a) that the curves can be divided into three stages. As for frequency of 35 Hz, the three stages (welding time of 0–0.6 s, 0.6–2.2 s, 2.2–5 s) of curve can be clearly distinguished. The slope of the curve at the first stage (welding time of 0–0.6 s) is obviously greater than that of the curve at the second (welding time of 0.6–2.2 s) and third (welding time of 2.2–5 s) stages. While the slope of the curve at the second stage is slightly larger than that of the curve at the third stage. As for frequency of 25 Hz, the three stages (welding time of 0–0.9 s, 0.9–3.5 s, 3.5–5 s) of curve can be distinguished. The slopes of the curve at the first (welding time of 0–0.9 s) and second (welding time of 0.9–3.5 s) stages are both obviously greater than that of the curve at the third (welding time of 3.5–5 s) stage. While the slope of the curve at the first stage is slightly larger than that of the curve at the second stage. As for frequency of 30 Hz, the three stages (welding time of 0–0.9 s, 0.9–3.5 s, 3.5–5 s) of curve can be distinguished. The slopes of the curve at the first (welding time of 0–0.9 s) and second (welding time of 0.9–3.5 s) stages are both obviously greater than that of the curve at the third (welding time of 3.5–5 s) stage.

While the slope of the curve at the first stage is slightly larger than that of the curve at the second stage, and frequency of 25 Hz, the three stages (welding time of 0–0.9 s, 0.9–3.5 s, 3.5–5 s) of curve can be distinguished. The slopes of the curve at the first (welding time of 0–0.9 s) and second (welding time of 0.9–3.5 s) stages are both obviously greater than that of the curve at the third (welding time of 3.5–5 s) stage. While the slope of the curve at the first stage is slightly larger than that of the curve at the second stage.

Influence of amplitude; (c) Influence of friction pressure; (d) Influence of free end length.

While the slope of the curve at the first stage is slightly larger than that of the curve at the second stage, and frequency of 25 Hz, the three stages (welding time of 0–0.9 s, 0.9–3.5 s, 3.5–5 s) of curve can be distinguished. The slopes of the curve at the first (welding time of 0–0.9 s) and second (welding time of 0.9–3.5 s) stages are both obviously greater than that of the curve at the third (welding time of 3.5–5 s) stage. While the slope of the curve at the first stage is slightly larger than that of the curve at the second stage.

Fig. 21(b) shows temperature-time curves of the joint interface center under different oscillation amplitudes (2 mm, 2.5 mm and 3 mm) and at frequency 30 Hz, friction pressure 70 MPa and free end length 10 mm. As shown in Fig. 21(b), the curve of amplitude 3 mm is clearly above the curves of amplitudes 2 mm and 2.5 mm, while the curve of amplitude 2.5 mm is slightly above the curve of amplitude 2 mm. As shown in Fig. 21(b), as for these three oscillation amplitudes, the joint interface center temperature all increases evidently with the increase of the welding time at the initial stage of the welding process. As for amplitudes of 3 mm, 2.5 mm and 2 mm, a quasi-steady state respectively occurs at approximate welding time 1.7 s, 2.5 s and 2.9 s. Fig. 21(c) shows temperature-time curves of the joint interface center under different friction pressures (65 MPa, 70 MPa and 75 MPa) and at frequency 30 Hz, oscillation amplitude 2.5 mm and free end length 10 mm. As shown in Fig. 21(c), as for these three friction pressures, the joint interface center temperature all increases evidently with the increase of the welding time at the initial stage of the welding process. When the welding time is less than 0.6 s, the three
Fig. 22 – Unilateral axial shortening-time curves of joint under different parameters. (a) Influence of frequency; (b) Influence of amplitude; (c) Influence of friction pressure; (d) Influence of free end length

curves in Fig. 21(c) are almost the same in variation trend. When the welding time is in the range of 0.6–2.8 s, the curve of friction pressure 75 MPa is clearly above the curve of friction pressures 65 MPa and 70 MPa, while the curve of friction pressure 70 MPa is above the curve of friction pressure 65 MPa. Fig. 21(d) shows temperature-time curves of the joint interface center under different free end lengths (8 mm, 10 mm and 12 mm) and at frequency 30 Hz amplitude 2.5 mm and friction pressure 70 MPa. As shown in Fig. 21(d), the two curves of free end lengths 8 mm and 12 mm are almost the same in variation trend during the whole welding time range. When the welding time is in the ranges of 0–0.6 and 2–5 s, the three curves in Fig. 21(d) are almost the same in variation trend. When the welding time is in the range of 0.6–2 s, the curves of free end lengths 8 mm and 12 mm are above the curve of free end length 10 mm.

Fig. 22 shows unilateral axial shortening-time curves of joint under different parameters. As shown in Fig. 22, the unilateral axial shortening increase with the increase of the welding time. Fig. 22(a) shows unilateral axial shortening-time curves of joint under different frequencies. It can be seen from Fig. 22(a) that when the welding time is lower than 2 s, as for these three frequencies (25 Hz, 30 Hz and 35 Hz), the influence of frequency on unilateral axial shortening is not obvious. While the welding time is larger than 2 s, compared with the other two frequencies 25 Hz and 30 Hz, the unilateral axial shortening of frequency 35 Hz increases sharply with the increase of the welding time. When the welding time is lower than 3 s, as for these two frequencies (25 Hz and 30 Hz), the influence of frequency on unilateral axial shortening is not obvious. While the welding time is larger than 3 s, compared with the frequency 25 Hz, the unilateral axial shortening of frequency 30 Hz increases sharply with the increase of the welding time.

Fig. 22(b) shows unilateral axial shortening-time curves of joint under different oscillation amplitudes. As shown in Fig. 22(b), the unilateral axial shortening increase with the increase of the welding time. The curves of amplitudes 2.5 mm and 3 mm are above the curve of amplitude 2 mm at the whole welding time range. When the welding time is lower than 2.2 s, the curve of amplitude 2.5 mm is above the curve of amplitude 3 mm. When the welding time is larger than 2.2 s, the curve of amplitude 3 mm is above the curve of amplitude 2.5 mm. Fig. 22(c) shows unilateral axial shortening-time curves of joint under different friction pressures. When the welding time is lower than 2.5 s, the three curves of friction pressures 65 MPa, 70 MPa and 75 MPa are almost the same in variation trend. When the welding time is larger than 2.5 s, the curve of fric-
Fig. 23 – Comparisons of the joint flash shapes obtained by the simulation and experiment. (a) Simulated result from the present model; (b) experimental result.

Fig. 24 – Comparison of the calculated axial shortening and experimental data.

5. Verification by experimental

Fig. 23 shows the comparison between the joint flash shape of the model and the specimen. Fig. 23(a) shows the simulated result from the present model. The actual macroscopic morphology and flash shapes of the linear friction welded joint are shown in Fig. 23(b). Here the simulation and experimental process parameters are the same. And the parameters are frequency 30 Hz, amplitude 2.5 mm, friction pressure 70 MPa, free end length 10 mm and welding time 5 s. As shown in Fig. 23(a), the high temperature zone is concentrated on the welding interface. As shown in Fig. 23(b), enough flash is extruded from the interface and the joint is well surrounded by the flash. It can be seen from the joint morphology in Fig. 23(a) and Fig. 23(b) that the flow viscosity of the material obtained from the experimental result is better than that of the simulation result. Generally, the metal material at high temperature not only has the elastoplastic characteristics, but also has the viscoplasticity characteristics.

Here the authors give the comparison of the calculated axial shortening and experimental data, shown in Fig. 24. As shown in Fig. 24, the changing trend of the simulated curve is in a good agreement with the experimental curve. When
the time is approximate less than 2 s, the curves obtained by simulation and experiment are basically consistent. The interface temperature of the welded joint rises slowly within 0 to 2 s of welding time, and it is much lower than the melting point of the material. This period belongs to the dry friction stage. Compared with the interface at high temperature, the deformation behavior of the material at this stage is relatively simple, and the degree of material deformation is relatively small. So in this stage, the simulation results agree well with the experimental results. In addition, the authors also can find from the simulation cloud diagram (Fig. 12), the axial shortening is small when the welding time is 0–2 s. But when the time is over 2 s, the curve obtained from experiment is always above the simulated curve. From Fig. 12, it is seen that the flash is gradually squeezed out (Fig. 12) when the welding time is over 2 s. In the high temperature stage, the deformation behavior of material becomes complicated. Therefore, there is a certain error between the simulation results and the experimental results. The final amount of axial shortening obtained from simulation is about 3.34 mm, and that obtained from experimental data is about 3.38 mm. In summary, the FEM model created in this paper can be used as an effective tool in predicting the changing trend of the axial shortening-time curve. And it also can be used to simulate the final amount axial shortening of TB9 alloy after LFW process.

Fig. 25 clarifies evolution of the macrostructure that is perpendicular to the direction of oscillation. According to different structure characteristics, LFWed TB9 joint can be divided into the weld zone (WCZ), thermo-mechanically affected zone (TMAZ) and the base metal (BM), and there isn’t apparent heat affected zone (HAZ). In spite of thermal effect subjected by the metal near the WCZ, but at the same time, it is impacted by the stronger mechanical friction, which makes the HAZ covered by the TMAZ. The width of the WCZ is 500–600 μm. The TMAZ is located in both sides of the WCZ, and has no distinct boundaries with the WCZ. The microstructure of the BM is bulky without deformation.

Fig. 26 shows the microstructure of the WCZ, TMAZ and the flash zones of the LFWed TB9 joint. The fine β phase grains with 10–20 μm in diameter were observed in the WCZ (Fig. 26(c)), and the microstructure was not continuous. As shown in Fig. 26(b), the elongated grains occur in the TMAZ. The average size of the grains in the TMAZ (Fig. 26(b)) is larger than that of in the WCZ (Fig. 26(c)). As shown in Fig. 26(d), the average size of the grains in the flash zone is evidently greater than those of in the WCZ and TMAZ (Fig. 26(c) and Fig. 26(b)). Fig. 27 shows EBSD map and misorientation distribution in different zones of the joint. It can be seen from Fig. 27 that the grains orientation are random and the average size of the grains in the WCZ (Fig. 27(c)) is evidently smaller than those of in the BM and TMAZ (Fig. 27(a) and Fig. 27(e)). A lot of low angle grain boundaries (LABs) appear in the BM zone (Fig. 27(b)), which accounts for about 73% of the total grain boundaries. Besides, the distribution of the high angle grain boundaries (HABs) is homogeneous without any obvious peak. It can be seen from Fig. 27(c), some adjacent grains in WCZ have similar orientation, indicating that the grains were not completely recrystallized. Compared with the BM, HABs in the WCZ increased to 38% (Fig. 27(d)). Subgrains during welding process were formed in the WCZ as a result of the generation and the tangled of dislocation. As the welding process progresses, sub-grain boundaries absorbed the dislocation continuously and angles increased which lead to more and more subgrains formed in the WCZ. The grains in the TMAZ are composed of recrystallized grains and deformed grains (Fig. 27(e)). As can be seen from Fig. 27(f), the proportion of HABs is approximately 31% and it is more than that of the BM, illustrating that dynamic recrystallization has occurred already in the TMAZ.

Fig. 28 proves β pole figures of different parts of the weld joint. a pole figures are not presented due to the negligible amount of α phase observed in the material. The texture intensity of the BM is not high (Fig. 28(a)), only reached to 5.64, which means there is nearly no texture existent in the BM.
Fig. 26 – Microstructure of LFWed TB9 joint in low magnification. 
(a) Section diagram of metallographic specimen, (b) Microstructure of the TMAZ zone, (c) Microstructure of the WCZ zone, (d) Microstructure of the flash zone.

Compared with the BM, obvious orientation began to appear in the TMAZ, as shown in Fig. 28(b). The texture intensity rose to 15.03, showing that dynamic recrystallization has occurred in the TMAZ. In Fig. 26(c), (112)<111> texture appeared in the WCZ, as same as that in the Ti-5553 [21]. This shear texture is transformed when high temperature deformation happens. A {001}<110> texture (rotation-cube texture) was also found in the WCZ (Fig. 28(d)).

6. Conclusions

1 Under the same temperature, the flow stress increases with the increase of the strain rate. Under the same strain rate, the flow stress increases with decreasing temperature. The JC constitutive models under low and medium-high temperatures were established, respectively. As for JC constitutive models under low temperatures, the mean relative error between calculated data and experimental values maintains at approximately 6% in the conditions of low temperatures. As for JC constitutive models under medium-high temperatures, the experimental results at medium-high temperatures agree well with the calculation values obtained from JC constitutive equation.

2 Two dimensional FEM was created to calculate the LFW process of TB9 titanium alloy. The temperature of the welded joint interface metal increases rapidly at the initial stage of friction welding process. With the increase of the welding
Fig. 27 – EBSD map and misorientation distribution in different zones of the joint.
(a) EBSD map of the BM zone, (b) Misorientation distribution of the BM zone,
(c) EBSD map of the WCZ zone, (d) Misorientation distribution of the WCZ zone,
(e) EBSD map of the TMAZ zone, (f) Misorientation distribution of the TMAZ zone.

The interface with high temperature zone is continuously expanded from the center of the interface. When the time is in the range of 0–3 s, the flash has not yet formed. When the time is over 3 s, a sufficient amount of viscoplastic metal was extruded to form a flash.

The microstructure of WCZ, TMAZ, BM and flash zones can be clearly identified. Very fine grains are present in the WCZ. The average size of the grains in the TMAZ is larger than that of in the WCZ zone. The average size of the grains in the flash zone is evidently greater than those of in the WCZ.
and TMAZ. The proportion of HABs in the WCZ and TMAZ are 38% and 31%, respectively.

4 There is almost no texture in BM. High-density transitional texture appears in the TMAZ and dynamic recrystallization occurs in this zone. The shear texture is transformed when high temperature deformation happens. Within the WCZ, the grains are oriented with $\{112\}<111>$ and $\{001\}<110>$. 

Fig. 28 – β Pole figures of the joint: (a) the BM, (b) the TMAZ, (c) $\{112\}<111>$ in the WCZ and (d) $\{001\}<110>$ in the WCZ.
Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgements

The authors would like to acknowledge the financial support from the National Natural Science Foundation of China (No. 51875470, No. 51405389), the Natural Science Foundation of Shaanxi Province (No. 2018JS159), and the National Key Research and Development Program of China (No. 2016YFB1100104).

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