TRANSIENT THERMO-STRESS FIELD OF BRAKE SHOE DURING MINE HOIST EMERGENCY BRAKING

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ABSTRACT
In this paper, the finite element (FE) model of the three-dimensional (3-D) transient thermo-stress field of a brake shoe was established and then the software ANSYS 13.0 was used to get the numerical solutions; an experiment was carried out on the X-DM friction tester to verify the FE model. It was found that both the whole temperature and the equivalent stresses of the brake shoe increased and then decreased during mine hoist emergency braking; region of 1 to 3 mm below the friction surface was suffered to larger temperature gradients and stresses.

Keywords: thermo-stress field, emergency braking, FE, brake shoe, mine hoist.

CHAMP DE STRESS THERMIQUE TRANSITOIRE D’UN SABOT DE FREIN DURANT UN FREINAGE D’URGENCE D’UN TREUIL D’EXTRACTION

RÉSUMÉ
Dans cet article, un modèle d’éléments finis d’un champ de stress thermique transitoire en 3 dimensions (3-D) d’un sabot de frein a été défini, et le logiciel ANSYS 13.0 a été utilisé pour trouver une solution numérique. Une expérience a été performée par le système de mesure du coefficient de frottement X-DM pour vérifier le modèle FE. On a constaté que toute la température et le stress du sabot de frein augmentent et diminuent durant le freinage d’urgence du treuil d’extraction. Un champ de 1 à 3 mm sous la surface de friction a souffert des gradients plus élevés de la température et du stress.

Mots-clés : champ de stress thermique ; freinage d’urgence ; FE ; sabot de frein ; treuil d’extraction.
1. INTRODUCTION

Lots of heat and elasto-plastic deformations are generated during sliding friction between brake pairs, which are typically thermal-mechanical coupling problems. Such problems of vehicle brakes have been studied by many scholars [1–16]. As emergency braking of a mine hoist, shown in Fig. 1, is characterized by high speed and heavy load [17, 18], importance should also be attached to thermal-mechanical coupling investigations of its brake shoe/disc pair whose failure will cause heavy casualties and enormous economic losses. Brake shoes are fixed and of bad heat conductivity and as a result are suffered to more intense temperature rise and
larger temperature gradient than brake discs during emergency braking, so this paper is aimed to understand distributions of the thermo-stress field of a brake shoe during emergency braking. The work will provide the theory basis for state monitoring of disc brakes and will be significant in guiding and ensuring safety in production of mines.

FE method is commonly used to solve such thermal-mechanical coupling problems of disc brakes. Kennedy and Ling [1] introduced the thermo-elastic FE method the first time to the analysis on a disc brake’s friction and wear in 1974. 3-D FE modeling methods of thermal-mechanical coupling consist of the direct one and the sequential one. The former adopted in the literatures [4–6] can simultaneously obtain temperature fields and stress fields of brake pairs by means of using coupled field elements whose nodes have both temperature and displacement degrees to mesh the CAD models, establishing their contact relation with a contact element, and driving the disc to rotate while fixing the pad; the latter applies temperatures of the whole nodes obtained from the thermal analysis as body load to the sequentially stress analysis, which is employed in most related studies [7–16]. Respectively, the 3-D FE model of a brake disc was established by Huang et al. [7] with the disc as a moving heat source and by Gao et al. [8] and Hwang et al. [9] with the pad as a moving heat source. The iterative solutions were all performed under the calculating cycle of contact pressure distribution, heat flux density (HFD), temperature field, thermal deformation and stress field. The authors’ previous work mainly focused on the 3-D temperature field of a brake shoe [19, 20], but any research on its thermo-stress field has not been reported as yet. In this study, the sequential method is used in the FE simulation with HFD applied to the friction surface in the temperature analysis and thermal load, pressure and friction applied in the stress analysis.

In order to experimentally obtain the brake shoe’s temperature change during emergency braking, one is adopted that two thermocouples are embedded to the proper locations in the shoe specimens, which is one of the conventional temperature measurement methods. However, reports on experimental measure of the stress field under sliding contact situations are few, none on that of a brake shoe’s stress field. In this study, strain gages are located in place to obtain the rule of the stress variations with time. The same method was used by Peng [17, 18] to obtain some strain curves of friction lining during high-speed slide and was proved workable.

2. THEORETICAL ANALYSIS

2.1. Temperature Field

Figure 2 presents a geometrical model for the friction pair formed by a brake disc and a brake shoe. In order to simplify the FE model of the brake shoe, the following assumptions are made:

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1. The two friction surfaces of the disc/shoe pair are considered to be smooth, and the materials of the friction pairs are isotropic and linearly elastic.

2. The fiction work is fully converted to heat which is allocated to the two bodies in the form of heat flux density.

3. The surface temperatures of the contacting bodies must be equal at every point within the contact zone based on the coupling condition continuity of temperature.

2.1.1. Differential equation of 3-D transient heat conduction
Shape and location parameters of the brake shoe are indicated in the coordinate system as shown in Fig. 2. The differential equation of 3-D transient heat conduction is

\[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{\rho c}{\lambda} \frac{\partial T}{\partial t}, \]  \hspace{1cm} (1)

where \( \lambda \) is the thermal conductivity; \( \rho \) is the density; \( c \) is the specific heat capacity.

2.1.2. HFD
According to the operating condition of emergency braking that the velocity of brake disc decreased linearly with time and according to Assumption 2, the expression of the HFD allocated to the brake shoe is obtained as

\[ q_s(r,t) = k \cdot \mu \cdot p(r,t) \cdot \omega(t) \cdot r = k \mu p(r,t) \omega_0 \left( 1 - \frac{t}{t_s} \right) \sqrt{x^2 + y^2}, \]  \hspace{1cm} (2)

where \( q_s \) is the HFD distributed to the brake shoe; \( k \) is the distribution coefficient; \( p \) is the contact pressure; \( \omega_0 \) is the initial angular velocity of the brake disc; \( \mu \) is the friction coefficient; \( t_s \) is the end time of emergency braking.

The distribution coefficient of HFD can be obtained according to the analysis of one-dimensional heat conduction. Figure 3 shows the contact schematic of two half-planes. Under the condition of a one-dimensional transient heat conduction, the temperature rise of the friction surface \((z = 0)\) is obtained as

\[ \Delta T = \frac{q}{\sqrt{\pi \rho c \lambda}} \sqrt{4t}, \]  \hspace{1cm} (3)

where \( q \) is the heat-flow absorbed by half-plane. From Eq. (3), the expression for \( q \) is obtained as

\[ q = \sqrt{\pi \rho c \lambda} \Delta T / \sqrt{4t}. \]  \hspace{1cm} (4)
Suppose the two half-planes has the same temperature rise on the friction surface, and then the ratio of heat-flow entering the two half-planes is given as

\[ \frac{q_s}{q_d} = \sqrt{\frac{\pi \rho_s c_s \lambda_s}{\sqrt{\frac{\rho_d c_d \lambda_d}{4t}}}} \frac{\Delta T}{\sqrt{4t}} = \sqrt{\frac{\rho_s c_s \lambda_s}{\rho_d c_d \lambda_d}}, \]  

where the subscript \( s \) and \( d \) represent the brake shoe and brake disc, respectively. According to Eq. (5), the distribution coefficient of HFD entering brake shoe is obtained with the form

\[ k = \frac{q_s}{q_s + q_d} = \left(1 + \frac{\rho_d c_d \lambda_d}{\rho_s c_s \lambda_s}\right)^{-1}. \]  

Substitute Eq. (6) into Eq. (2) and then the HFD allocated to the brake shoe is represented by

\[ q_s(x, y, t) = \mu p \omega_0 \frac{\left(1 - \frac{z}{h}\right) \sqrt{x^2 + y^2}}{1 + \sqrt{\frac{\rho_d c_d \lambda_d}{\rho_s c_s \lambda_s}}}. \]  

### 2.1.3. Initial and boundary conditions

The brake shoe’s friction surface is subjected to \( q_s \) and other surfaces are of natural convection with the air approximately, so the initial conditions and boundary conditions can be represented by

\[ T(x, y, z, 0) = T_0, \quad a \leq x \leq b, \quad -l/2 \leq y \leq l/2, \quad 0 \leq z \leq h, \]  

\[ \lambda \frac{\partial T}{\partial x} = h_{s1}(T - T_0), \quad t \geq 0, \quad x = a, \quad -l/2 \leq y \leq l/2, \quad 0 \leq z \leq h, \]  

\[ -\lambda \frac{\partial T}{\partial x} = h_{s2}(T - T_0), \quad t \geq 0, \quad x = b, \quad -l/2 \leq y \leq l/2, \quad 0 \leq z \leq h, \]  

\[ \lambda \frac{\partial T}{\partial y} = h_{s3}(T - T_0), \quad t \geq 0, \quad a \leq x \leq b, \quad y = -l/2, \quad 0 \leq z \leq h, \]  

\[ -\lambda \frac{\partial T}{\partial y} = h_{s4}(T - T_0), \quad t \geq 0, \quad a \leq x \leq b, \quad y = l/2, \quad 0 \leq z \leq h, \]
\[ -\lambda \frac{\partial T}{\partial y} = h_{15}(T - T_0), \quad t \geq 0, \quad a \leq x \leq b, \quad y = l/2, \quad 0 \leq z \leq h, \]  
\[ -\lambda \frac{\partial T}{\partial z} = q_s, \quad t \geq 0, \quad a \leq x \leq b, \quad -l/2 \leq y \leq l/2, \quad z = 0, \]  
\[ \frac{\partial T}{\partial z} = h_{15}(T - T_0), \quad t \geq 0, \quad a \leq x \leq b, \quad -l/2 \leq y \leq l/2, \quad z = h, \]  
\[ \frac{\partial w}{\partial x} = 0, \quad \sigma_z = -p_0, \quad z = h, \quad a \leq x \leq b, \quad -l/2 \leq y \leq l/2. \]

where \( T_0 \) is the ambient temperature and also the initial one of the brake shoe; \( h_s \) is the convection coefficient; \( h_{15} = 1.42(\Delta T/h)^{0.25} (i = 1, 2, 3, 4) \) and \( h_{15} = 0.59(\Delta T/l)^{0.25} \) are obtained according to the natural heat convection boundary condition of upright plate and horizontal plate, and here \( \Delta T \) is the temperature difference between the boundary and the ambient.

2.2. Stress Field
2.2.1. Thermoelastic motion equations

The strain is derived from deformations induced by not only mechanical load and constrains but also thermal expansion. Six equations of strain compatibility and three differential balance equations of stress are given respectively in the tensor form

\[ \varepsilon_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (i, j = 1, 2, 3), \]  

and

\[ \sigma_{ij} = \alpha \left( T - T_0 \right) \left[ \begin{array}{cccc} 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{array} \right], \]  

\[ D = \frac{E}{(1 + \nu)(1 - 2\nu)} \]

where \( \varepsilon_0 \) is the thermal strain vector; \( \alpha \) is the coefficient of linear expansion; \( D \) is the elastic matrix.

The strain is derived from deformations induced by not only mechanical load and constrains but also thermal expansion. Six equations of strain compatibility and three differential balance equations of stress are given respectively in the tensor form

\[ \nabla^2 u + \frac{1}{1 - 2\nu} \frac{\partial \theta}{\partial x} - \frac{2(1 + \nu)}{1 - 2\nu} \alpha \frac{\partial T}{\partial x} = 0 \]  
\[ \nabla^2 v + \frac{1}{1 - 2\nu} \frac{\partial \theta}{\partial y} - \frac{2(1 + \nu)}{1 - 2\nu} \alpha \frac{\partial T}{\partial y} = 0 \]  
\[ \nabla^2 w + \frac{1}{1 - 2\nu} \frac{\partial \theta}{\partial z} - \frac{2(1 + \nu)}{1 - 2\nu} \alpha \frac{\partial T}{\partial z} = 0 \]

where \( \theta = \partial u/\partial x + \partial v/\partial y + \partial w/\partial z \) represents the bulk strain, and \( \nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2 \) is the Laplace operator; \( u, v, w \) represent displacements in \( x, y, z \) directions respectively.
Table 1. Shape and location parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$a$ (mm)</th>
<th>$b$ (mm)</th>
<th>$l$ (mm)</th>
<th>$h$ (mm)</th>
<th>$G$ (mm)</th>
<th>$R$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>137.5</td>
<td>162.5</td>
<td>25</td>
<td>6</td>
<td>2</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 2. Conditions used in the temperature field simulation.

<table>
<thead>
<tr>
<th>$T$ ($^\circ$C)</th>
<th>$\lambda_s$ (W/m/K)</th>
<th>$c_s$ (J/kg/K)</th>
<th>$\lambda_d$ (W/m/K)</th>
<th>$c_d$ (J/kg/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.706</td>
<td>1004</td>
<td>53.2</td>
<td>473</td>
</tr>
<tr>
<td>90</td>
<td>1.701</td>
<td>1168</td>
<td>61.0</td>
<td>476</td>
</tr>
<tr>
<td>150</td>
<td>1.562</td>
<td>1224</td>
<td>60.6</td>
<td>483</td>
</tr>
<tr>
<td>210</td>
<td>1.489</td>
<td>1295</td>
<td>60.1</td>
<td>494</td>
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<tr>
<td>270</td>
<td>1.458</td>
<td>1347</td>
<td>58.2</td>
<td>512</td>
</tr>
</tbody>
</table>

2.2.2. Boundary conditions

The boundary conditions are obtained as

$$\sigma_x = \tau_{xy} = \tau_{xz} = 0, \quad 0 \leq z < g, \quad x = a \text{ or } x = b,$$

$$\sigma_y = \tau_{yx} = \tau_{yz} = 0, \quad 0 \leq z < g, \quad y = -l/2 \text{ or } y = l/2,$$

$$u = 0, \quad g \leq z \leq h, \quad x = a \text{ or } x = b,$$

$$v = 0, \quad g \leq z \leq h, \quad y = -l/2 \text{ or } y = l/2,$$

$$w = 0, \quad \tau_{zy} = -f, \quad z = 0, \quad a \leq x \leq b,$$

$$\frac{\partial w}{\partial x} = \frac{\partial w}{\partial y} = 0, \quad \sigma_z = -p_0, \quad z = h, \quad a \leq x \leq b, \quad -l/1 \leq y \leq l/2.$$

When the temperature field is given, the solution of the displacement fields is obtained according to Eq. (14) and Eqs. 15(c–f), and then the strain field and the stress field are gained according to Eqs. (11) and (12) and Eqs. (15a) and (15b), respectively.

3. NUMERICAL SIMULATION AND EXPERIMENT SETUP

The ANSYS software is used to get the numerical simulation solutions of the temperature and stress fields with the sequential thermal-mechanical coupling method. The parameters $t_s = 7.75$ s, $\omega_0 = 88.3$ rad/s, $p_0 = 0.98$ MPa and $T_0 = 15^\circ$C are all set in accordance with those involved in the following experiment.

3.1. Numerical Simulation of the Thermo-Stress Field

The 3-D thermal solid element SOLID90 was selected to mesh the model of the brake shoe which is consistent with what Fig. 2 presents and the surface effect element SURF 152 was used to cover the friction surface. The shape and location parameters of the brake shoe are list in Table 1. The dynamic thermophysical property parameters which were measured by using the instrument NETZSCH LFA 447 Nano Flash are given in Table 2. In addition, the density of the brake shoe $\rho_s$ is 1788 kg·m$^{-3}$ and that of the brake disc $\rho_d$ is 7866 kg·m$^{-3}$. The thermal boundary conditions Eqs. (8a–8g) were applied to the shoe model, as shown in Fig. 4(a). As to loading HFD, the specific steps are defining the HFD function according to Eq. (7) with $x, y, t$ as the main variables, loading it as a table array, then adding it to the all the surface effect elements. The element size was set to 1 mm and consequently the overall number of elements were 4375 consisting of 625 SURF 152 elements and 3750 SOLID90 elements and that of nodes were 17888.
When the thermal physical field is transformed to the structural, SOLID90 elements are converted to SOLID95 elements and SURF152 elements to SURF154 elements. As shown in Fig. 4(b), constrains and loads are applied according to the boundary conditions (Eq. 15) and temperatures of the brake shoe body gained from transient thermal analysis are applied as the body load to the stress field in each loadstep. The parameters used in the stress field simulation are presented in Table 3. The constant friction coefficient \( \mu \) is got from the result of a braking experiment of sliding friction between the shoe material and a brake disc, conducted on a friction tester which is described in detail in Section 2.2. The curve of friction coefficient versus time, obtained by the friction torque measurement system of the friction tester, is presented in Fig. 5. It can be seen that \( \mu \) varies near its average 0.45 with a small fluctuation. So, in the simulation, the friction coefficient is set to 0.45.

### Table 3. Parameters used in the stress field simulation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E ) (GPa)</td>
<td>1.9</td>
<td>( 2.2 \times 10^{-5} )</td>
</tr>
<tr>
<td>( \alpha ) (K(^{-1}))</td>
<td>0.45</td>
<td>0.28</td>
</tr>
</tbody>
</table>
3.2. Experiment Setup

A single braking experiment was carried out on X-DM friction tester, shown in Fig. 6(a) to simulate the operating condition of the hoist’s emergency braking so as to validate the correctness of the theoretical models. Before the test, two brake shoe specimens were polished up to 3000 rotations at 100°C so as to ensure its contact well with the disc.

The experimental principle, shown in Fig. 6(b), is as follows: the experiment began with the angular velocity of the disc set to $\omega_0$ which and $t_s$ were set by a transducer to accomplish the disc’s constant deceleration motion, then the shoe specimen pushed to the disc with the pressure $p_0$, and simultaneously the temperature control system and the motor of the tester shut up to simulate the braking work condition of a mining hoist.

Embedded thermocouples of TT-K-36-SLE type with a range from $-200$ to $+260$°C and BE120-4AA(11) typed strain gages with the gage factor $2.18 \pm 1\%$ were selected to respectively measure temperature variations of Points 1, 2 and the strain of Point 3. The specific locations of the three points are shown in Fig. 4.

4. RESULTS AND DISCUSSION

4.1. Numerical Simulation of the Thermo-Stress Field

Figure 7(a) presents the temperature contour characterized by the maximum up to 78.07°C and the minimum 27.35°C at the end of the braking process. Also the heterogeneous distribution of the temperature can be seen that, with the nodes on the same layer, temperatures of the nodes at larger frictional radius are higher and at the same radius are almost identical; the farther a layer is from the frictional surface, the lower the temperatures of that place are. All these are mainly due to that the HFD applied to the friction surface is proportional to the frictional radius $\sqrt{x^2 + y^2}$, according to Eq. (7); the speed of heat generation of the friction surface is higher than that of heat conduction into the shoe material.

Figure 7(b) shows the temperature gradient sum contour of brake shoe at 7.75 s, and it can be clearly seen that the maximum temperature gradient sum is 14881.7°C/mm, located at the rectangular region with the $z$ coordinate range [1 mm, 2 mm] of the lateral surface indicated by $x = 162.5$ mm; the minimum 6.58466°C/mm located at the whole friction surface ($z = 0$). In addition, it reveals that heat conduction is mainly along the positive $z$ direction which is due to the phenomenon the variation of temperature gradient sum along $z$ direction is the largest than that along the other two directions.

Temperature variations of some nodes are shown in Fig. 8 to study further the temperature variation during emergency braking. The friction surface temperature increases first and then decreases at about 4 s, indicated in Fig. 8(b). The heat income from HFD, which is degressive from being proportional to $\omega_0(1 - t/t_s)$, is
larger than the heat release depended on heat convection and heat conduction at the forepart of emergency braking, so it is characterized by temperature rising which however promotes the heat convection and heat conduction; once the heat release surpasses the heat income, temperature decreases. Heat conduction takes time along the $z$ axis, so the temperature-time curve turning point of the node the $z$ coordinate of which is larger arrives later; Heat absorption of the place with a larger $z$ coordinate value is much less due to the poor heat conductivity, so is the heat emit here, and therefore temperatures of some nodes are merely shown increasing in Fig. 8(b), from which it also can be seen that the temperature difference at $t = 7.75$ s between Node (162.5 mm, 0, 1 mm) and Node (162.5 mm, 0, 2 mm) and the temperature difference between Node (162.5 mm, 0, 2 mm) and Node (162.5 mm, 0, 3 mm) are larger, which can be explained by the fact that the three nodes locate in the region of the maximum temperature gradient sum according to Fig. 7(b).

As shown in Fig. 9, temperature variation with time of measuring point indexed by 1 has the trend of increasing first and then decreasing over about 7 s, in conformity with the corresponding simulation result (the curve indicated by $z = 2$ mm in Fig. 8(b)).

With the simulation and experimental results of the temperature variation of Point 2 being contrasted in Fig. 10, it can be seen that the experimental temperature has the variation trend of increasing first and then
decreasing, the is slightly larger at the beginning, is caught up by the simulation curve at about 5.25 s and declines at about 6.7 s; while the simulation temperature of Point 2 increases throughout the emergency braking, only at the end is shown the trend of declining.

The error is caused mainly by that thermal radiation is neglected and its impact is more and more distinct with the braking time going on; besides, the contact pressure proved varying in [11, 13] is kept equal to $p_0$. As a whole, the two curves are in good correlation, with the difference at $t = 7.75$ s up to 2.8°C, which validates the feasibility of the FE model in the short braking time.
4.2. Numerical Simulation of the Thermo-Stress Field

Figure 11 gives the equivalent stress contour of the brake shoe at time $t = 7.75 \text{ s}$. It can be seen from Fig. 11 that the two small regions of the equivalent stress maximum, locating at about $z = 2 \text{ mm}$ on two boundary lines of the shoe model, indicate some kind of stress concentration; excluding the stress concentration labeled by $C$, an apparent division line of the whole equivalent stress contour (labeled by dashed line) existing at about $z = 2$ on the lateral surface ($y = +l/2$) is a result of the displacement constraint boundary labeled by $g$ which is $2 \text{ mm}$ (shown in Fig. 2). It can be seen that the layer at about $2 \text{ mm}$ below the friction surface is suffered to much larger equivalent stresses than the other layers. Of the layer $z = 2 \text{ mm}$, equivalent stresses of the center region are smaller, the periphery has the larger equivalent stresses.

In Fig. 12 the time-dependent curves of equivalent stress are given for nodes of different $z$ coordinate on the line indicated by $x = 162.5 \text{ mm}$ and $y = 0$. Equivalent stresses of all the nodes have the similar trend of increasing and then decreasing with the temperature-time variations of the nodes. This reveals that stresses are related to thermal expansions induced by temperature rises. However, the time for equivalent stress reaching its maximum value of each nodes’ equivalent stress-time curve is not consistent with those of the nodes’ temperature-time curves shown in Fig. 8(b). In addition, Node (162.5 mm, 0, 2 mm) has the largest equivalent stress during emergency braking than other four nodes, which are different with the phenomenon: the node with larger $z$ coordinate, that is, the further away the friction surface, the higher the temperature. All these are naturally connected with that the node (162.5 mm, 0, 2 mm) is subjected to much severer condition, seen from the stress boundary condition (15a) and (15c), and locates in the region of the largest temperature gradient sum. Also, the two curves of Node (162.5 mm, 0, 4 mm) and Node (162.5 mm, 0, 5 mm) are similar, which is due to the fact that the differences between the temperatures of the two nodes...
are not significant and their temperature gradients are all very small. In conclusion, thermal stress results from the interaction among temperature rise, temperature gradient and structural load and constrain.

As shown in Fig. 13, the measured strain along the $y$ direction collected at Point 3 experiences a declining process in the initial period when the compressive strain caused by the brake pressure and friction takes the lead, which is mainly due to low-response of the measurement system and the specimen and a response time being needed for it to be embodied fully; the strain reaches the minimum about one second later and then increases; about 1.7 s later, the strain becomes positive, which indicates that thermal expansion gradually plays the leading role; it continues to get larger until about the moment $t = 6.5$ s, and then decreases.

With the experiment curve of strain at Point 3 contrasted with the simulated ones, it can be seen that the simulation curve is of no declining process and the strain is $-3.28 \times 10^{-4}$ at the beginning caused entirely by the pressure and friction applied, for which the reason is that there is no response delay for the software. The error causes for temperature field discussed before is also the ones here, which is due to that thermal strain is proportional to temperature variation (reflected in Eq. 12). Overall, the two curves agree well, certifying the validity of the theoretical models for the brake shoe’s stress field.

5. CONCLUSIONS

In this study, the FE model of the 3-D transient thermo-stress field of a brake shoe during mine hoist emergency braking was established by adopting the sequential thermal-mechanical coupling method and an experiment was carried out on the X-DM friction tester to verify the FE model. The numerical solutions agreed well with the experimental results and it was concluded as follows:

1. The results of the temperature field indicate that the whole temperature has the trend of increasing first and then decreasing; with the increase of distance away from the friction surface, the temperature there declines and the time for its temperature reaches the maximum value arrives later; the larger the frictional radius on the same layer, the higher the temperature of the place; and heat conduction is mainly along the positive $z$ direction, namely perpendicular to the friction surface and into the mate-
rial, during emergency braking based on the phenomenon that the variation of temperature gradient sum along the $z$ direction is the largest than that along the other two directions.

2. The results of the temperature field indicate that the whole temperature has the trend of increasing first and then decreasing; with the increase of distance away from the friction surface, the temperature there declines and the time for its temperature reaches the maximum value arrives later; the larger the frictional radius on the same layer, the higher the temperature of the place; and heat conduction is mainly along the positive $z$ direction, namely perpendicular to the friction surface and into the material, during emergency braking based on the phenomenon that the variation of temperature gradient sum along the $z$ direction is the largest than that along the other two directions.

3. It is found that the brake shoe’s friction surface accumulates lots of heat and due to poor heat conduction ability of brake shoe material, region of 1 to 3 mm below the friction surface is suffered to larger temperature gradient, which together with severe constrain conditions and relative high temperature rise induce larger stress, that can lead to braking failure of disc brakes of mine hoist. Therefore, attention should be paid to improving the heat transfer capability of brake shoes.

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