GENERATION OF FRICTIONAL HEAT DURING UNIFORM SLIDING OF TWO PLANE-PARALLEL STRIPS

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Abstract: The thermal problem of friction for a tribosystem consisting of two plane-parallel strips is studied. It is assumed that the relative sliding speed is constant. The convective cooling on free surfaces of strips and the heat transfer through a contact surface are considered, too. The evolution of the contact temperature and its spatial distribution in materials of frictional pair such as aluminum/steel, was investigated.

1. INTRODUCTION

The evolution and distribution of temperature in a plane-parallel strip/the semi-space tribosystem, at sliding with a constant speed have been investigated in articles (Yevtushenko and Kuciej, 2009a; Yevtushenko et al., 2009), and with a constant deceleration – in articles (Yevtushenko and Kuciej, 2009b, 2010a). The corresponding solution with a time-dependent contact pressure has been obtained in article (Yevtushenko et al., 2011). The influence of the duration of increase in pressure from zero (at the initial moment of time) to nominal value (at the moment of stop) on the temperature for a friction pair metal-ceramic strip/cast iron semi-space has been studied in article (Yevtushenko et al., 2010). The distribution of the thermal stresses for the same friction couple has been investigated in article (Yevtushenko and Kuciej, 2010b). The analytical solution of the contact problem with frictional heat generation for a two-element tribosystem – the composite strip sliding on a surface of the homogeneous semi-space – have been obtained in article (Kuciej, 2011a, 2011b).

In the present article we investigate the transient temperature distribution in tribosystem consisting of two plane-parallel strips. We assumed that the heat contact of the strips is imperfect, and on its outer surfaces there are convective heat exchange with environment, according to the Newton's law. The exact solution of the problem is obtained by method of separation of variables.

2. STATEMENT OF THE PROBLEM

The problem of contact interaction of plane-parallel strips of thickness $d_i, i = 1,2$ is under consideration. The scheme of contacting bodies is shown in Fig. 1. The strips are compressed by the normal pressure p_0, applied to their outer surfaces. In the initial time moment $t = 0$ the relative sliding of the strips begins with constant speed V_0 in the direction of y-axis of a Cartesian coordinate system $Oxyz$. The sliding is accompanied by frictional heat generation on a contact plane $z = 0$. The sum of the intensities of the frictional heat fluxes directed into each component of friction pair is equal to the specific friction power $q_0 = fV_0p_0$ (f is a frictional coefficient) and the thermal contact of the strips is imperfect – the heat transfer between the contact surfaces of the strips takes place. On the outer surfaces $z = d_1$ and $z = -d_2$ of the strips the convective heat exchange with the environment occurs. It is assumed that the contact heat transfer coefficient h and the coefficients of the heat exchange $h_i, i = 1,2$ are constant. All the values and parameters which refer to strips in the further considerations will have bottom indexes $i = 1,2$.

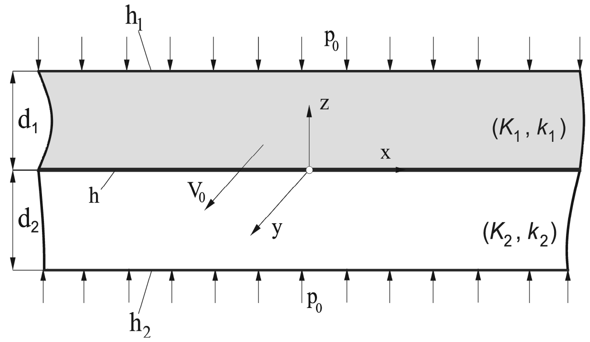

Fig. 1. Scheme of the contact problem

In such statement, the transient temperature $T_i(z,t)$, $i = 1,2$ fields in strips can be found, from the solution of a boundary-value problem of heat conduction:

$$\frac{\partial^2 T_1^*(\zeta,\tau)}{\partial \zeta^2} = \frac{\partial T_1^*(\zeta,\tau)}{\partial \tau}, \quad 0 < \zeta < 1, \tau > 0, \tag{1}$$

$$\frac{\partial^2 T_2^*(\zeta,\tau)}{\partial \zeta^2} = \frac{1}{k^*}\frac{\partial T_2^*(\zeta,\tau)}{\partial \tau}, -d^* < \zeta < 0, \tau > 0, \tag{2}$$

$$K^*\frac{\partial T_2^*}{\partial \zeta}\bigg|_{\zeta=0-} - \frac{\partial T_1^*}{\partial \zeta}\bigg|_{\zeta=0+} = 1, \quad \tau > 0, \tag{3}$$

$$K^*\frac{\partial T_2^*}{\partial \zeta}\bigg|_{\zeta=0-}+\frac{\partial T_1^*}{\partial \zeta}\bigg|_{\zeta=0+}+ \\ +\mathrm{Bi}[T_2^*(0,\tau)-T_1^*(0,\tau)]=0,\ \tau>0, \tag{4}$$

$$\frac{\partial T_1^*}{\partial \zeta}\bigg|_{\zeta=1}+\mathrm{Bi}_1 T_1^*(1,\tau)=0,\quad \tau>0, \tag{5}$$

$$K^*\frac{\partial T_2^*}{\partial \zeta}\bigg|_{\zeta=-d^*}-\mathrm{Bi}_2 T_2^*(-d^*,\tau)=0,\quad \tau>0, \tag{6}$$

$$T_1^*(\zeta,0)=0,\ 0\le\zeta\le 1,\ T_2^*(\zeta,0)=0,\ -d^*\le\zeta\le 0\,. \tag{7}$$

$$\zeta=\frac{z}{d_1},\ \tau=\frac{k_1 t}{d_1^2},\ d^*=\frac{d_2}{d_1},\ K^*=\frac{K_2}{K_1},\ k^*=\frac{k_2}{k_1}, \tag{8}$$

$$T_0=\frac{q_0 d_1}{K_1},\ \mathrm{Bi}=\frac{\mathrm{h}d_1}{K_1},\ \mathrm{Bi}_i=\frac{\mathrm{h}_i d_1}{K_1},\ T_i^*=\frac{T_i-T_s}{T_0},\ i=1{,}2\,,$$

where K is a coefficient of thermal conductivity and k is a coefficient of thermal diffusivity.

3. SOLUTION TO THE PROBLEM

The complete solution to a boundary-value problem of heat conduction (1)–(7) we shall present in the form:

$$T_1^*(\zeta,\tau)=\theta_1(\zeta)+\Theta_1(\zeta,\tau)\,,\ 0\le\zeta\le 1\,,\ \tau\ge 0\,, \tag{9}$$

$$T_2^*(\zeta,\tau)=\theta_2(\zeta)+\Theta_2(\zeta,\tau)\,,\ -d^*\le\zeta\le 0\,,\ \tau\ge 0\,, \tag{10}$$

where the stationary components $\theta_i(\xi),\ i=1{,}2$ are given as:

$$\theta_1(\zeta)=a_1\zeta+b_1,\ 0\le\zeta\le 1, \\ \theta_2(\zeta)=a_2\zeta+b_2,\ -d^*\le\zeta\le 0, \tag{11}$$

$$a_i=\frac{\hat{a}_i}{a}\,,\ b_1=-\left(1+\frac{1}{\mathrm{Bi}_1}\right)a_1\,,\ b_2=\left(d^*+\frac{K^*}{\mathrm{Bi}_2}\right)a_2\,, \tag{12}$$

$$\hat{a}_1=-\mathrm{Bi}_1[K^*\mathrm{Bi}_2+(K^*+d^*\mathrm{Bi}_2)\mathrm{Bi}], \\ \hat{a}_2=\mathrm{Bi}_2[\mathrm{Bi}_1+(1+\mathrm{Bi}_1)\mathrm{Bi}], \tag{13}$$

$$a=2K^*\mathrm{Bi}_1\mathrm{Bi}_2+[K^*(\mathrm{Bi}_1+\mathrm{Bi}_2)+ \\ +(K^*+d^*)\mathrm{Bi}_1\mathrm{Bi}_2]\mathrm{Bi}, \tag{14}$$

and the dimensionless transient temperatures $\Theta_i(\xi,\tau)$, $i=1{,}2$ are taken as the solution of the following homogeneous boundary-value problem:

$$\frac{\partial^2\Theta_1^*(\zeta,\tau)}{\partial\zeta^2}=\frac{\partial\Theta_1^*(\zeta,\tau)}{\partial\tau},\quad 0<\zeta<1,\ \tau>0, \tag{15}$$

$$\frac{\partial^2\Theta_2^*(\zeta,\tau)}{\partial\zeta^2}=\frac{1}{k^*}\frac{\partial\Theta_2^*(\zeta,\tau)}{\partial\tau},-d^*<\zeta<0,\ \tau>0, \tag{16}$$

$$K^*\frac{\partial\Theta_2^*}{\partial\zeta}\bigg|_{\zeta=0-}-\frac{\partial\Theta_1^*}{\partial\zeta}\bigg|_{\zeta=0+}=0,\quad \tau>0, \tag{17}$$

$$K^*\frac{\partial\Theta_2^*}{\partial\zeta}\bigg|_{\zeta=0-}+\frac{\partial\Theta_1^*}{\partial\zeta}\bigg|_{\zeta=0+}+ \\ +\mathrm{Bi}[\Theta_2^*(0,\tau)-\Theta_1^*(0,\tau)]=0,\ \tau>0, \tag{18}$$

$$\frac{\partial\Theta_1^*}{\partial\zeta}\bigg|_{\zeta=1}+\mathrm{Bi}_1\Theta_1^*(1,\tau)=0,\quad \tau>0, \tag{19}$$

$$K^*\frac{\partial\Theta_2^*}{\partial\zeta}\bigg|_{\zeta=-d^*}-\mathrm{Bi}_2\Theta_2^*(-d^*,\tau)=0,\quad \tau>0, \tag{20}$$

$$\Theta_1^*(\zeta,0)=-\theta_1(\zeta),\quad 0\le\zeta\le 1, \\ \Theta_2^*(\zeta,0)=-\theta_2(\zeta),\quad -d^*\le\zeta\le 0. \tag{21}$$

The solution of the transient heat conduction problem (15)–(21) is constructed by method of separation of variables as (Ozisik, 1980):

$$\Theta_1(\zeta,\tau)=\sum_{n=1}^{\infty}C_n\Phi_{1,n}(\zeta)e^{-\lambda_n^2\tau}\,,\ 0\le\zeta\le 1\,,\ \tau\ge 0\,, \tag{22}$$

$$\Theta_2(\zeta,\tau)=\sum_{n=1}^{\infty}C_n\Phi_{2,n}(\zeta)e^{-\lambda_n^2\tau}\,,\ -d^*\le\zeta\le 0\,,\ \tau\ge 0\,, \tag{23}$$

where:

$$\Phi_{1,n}(\zeta)=A_{1,n}^*\sin(\lambda_n\zeta)+B_{1,n}^*\cos(\lambda_n\zeta)\,, \tag{24}$$

$$\Phi_{2,n}(\zeta)=A_{2,n}^*\sin\left(\frac{\lambda_n}{\sqrt{k^*}}\zeta\right)+B_{2,n}^*\cos\left(\frac{\lambda_n}{\sqrt{k^*}}\zeta\right), \tag{25}$$

$$A_{1,n}^*=(\mathrm{Bi}_1\cos\lambda_n-\lambda_n\sin\lambda_n)\times \\ \times\left\{\varepsilon\lambda_n\left[\varepsilon\lambda_n\sin\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)-\mathrm{Bi}_2\cos\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\right]-\right. \\ \left.-\mathrm{Bi}\left[\varepsilon\lambda_n\cos\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)+\mathrm{Bi}_2\sin\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\right]\right\}, \tag{26}$$

$$A_{2,n}^*=[\lambda_n(\lambda_n\sin\lambda_n-\mathrm{Bi}_1\cos\lambda_n)- \\ -\mathrm{Bi}(\lambda_n\cos\lambda_n+\mathrm{Bi}_1\sin\lambda_n)]\times \\ \times\left[\varepsilon\lambda_n\sin\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)-\mathrm{Bi}_2\cos\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\right], \tag{27}$$

$$B_{1,n}^{*}=(\lambda_n\cos\lambda_n+\mathrm{Bi}_1\sin\lambda_n)\times \\ \times\left\{\varepsilon\lambda_n\left[\mathrm{Bi}_2\cos\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)-\varepsilon\lambda_n\sin\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\right]\right. \\ \left.+\mathrm{Bi}\left[\varepsilon\lambda_n\cos\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)+\mathrm{Bi}_2\sin\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\right]\right\}, \tag{28}$$

$$B_{2,n}^{*}=[\lambda_n(\mathrm{Bi}_1\cos\lambda_n-\lambda_n\sin\lambda_n)+ \\ +\mathrm{Bi}(\lambda_n\cos\lambda_n+\mathrm{Bi}_1\sin\lambda_n)]\times \\ \times\left[\varepsilon\lambda_n\cos\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)+\mathrm{Bi}_2\sin\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\right], \tag{29}$$

$$C_n=-\frac{r_n}{R_n},\ n=1,2,..., \tag{30}$$

$$r_n=k^*r_{1,n}+K^*r_{2,n},\ R_n=0.5(k^*R_{1,n}+K^*R_{2,n}), \tag{31}$$

$$r_{i,n}=a_iI_{i,n}+b_iJ_{i,n}, i=1,2, \tag{32}$$

$$I_{1,n}=A_{1,n}^{*}(\lambda_n^{-1}\sin\lambda_n-\cos\lambda_n)+ \\ +B_{1,n}^{*}[\sin\lambda_n-\lambda_n^{-1}(1-\cos\lambda_n)], \tag{33}$$

$$I_{2,n}=A_{2,n}^{*}\left[\frac{\sqrt{k^*}}{\lambda_n}\sin\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)-d^*\cos\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\right]+ \\ +B_{2,n}^{*}\left\{\frac{\sqrt{k^*}}{\lambda_n}\left[1-\cos\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\right]-d^*\sin\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\right\}, \tag{34}$$

$$R_{1,n}=A_{1,n}^{*\,2}(\lambda_n-\sin\lambda_n\cos\lambda_n)+ \\ +2A_{1,n}^{*}B_{1,n}^{*}\sin^2\lambda_n+B_{1,n}^{*\,2}(\lambda_n+\sin\lambda_n\cos\lambda_n), \tag{35}$$

$$R_{2,n}=A_{2,n}^{*\,2}\left[\frac{d^*\lambda_n}{\sqrt{k^*}}-\sin\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\cos\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\right]- \\ -2A_{2,n}^{*}B_{2,n}^{*}\sin^2\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)+ \\ +B_{2,n}^{*\,2}\left[\frac{d^*\lambda_n}{\sqrt{k^*}}+\sin\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\cos\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)\right], \tag{36}$$

$$J_{1,n}=A_{1,n}^{*}(1-\cos\lambda_n)+B_{1,n}^{*}\lambda_n^{-1}\sin\lambda_n, \tag{37}$$

$$J_{2,n}=A_{2,n}^{*}\left[\cos\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right)-1\right]+B_{2,n}^{*}\sin\left(\frac{d^*\lambda_n}{\sqrt{k^*}}\right), \tag{38}$$

and $\lambda_1,\ \lambda_2, ..., \lambda_n, ...$ are the real roots of the characteristic equation:

$$\Delta(\lambda)=\varepsilon[2\lambda(\lambda\sin\lambda-\mathrm{Bi}_1\cos\lambda)- \\ -\mathrm{Bi}(\lambda\cos\lambda+\mathrm{Bi}_1\sin\lambda)]\times \\ \times\left[\varepsilon\lambda\sin\left(\frac{d^*\lambda}{\sqrt{k^*}}\right)-\mathrm{Bi}_2\cos\left(\frac{d^*\lambda}{\sqrt{k^*}}\right)\right]- \\ -\mathrm{Bi}(\lambda\sin\lambda-\mathrm{Bi}_1\cos\lambda)\times \\ \times\left[\varepsilon\lambda\cos\left(\frac{d^*\lambda}{\sqrt{k^*}}\right)+\mathrm{Bi}_2\sin\left(\frac{d^*\lambda}{\sqrt{k^*}}\right)\right]=0, \tag{39}$$

where:

$$\varepsilon=\frac{K^*}{\sqrt{k^*}}. \tag{40}$$

4. SOLUTION TO THE PROBLEM

The numerical results have been obtained for the friction couple an first strip – aluminum ($K_1=209\mathrm{Wm^{-1}K^{-1}}$, $k_1=8{,}6\cdot10^{-5}\mathrm{m^2s^{-1}}$) and a second strip – steel ($K_2=22\mathrm{Wm^{-1}K^{-1}}$, $k=1{,}1\cdot10^{-5}\mathrm{m^2s^{-1}}$). The friction conditions are: $p_0=1\mathrm{MPa}$, $V_0=10\mathrm{ms^{-1}}$, $f=0{,}45$ and $d_1=5$ mm. The choice of materials above were taken from the article (Yevtushenko and Kuciej, 2009a), in which the solution was obtained to the heat conduction problem of friction, where the strip is sliding with the constant speed on the surface of the semi-space.

The results, presented in Figs. 2–4 have been obtained in the case of the perfect thermal contact of strips at $h\to\infty$ ($\mathrm{Bi}\to\infty$) for two variants of boundary conditions on the outer surface $z=d_1$ of the aluminum strip: a) thermal isolation at $h_1\to\infty$ ($\mathrm{Bi}_1\to\infty$) or b) maintaining initial temperature at $h_1\to\infty$ ($\mathrm{Bi}_1\to\infty$).

Evolutions of temperature (22)–(25), (30) on the contact surface $z=0$ for two strips and for three values of steel strip thickness d_2 are presented in the Fig. 2. Thermal isolation on the outer surface of aluminum strip causes increase of the contact surface temperature, nearly 2.5 times in relation to the temperature obtained in the case of maintenance of the initial temperature at the same surface $z=d_1$. At the beginning of sliding temperature increases rapidly at the contact surface, and after some time it reaches a steady state. Time to reach the steady state temperature increases with increase of the steel strip thickness. After exceeding value $d_2=20$ mm, the contact temperature and duration of reaching the steady state temperature do not change.

Influence of the coefficient of heat exchange on the contact surfaces h(Bi) on the contact surface temperature of the aluminum and steel strips is shown in Fig. 3. It should be noted that the parameter h is the value inversely proportional to the thermal resistance of the contact area. The highest jump of temperature on the contact surface is observed when $h\to0$ (thermal resistance is greatest). The value of the temperatures difference is also influenced by the boundary conditions on the outer surface of the strips i. e. Bi_1. Reducing the thermal resistance of the contact surface causes the alignment of the contact temperature between strips. For $\mathrm{Bi}>15$, the thermal contact between the strips becomes perfect. The value of the temperatures difference at the contact surface depends also on the boundary conditions on the outer surface of aluminum strip: maximum difference is about 250℃ at $\mathrm{Bi}_1 \to 0$ (Fig. 3a) and 180℃ (Fig. 3b) at $\mathrm{Bi}_1 \to \infty$). The largest temperature changes are noticeable for the steel strip. However, in the case of the aluminum strip after increase of the initial temperature, together with a slight increase Biot number Bi, the temperature gets a steady state.

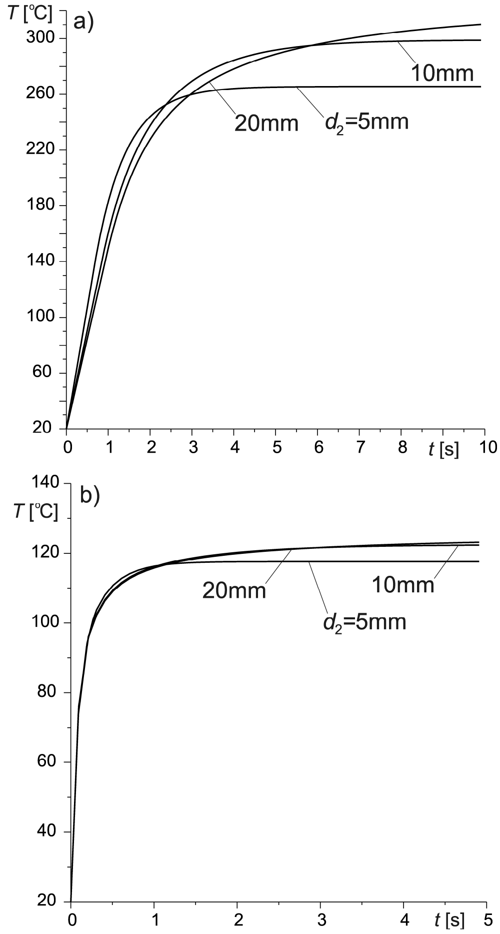

Fig. 2. Evolution of the temperature $T(0,t)$ on the contact surface at $d_1 = 5\mathrm{mm}$, $\mathrm{Bi} \to \infty$, $\mathrm{Bi}_2 \to \infty$, for three values $d_2 = 5\mathrm{mm}, 10\mathrm{mm}, 15\mathrm{mm}$; a) $\mathrm{Bi}_1 \to 0$; b) $\mathrm{Bi}_1 \to \infty$

To verify exactly the presented solutions for the strip/strip system, analysis of the evolution of dimensionless temperature $T^*(0,\tau)$ for four values d^* of relative thickness of strips, calculations were carried out for two tribosystems aluminum /steel and steel /aluminum (Fig. 4). In the case when the first strip is made of aluminum, the contact temperature decreases while thickness of the steel strip increases. However, in other case, when the first strip is made of steel, the temperature on the contact surface increases while thickness of the aluminum strip increases, too. For the first aluminum strip at $d^* \geq 2$ and steel strip at $d^* \geq 4$ as was established above (in dimension form), one of the strip (the second one), can be replaced with the semi-space (Fig. 4). The presented curves for $d^* = 4$ in Fig. 5 corresponds closely with the results shown in Fig. 4 in the article (Yevtushenko and Kuciej, 2009a) for the strip/semi-space tribosystem.

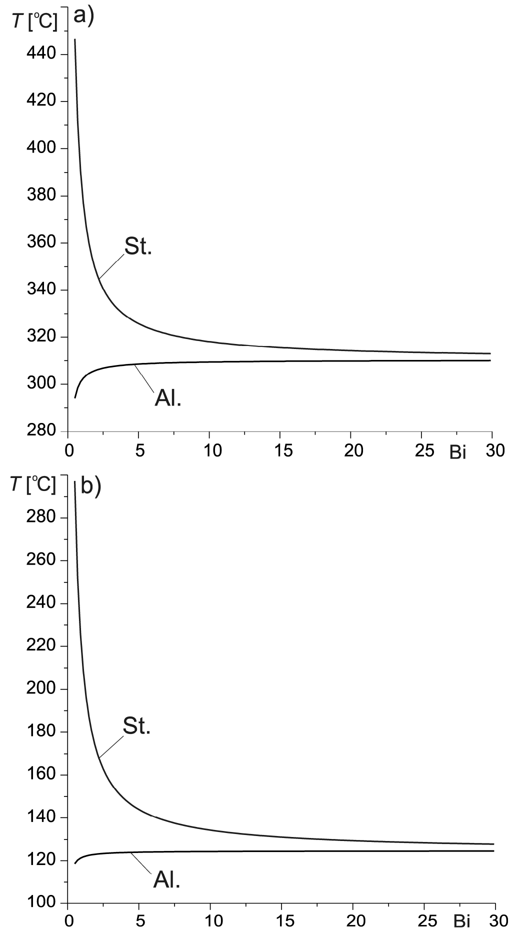

Fig. 3. Dependence of the temperatures $T_i(0,t), i = 1,2$ on the contact surfaces on Biot number Bi at $d_1 = 5\mathrm{mm}$, $d_2 = 20\mathrm{mm}$, $\mathrm{Bi} \to \infty$, $\mathrm{Bi}_2 \to \infty$, $t = 10\mathrm{s}$: a) $\mathrm{Bi}_1 \to 0$; b) $\mathrm{Bi}_1 \to \infty$

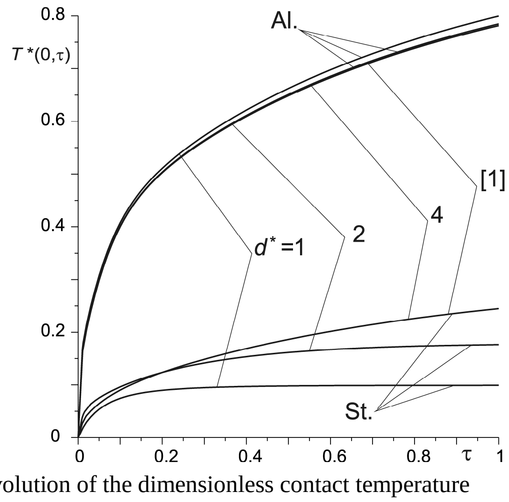

Fig. 4. Evolution of the dimensionless contact temperature $T^*(0,\tau)$ for four values d^* at $\mathrm{Bi} \to \infty$, $\mathrm{Bi}_1 = 10$, $\mathrm{Bi}_1 \to \infty$

5. CONCLUSIONS

We obtained the analytical solution to the heat conduction problem of friction for the two-element tribosystem. The heat exchange through the contact surfaces of strips and convective cooling on their outer surfaces are taken into account.

We carried out the numerical analysis for the aluminum /steel tribosystem, where one strip is sliding on the surface of the other strip with the constant velocity. We investigated the influence of strip thickness, the contact conductivity and the type of boundary conditions on the evolution of the temperature on the contact surface. This allowed us to determine the limits of the thickness of the strip, at which the solution may be replaced with a suitable solution for the strip /semi-space tribosystem (Yevtushenko and Kuciej, 2009a). For the relative thickness strip $d^* \geq 3$ we can calculate temperature from the solution obtained for strip /semi-space, but for smaller values of d^* calculation of temperature should be carried out using the solution for the strip /strip system.

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