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MATHEMATICAL MODEL OF CALCULATION OF THE TEMPERATURE IN THE CONTACT ZONE OF INTERACTION BETWEEN THE SHUTTLE SOCKET AND THE BOBBIN OF SEWING MACHINES

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Abstract. The article covers the issues of increasing the level of hardness and wear resistance, reducing the level of friction resulting from sliding, or some shuttle components may have an external coating simply for the purpose of protecting against rust. The use of one or another type of coating depends on the choice of the shuttle manufacturer; in particular, hard chrome plating has been used for many years on all shuttle devices, not just on the shuttles of high-speed sewing machines. Calculations determining the effectiveness of introducing antifriction coatings on the surfaces of contacting parts have been done, in particular, tribological couplings of the shuttle socket with a bobbin have been studied in detail, which leads to an improvement in the temperature conditions of operation in the contact zone and, as a consequence, to a reduction in wear of the surfaces of contacting parts and an increase in the durability of tribological couplings.

Keywords: temperature, slip, chrome plating, high-speed sewing machine, contract parts, durability, semi-finished products, heat treatment.

Introduction. In order to produce different shuttle components different types of steel are used. The requirements for the steel used are determined at the designing stage, and its choice is directly related to the corporate quality strategy. Harder types of steel will produce a more wear-resistant shuttle, but will result in a lower level of product machinability, which will negatively impact production costs. Because of extensive experience and the desire to always provide clients with only the highest quality shuttles, only the highest quality shuttles, differentiated steel selection depending on the shuttle components, even going as far as using very hard bearing steel types to produce components subject to maximum load. Where other shuttle manufacturers have opted for synthetic materials (polymers) for the production of various parts of the shuttle (shuttles for home sewing machines) or only for bobbin holders (shuttles for sewing machines that do not require lubrication), more expensive solutions made of steel with a special coating, thereby guaranteeing a longer service life for their products have been settled on.

Higher quality products, resulting from the use of more refined raw materials, the processing of which produces steel with a more homogeneous structure and the absence of stress, are much more expensive, but are considered more reliable and wear-resistant. In order to guarantee the maximum quality of the raw materials used, only the best European steel foundries source steel, always accompanied by certification of casting, chemical and metallographic analysis, surface and internal analysis using ultrasound and induced flows has been used.

After processing the steel by removing chips through turning, milling, through-hole cutting, internal threading, polishing and grinding, the semi-finished shuttles are heat treated to achieve the required level of hardness and final structure of the product. For the life of the shuttle, a huge role is played by both the hardness and structure of the surface (guarantee of wear resistance), the depth of carburization (i.e., the thickness of the top layer: the harder it is, the longer the shuttle will last), and the hardness of the core (which, in order to avoid fragility of the shuttle, must be less than surface hardness). This type of processing is very delicate, so to ensure the best final results and a high level of repeatability requires extensive experience and expensive equipment, leaving nothing to chance, therefore cooperation for many years is set with the best suppliers in the field of heat treatment - those who process machine components from the aerospace industry and Formula 1, where Italy has no equal.

In order to increase the level of hardness and wear resistance, reduce the level of friction resulting from sliding, or simply to protect against rust, some shuttle components may have an external coating. The use of one or another type of coating depends on the choice of the shuttle manufacturer; in particular, hard chrome plating has been used for many years on all shuttle devices, and not just on the shuttles of high-speed sewing machines. In addition, obtaining a high-quality coating that provides the best technical performance of the shuttle requires knowledge of high technology and extensive experience. Hard chrome plating, in which considerable capital has been invested, is carried out today in the Company's production premises. Many years of research and comparative analysis have allowed strengthening cooperation with the best suppliers of coatings, in particular special coatings. Many shuttle manufacturers claim that they use certain types of coatings for their products, however, as they say in Italy, “all that glitters is not gold.” The technology behind a quality coating, as well as the technology behind a quality shuttle.

These two aspects help determine the coefficient of friction between the components of the shuttle in motion (specifically, between the bobbin case holder and the shuttle body). The lower the friction, the less wear and longer the life of the shuttle. These characteristics when processing a shuttle can only be achieved through the use of high technology and the availability of expensive high-precision equipment, and this requires extensive experience and considerable investment. In order to achieve a high level of automation and maximum precision, the company itself develops and produces such equipment for the production of shuttles.

Theoretical Basis. The development of measures to increase the durability of tribological couplings is a very urgent task. Therefore, much attention is paid to the engineering of the surfaces of elements of tribological couplings, in particular when using antifriction coatings [1].

There are various ways to select materials for tribological couplings for newly designed machines: they use analogue data, information on wear resistance, strength, hardness, etc. But, as a rule, these data may not be reliable and do not take into account the requirements for operating modes. As an integral indicator when choosing a material or coating, it is advisable to use the flash point on the contacting surfaces of tribological interfaces. As a result, an urgent task is to create a model for theoretical calculation of the flash point on surfaces in contact with coatings. The solution to this problem allows analyzing the influence of the main design parameters and material characteristics on the flash point and, on this basis, already at the design development stage, select the necessary coating materials and select optimal operating modes for the contacting structural elements.

An analysis of the results of studies carried out for frictional contact [2] shows that the value of the flash point significantly depends on the thermophysical characteristics of the materials of the contacting surfaces, the relative sliding speed and the actual pressure at the contact area. In addition, the value of the flash point also depends on the elastic physical constants of the material, which significantly determine the amount of deformation in the zone of the actual contact area.

In engineering practice, the formulas of H. Blok and A.V. Chichinadze are often used to calculate the flash point [3,4]. However, these formulas do not consider the presence of antifriction coatings on the surfaces of tribological interfaces.

A model for calculating the flash point on surfaces in contact with coatings is given in the article. Since the contact zone is quite small, the following hypotheses are accepted:

- the amount of heat generated in the contact zone due to friction is transferred to the contacting bodies with almost no losses;

- the contacting bodies are semi-infinite solids, i.e., the dimensions of the actual contact area are small compared to the radii of curvature of the contacting elements;

- for a moving source, the heat flow at the contact area is considered as one-dimensional, propagating normal to the contacting surfaces;

- thermophysical quantities for materials of contacting bodies are constant in the temperature range under study.

The calculation model is shown in Fig. 1, where 1 is the coating layer; 2 is the main material. Here I_h is the thickness of the coating layer; x, y is coordinate system; λ_1, λ_2 are the thermal conductivity coefficients of the coating material and the base material, respectively; k_1, k_2 are the thermal diffusivity coefficients in the coating layer and the base material. Since the coating is thin, the layer of base material is considered quite thick. For the region under consideration, the solution to the heat equation [5] after using operational calculus methods is written in the form:

$$d\Theta = \frac{dq*k_1}{2\lambda_1\sqrt{\pi k_1 t}} - \frac{dq*k_1}{2\lambda_1\sqrt{\pi k_1 t}}\sum_{n=1}^{\infty} a^n exp\left\{-\frac{(nI_h)^2}{k_1 t}\right\} + \frac{3dq*k_1 a}{2\lambda_1\sqrt{\pi k_1 t}}\sum_{n=1}^{\infty} a^n exp\left\{-\frac{(n+1I_h)^2 I_h^2}{k_1 t}\right\}, (1)$$

where $d\Theta$ is the increment in flash point on the surface; $a = \frac{1-\omega}{1+\omega}$, $\omega = \frac{\lambda_{2\sqrt{k_1}}}{\lambda_{1\sqrt{k_2}}}$ are dimensionless parameters; dq is the increment in the intensity of the heat flow moving along the surface of the layer $x = o$ (Fig. 1); t is time.

In [6] it is shown that since the heat caused by friction is proportional to the magnitude of the contact load and the friction coefficient, the heat flow distribution region is elliptical and can be represented as two parabolas. In this case, the heat flow intensity can be described by the following expression:

$$q = q_o\left[1 - \frac{(\varepsilon V - l_o)}{l_o^2}\right], \qquad (2)$$

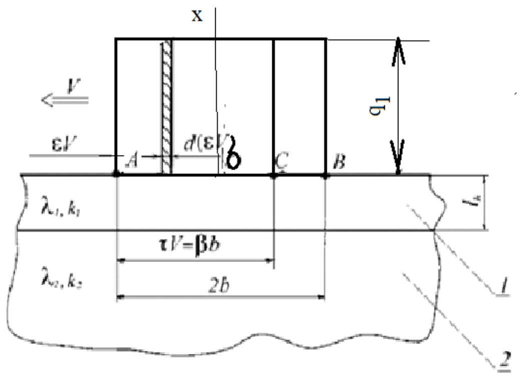

Fig. 1. Model for calculating the flash point value

where q_o is the maximum value of heat flow; l_o is half the width of the contact pad; V is the speed of relative sliding of the heat source in the contact zone; $t = \tau - \varepsilon$ is the time of passage of the contact zone; ε is the time of passage of part of the contact area; $\beta = \frac{\tau V}{I_o}$ is a dimensionless parameter.

Using expression (2) and performing integration in equation (1), we obtain the following expression for determining the surface flash temperature Θ at an arbitrary point of the contact pad C.

$$\Theta = \frac{k_1 q_1}{2\lambda_1\sqrt{\pi k_1}}\left\{\int_0^{\tau}\left[1 - \frac{(\varepsilon V - l_o)}{l_o^2}\right] * \frac{d\varepsilon}{\sqrt{\tau - \varepsilon}} + \sum_{n-0}^{\infty} a^n \int_0^{\tau}\left[1 - \frac{(\varepsilon V - l_o)}{l_o^2}\right] * \frac{1}{\sqrt{\tau - \varepsilon}} * exp\left[-\frac{(nl_k)^2}{k_1(\tau - \varepsilon)}\right] d\varepsilon + 3a\sum_{n=0}^{\infty} a^n \int_o^{\tau}\left[1 - \frac{(\varepsilon V - l_o)}{l_o^2}\right] * \frac{1}{\sqrt{\tau - \varepsilon}} * exp\left[-\frac{(n+1)^2 l_h^2}{k_1(\tau - \varepsilon)}\right] d\varepsilon\right\} \qquad (3)$$

In order to generalize the calculation results, we introduce a dimensionless expression for the flash temperature T:

$$T = \frac{\pi\lambda_1 V}{2k_1 q_o} * \Theta \qquad (4)$$

Carrying out integration in (3) taking into account (4), we obtain the following equation for determining the dimensionless characteristic of the flash point:

$$T = \sqrt{\frac{1}{2}\pi L\beta}\left[\frac{4}{15}\beta(5 - 2\beta)4\beta\left(\frac{1}{3} - \frac{2}{15}\beta\right)\sum_{n=0}^{\infty} a^n exp\left(-2n^2h^2\frac{L}{\beta}\right) + 4\left(\frac{2}{3} - \frac{3}{5}\beta\right)Lh^2\sum_{n=0}^{\infty} a^2n^2 exp\left(-2n^2h^2\frac{L}{\beta}\right) - \frac{16}{15}L^2h^4\sum_{n=0}^{\infty} a^n exp\left(-2n^2h^2\frac{L}{\beta}\right) -\right.$$

$$\frac{\sqrt{\pi}}{2}\sum_{n=0}^{\infty} a^n erfc\left(nh\sqrt{\frac{2L}{\beta}}\right)\left\{nh\sqrt{\frac{2L}{\beta}}2\beta(2-\beta)+\frac{8}{3}n^3h^3(2L)^{\frac{3}{2}}*\frac{1}{\sqrt{\beta}}(1-\beta)-\frac{8}{15}n^5h^5(2L)^{\frac{5}{2}}*\frac{1}{\sqrt{\beta}}\right\}12\beta\left(\frac{1}{3}-\frac{2}{15}\beta\right)\sum_{n=0}^{\infty} a^{n+1}exp\left(-2\,(n+1)^2h^2\frac{L}{\beta}\right)12(\frac{2}{3}\frac{3}{5}\beta)Lh^2\sum_{n=0}^{\infty} a^{n+1}\,(n+1)^2\,exp\left(-2(n+1)^2h^2-\frac{1}{\sqrt{\beta}}\right)\frac{16}{5}L^2h^4\sum_{n=0}^{\infty} a^{n+1}(n+1)^4exp\left(-2(n+1.)^2h^2\frac{L}{\beta}\right)-\frac{3}{2}\sqrt{\pi}\sum_{n=0}^{\infty} a^{n+1}erfc\left((n1)h\sqrt{\frac{2L}{\beta}}\right)\left\{2(n1)h\sqrt{\frac{2L}{\beta}}\beta(2-\beta)+\frac{8}{3}(n+1)^3h^3(2L)^{\frac{3}{2}}\frac{1}{\sqrt{\beta}}(1-\beta)-\frac{8}{15}(n+1)^5h^5(2L)^{\frac{5}{2}}\frac{1}{\sqrt{\beta}}\right\}\Bigg| \qquad (5)$$

where $erfc(x)=1-\mathrm{erf}(x)$, a $erf(x)=\frac{2}{\sqrt{\pi}}\int_0^x \exp\,(-\xi^2)d\xi$ is the error function of the parameter *x*.

The following dimensionless parameters are introduced in (5):

$L=\frac{Vl_o}{2k_1}$ is a dimensionless sliding speed in the contact zone of bodies;

$\beta=\frac{\tau V}{l_o}$ is a dimensionless coordinate that determines the position of an arbitrary point C on the contact area and a dimensionless coordinate that determines the position of an arbitrary point C on the contact area (see Fig. 1). Point *A* corresponds to $\beta=0$, point *O* corresponds to $\beta=1$, $\beta=2$, $h=\frac{I_h}{Io}$ 2; $h=I_h/I_o$ is relative thickness of the surface layer.

Results and Discussion. The scheme of contact of a gear transmission with coatings of thickness I_{hj} is considered as an example of tribological coupling. In the most general case, we consider that the surface layers and the main material of the contacting bodies have different thermophysical characteristics λ_{kj} and k_{kj}, where kj =1,2 are indices corresponding to the designation of the layer number and the number of the contacting bodies, respectively.

Using relations (4; 5), we obtain the following expression for the flash temperature on the surface of the *j*th body:

$$\Theta_j=\frac{2k_{1j}*q_o}{\pi\lambda_{1j}V_j}*T_j \qquad (6)$$

Using relations (4; 5), we obtain the following expression for the flash temperature on the surface of the *j*th body:

where T_j is determined from equation (5) by substituting $\lambda_1=\lambda_{1j}$; $k_1=k_{1j}$; and $\lambda_2=\lambda_2$; $k_2=k_{2j}$.

If we assume that the temperature of the surfaces of the contacting bodies is the same, and the amount of heat released at the contact area is determined by the heat transfer coefficients (ψ to the first body and $1-\psi$ to the second body), then we obtain the following expression for the flash temperature at the contact area:

$$\Theta=\psi\frac{2k_{11}*q_o}{\pi\lambda_{11}V_1}*T_1 \qquad (7)$$

The heat transfer coefficient is determined by the expression:

$$\psi=\frac{k_{12}\lambda_{11}T_2V_1}{k_{12}\lambda_{12}T_1V_2+k_{12}\lambda_{11}T_2V_1} \qquad (8)$$

The heat transfer coefficient is determined by the expression:

The maximum value of the intensity of the heat flux released at the contact area is calculated by the formula:

$$q_o=\frac{3}{4l_o}\delta fP_L(V_1-V_2)\,, \qquad (9)$$

The heat transfer coefficient is determined by the expression:

where f is the friction coefficient, P_L is the running load, δ is the coefficient of the considered load, the value of which depends on the geometry of the contacting surfaces and the operating features of the structure in the contact zone.

The dependences of the flash point on the main parameters of tribological coupling are nonlinear. From the analysis of relation (5) it follows that at $\omega=1$ the maximum flash point is achieved at $\beta=1{,}5$. The main interest is in cases where $\omega<1$, i.e., surface layers of contacting bodies have improved thermal properties. In this case, the maximum value of the flash temperature T_{max} corresponds to the condition $1{,}5<\beta<2$ the value T_{max} itself shifts towards the rear boundary of the heat source as the parameter ω decreases. This corresponds to the fact that with an increase in thermal conductivity in the surface layers λ_1, the maximum value of the flash temperature T_{max} is achieved at points *C* of the contact pad (Fig. 1), which are shifted to the rear zone of the heat flow front, which is a consequence of the thermal “inertia” of the system.

The results of calculating the flash point in the contact zone in the presence of coatings made of various materials are shown in Fig. 2, where the concept of coating efficiency coefficient is introduced, which is defined as:

$$K_{\mathrm{c}} = \frac{max\Theta}{max\Theta_o}, \qquad (10)$$

Here $max\Theta$, $max\Theta_o$ are the maximum flash point values for contacting surfaces with and without coating, respectively. This coefficient characterizes the decrease in flash point ($K_{\mathrm{c}} < 1$) or its increase ($K_{\mathrm{c}} > 1$) in the contact zone (in calculations: $K_{\mathrm{c}} = 1$ for shuttle steel) in the presence of a coating.

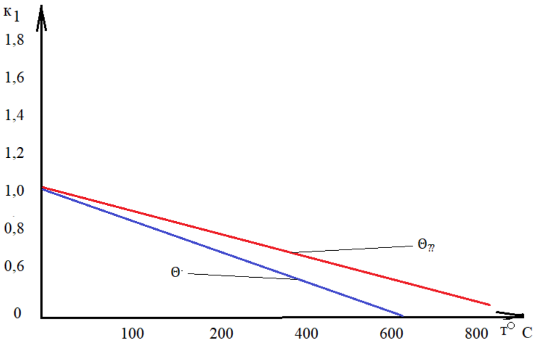

Fig. 2. Dependence of the flash point on the efficiency coefficient of coating the shuttle socket with the bobbin of a sewing machine. $max\Theta$ is flash point of a needle with coating; $max\Theta_o$ is flash point of a needle without coating

Conclusion. The results obtained show that the use of copper coating is effective from the point of view of reducing the flash point in the contact zone. The consequence of a decrease in the flash point is a decrease in volume and surface temperatures, which has a positive effect on lubrication conditions and, as a consequence, on increasing the wear resistance of the shuttle mechanism of sewing machines. The calculations carried out confirm the high efficiency of introducing antifriction coatings on the surfaces of contacting parts of tribological interfaces to reduce the flash point. This leads to an improvement in the operating temperature in the contact zone and, as a consequence, to a decrease in wear on the surfaces of contacting parts and an increase in the durability of the shuttle with a bobbin during tribological coupling.

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