Aspects of thermal field by wide burnishing

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Abstract: This research features 3D model of development of thermal fields by wide burnishing. By development of 3D model the source of heat build-up is represented as additive aggregate of connecting by width of spot heat sources, operating on the surface of the tool.

Introduction
An important aspect affecting the quality of the part's surface layer, is the roughness and performance of the tool during operation by using methods of surface-plastic deformation is the temperature of the tool and part, including contact area between them.

A model of thermal pattern of the process of smoothing without lubricants was created, allowing estimating the temperature effects in the contact area between the treated surface and the burnishing tool. Determination of the thermal pattern allows to develop the technological limitations of the process in terms of two factors:
- possible structural transformations in the surface layer after burnishing, which can affect the quality performance of the machined surface;
- wear rate of the tool and the ability to predict tool life at the stage of the process planning that plays an important role in the burnishing technology stability in mass production.

Research of Reznikov A.N. features a block diagram of the total heat transfer during burnishing \cite{1} (Fig. 1), separate components of the solids are represented as separate components (burnishing tool and part) involved in the process system. The author mentioned “in order to rationally organize the burnishing process, providing the most efficient performance and creation of conditions for normal operation of diamond, it’s necessary to define the temperatures, appearing on the contact surface of the later”. In accordance with the block diagram establish theoretical calculation to determine the temperature dependence over a wide burnishing, including contact area. For different types of processing SPD methods heat is released to a certain extent. Therefore, the source of heat in the developed model is three-dimensional. However, by schematization of the problem, an assumption accepted that the sources operating in the area of contact of indentor with the blank are two-dimensional. Now, let us consider the laws of heat flow density distribution in the volume of heat area.
Thermal field model while burnishing by a wide self-adapting tool
As the results of solving the problem of Hertz are shown on the contact of two cylinders of limited length with parallel axes, the contact patch shape is a rectangular. Therefore, at small depths t, characteristic for wide burnishing let us represent heat sources as two-dimensional rectangular shape \( b \times l \), located on the surface of the blank (moving source \( J_1 \) and \( J_2 \); and stationary source on the surface of the tool \( J_3 \) and \( J_4 \), see Fig. 1).

The density distribution of these sources can initially be rendered as equal (Fig. 2a), although linear or normal distribution is more accurate (Fig. 2b, c).

Let us more precisely consider the problem of the distribution of the intensity of the heat on the contact area of the indentor with the part. For the burnishing process the issue described in details in [2]. The author put forward a proposal for a normal distribution. It is confirmed by the fact that the nature of the thermal intensity corresponds to a change of the degree of strain hardening (change of micro hardness), which almost corresponds to the normal distribution [3, 4].

Therefore, to clarify the calculation of the temperature by a wide burnishing procedure we accept normal distribution of temperature on the \( x \)-axis in the direction of the tool (Fig. 2c):

\[
q(x) = q_{\text{max}} \cdot \exp \left[ -k \cdot \left( \frac{2(x - 0.5l)}{l} \right)^2 \right],
\]

where \( k \) - coefficient characterizing the concentration of heat flow in the focus of deformation in the direction of flow; \( q_{\text{max}} \) - maximum heat flux in the center of the contact area.

\[
k = \frac{\pi \cdot l}{\Delta}
\]

where \( \Delta \) – the thickness of the plastically deformed layer of machined material.

For the actual burnishing process conditions factor is concentrated within a range of from 5 to 6 - when the processing of high-hardened steel (HRC 62 ... 64); 3 ... 4 - when processing steel hardness of 40 ... 50 HRC and not more than 2.5 ... 3 - carbon steel processing in the state of delivery and non-ferrous metals [2].

To solve the problem we schematize the shape of solids existing in the process system.

Tools (burnishing tool) schematized as half-space, on the surface of which acts rectangular flat heat source dimensions \( b \times l \).
A part, due to the small size of the source in the \( l \) direction of movement in relation to the size of the items, as the half schematized as a half space, onto surface of which a flat rectangular heat source size \( b \times l \) is moving at a speed (Fig. 2).

Such a transition at schematization of the shape of the part is considered in [2]. In the present research we investigated the amendments made to the calculation of the temperature at such transitions. The need for such amendments in the calculation of the temperature in a wide burnishing discussed in more detail below.

However, it is necessary to make a comment. Subsequently, the calculation should take into account the overall temperature of the accumulation of heat in the tool during the \( N \) cycles of processing time. This condition is taken into account through the calculation of non-stationary thermal pattern in the tool [5, 6].

Considering the boundary conditions on the surfaces of solids, not occupied by heat sources or sinks. As a first approximation we take these surfaces as adiabatic, provided the process of smoothing without cooling cutting fluid. If necessary to take into account the effect of the lubricant should introduce additional heat sinks into considered structural diagram.

Consider the definition of the maximum heat flux \( q \) at the contact surface with the heat source power \( Q_u \).

For equal distribution law (Fig. 2, a):

\[
q_{\text{max}} = \frac{Q_u}{b \times l}.
\]  

(3)

For a linear distribution law (Fig. 2, b):

\[
q_{\text{max}} = \frac{2Q_u}{b \times l}.
\]  

(4)

For a normal distribution of heat source (Fig. 2, c):

\[
Q_u = b \cdot q_{\text{max}} \int_0^l \exp \left[-k \left( \frac{2 \cdot \left( x - 0.5 \cdot l \right)}{l} \right)^2 \right] \, dx
\]

(5)

For convenience of integration displace the origin along the \( x \) axis to the point \( x = \frac{l}{2} \) and introduce the notation \( R = \frac{l}{2} \).

Formula (5) will take on appearance of:
\[ Q_u = b \cdot q_{\text{max}} \int_{-R}^{R} \exp \left[ -k \left( \frac{x}{R} \right)^2 \right] \cdot dx \]  

(6)

Let us integrate and transform the formula (6) with respect to \( q_{\text{max}} \).

\[ q_{\text{max}} = \frac{Q_u}{b \cdot \sqrt{\pi R} \cdot \text{erf} \left( \sqrt{k} \right)} \]

(7)

**Definition of basic dependencies for calculating temperatures**

To derive the mathematical laws apply the method of heat sources [1].

The total capacity of the heat source is described by

\[ Q = P_{Z'} \cdot \psi \]

(8)

Where \( \psi \)- indenitor movement speed; \( P_{Z'} \) - the main component of the force during machining.

Expressing thermal source power through the normal force \( P_N \) and friction coefficient \( f \), let us put down (8) in the form of:

\[ Q = P_{Z'} \cdot \psi = P_N \cdot f \cdot \psi \]

(9)

As noted in [7], while plastic contact (burnishing) the coefficient of friction includes \( f_{\text{def}} \), deflection \( f \) and adhesive components \( f_{\text{adh}} \):

\[ f = f_{\text{def}} + f_{\text{adh}} \]

(10)

An adhesive component [7] is negligible for most materials \( f_{\text{adh}} = 0.01 \ldots 0.05 \), and depends on the material and surface roughness, not the machining modes.

The deformation component can be determined by the approximate formula:

\[ f_{\text{def}} = m \cdot \frac{h_b}{R}, \]

(11)

where \( h_b \) - the depth of the burnishing tool penetration; \( R \) - radius of the operating part; \( m \) - the coefficient depending on the parameter of support surfaces (at by burnishing \( m = 0.2 \ldots 0.55 \)).

The research features [8] the experimental dependence of the friction coefficient \( f \) of micro hardness at burnishing different steels, which shows that \( f \) is found in the range of values of \( f = 0.04 \ldots 0.08 \). There are also some general estimates of the magnitude of the coefficient of friction at different burnishing materials \( f = 0.03 \ldots 0.12 \).

In the solution of the obtained problem the expression for the coefficient \( b^* \), which describes the share of heat going into the tool:

\[ b^* = \frac{1}{1 + 2 \cdot \sqrt{2} \cdot \frac{\lambda_q}{\lambda_n} \cdot \sqrt{\frac{V \cdot L}{a_n}}}, \]

(12)

The research features [9] a rather more general dependence of \( \beta_f \), taking into account the ratio of \( q \) and heat, leaving a tool with respect to heat, \( Q_t \) obtained by parts surface:

\[ \beta_f = \frac{Q_u}{Q_n} = \frac{\lambda_u}{\lambda_n} \cdot \frac{a_u}{a_n} \]

(13)

Thus, the proportion of heat going into the tool and the part can be determined according to the formula, respectively:
\[ Q_u = b^* \cdot Q; \quad Q_n = (1 - b^*) \cdot Q \]  \hspace{1cm} (14)

or

\[ Q_u = \frac{Q \cdot \beta_b}{1 + \beta_b}; \quad Q_n = \frac{Q}{1 + \beta_f} \]  \hspace{1cm} (15)

**Calculation of the temperature in the tool using heat sources approach**

As an initial expression let us attribute known expression for the isolated continuous source intensity \( q_{\text{max}} \), located in unlimited body:

\[ \Theta(x, y, z) = \frac{q_{\text{max}}}{4\pi \lambda R} \left(1 - \text{erf} \left[ \frac{R}{\sqrt{4\omega}} \right] \right) \]  \hspace{1cm} (16)

Where \( \lambda \) – heat-conduction coefficient, \( \text{J/(m·s·ºC)} \); \( \omega \) – temperature conductivity coefficient, \( \text{m}^2/\text{s} \); \( R = \sqrt{(x_u - x)^2 + (y_u - y)^2 + (z_u - z)^2} \).

Considering adopted at schematization body shape (half-space), taking into account the principle of sources reflection, the transition to the final expression multiply it by 2.

Since the source adopted located on the part’s surface, we attribute \( y_u = 0 \).

It is necessary to carry out the integration of the original mathematical expression for the corresponding coordinates. This requires taking into account the shape and size of the heat source, source reflection principle, the nature of the intensity distribution on the heating contact surface schematization body shape, etc [10, 11]. Since the source adopted located on the surface tool, attribute \( y_u = 0 \).

Integrating over \( x_u \) and \( z_u \) within the contact area, we obtain for the case of uniform density distribution of the heat source:

\[ \Theta(x, y, z) = \frac{q_{\text{max}}}{2\pi \lambda} \cdot T_2(x, y, z) \]  \hspace{1cm} (17)

\[ T_2(x, y, z) = \int\int \frac{1 - \text{erf} \left[ \sqrt{\frac{(x_u - x)^2 + (z_u - z)^2 + y^2}{4\omega}} \right]}{\sqrt{(x_u - x) + (z_u - z) + y^2}} \cdot dx_u \cdot dz_u \]  \hspace{1cm} (8)

In case of the normal distribution in one direction of the heat source, depending on (17, 18) are transformed as follows:

\[ T_2'(x, y, z) = \int\int \exp \left[-k \left(\frac{2(x_u - 0.5l)}{l}\right)^2 \right] \times \] 

\[ \left(1 - \text{erf} \left[ \sqrt{\frac{(x_u - x)^2 + (z_u - z)^2 + y^2}{4\omega}} \right] \right) \] 

\[ \frac{1}{\sqrt{(x - x_u)^2 + (z - z_u)^2 + y^2}} \] 

\[ dx_u \cdot dz_u \cdot \]  \hspace{1cm} (18)
Results and Discussion
Figures 3-4 present the results of calculations using formulas (17-19). From these graphs we can see that the maximum temperature is reached by the center line of contact between the burnishing tools and the machined surface. As by classic burnishing [12], the magnitude of temperatures that occur during the normal speed burnishing (5 ... 25 m / min), do not exceed the critical temperatures by which would be structural changes in the surface after burnishing [13, 14, 15] that has no negative impact on the surface quality indicators.

![Figure 3. The temperature distribution on the surface by burnishing with a force F = 8000 N, and \( \nu \) = velocity of 10 m / min, high-duty cast iron 75-50-03 (HRC 45) ](image)

![Figure 4. Dependence of the average temperature in the contact area by the wide burnishing high-duty cast iron 75-50-03 on speed: 1- P = 40 N/mm; 2 - F = 56 N/mm; 3 - 80 N/mm](image)

Conclusion
1. Understanding of conditions of heat build-up and thermal distribution and their quantitative evaluation on the final stages of treatment of the parts is always challenging, because there is a possibility of negative and nonreciprocal effect onto the development of performance properties of treated parts. This issue gains particular importance during treatment, including burnishing using no means of lubrication.

2. The calculation data, received with the help of this 3D model of heat fields development could be further used by prognostication of wear process of the burnishing tool, which is relevant by treatment using no means of lubrication.
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