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Thermophysical Properties of Heat-Resistant Steels and Alloys in Machining

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***Abstract*—The paper suggests a technique to determine thermophysical properties of heat-resistant steels and alloys in machining. The method of sources serves the basis for the technique. Three heat sources are considered: primary chipping zone, contact area between a tool face and chipping, contact area between a tool clearance and a detail. The results on heating of the processed material are received.**

***Keywords*—heat-resistant steels and alloys; machining; thermophysical properties; temperature; method of sources**

I. Introduction

The machining of heat-resistant steels and alloys causes the decrease of tensile strength σ_u and the yield point σ_{ys} of a processed detail with the increase in cutting temperature. Some heat-resistant alloys have plasticity drops [1] in the temperature range of 750-1100°C. The specified fact is connected with high viscosity of heat-resistant alloys and sensitivity to thermomechanical surface actions. The specified phenomena and their influence on thermophysical properties of materials require in-depth theoretical and experimental studies. The study of the influence of the specified properties on heating of a processed workpiece near the cutting zone deserves special attention. The value, nature and rate of heating substantially define the properties of a surface layer and, hence, the quality of detail.

II. Methods and Materials

The method of sources was used to study thermophysical properties of metals and alloys in machining [2, 3]. Fig. 1 shows the scheme of sources of thermal fields in a cutting zone: 1 – chipping; 2 – detail; 3 – tool; AB – flow line; Φ – shear angle; γ – tool rake; α – tool clearance; V – cutting speed; V_1 – chipping speed; l_{AB} – flow line length; l_1– contact line length between chipping and tool rake; l_2 – contact line length between detail and tool clearance; q_p – heat source intensity in a primary chipping zone (along the flow line AB); q_{1p} – heat source intensity in a primary chipping zone for chipping; q_{2p} – heat source intensity in a primary chipping zone for a detail; q_{1t} – heat source friction intensity on a contact area between a tool rake and chipping for chipping; q_1 – heat source friction intensity on a contact area between a tool rake and chipping for a tool; q_{2t} – heat source friction intensity on a contact area between a tool clearance and a detail for a detail; q_2 – heat source friction intensity on a contact area between a tool clearance and a detail for a tool.

According to A.N. Reznikov's classification of thermal sources and drains, the considered heat source can be coded as follows:

• for a detail – two-dimensional, banded source limited by one coordinate axis, evenly distributed, fast-moving within an established process, half-space, Newmann's boundary condition;

• for chipping – two-dimensional, banded source limited by two coordinate axes, evenly distributed, fast-moving within an established process, core, Newmann's boundary condition.

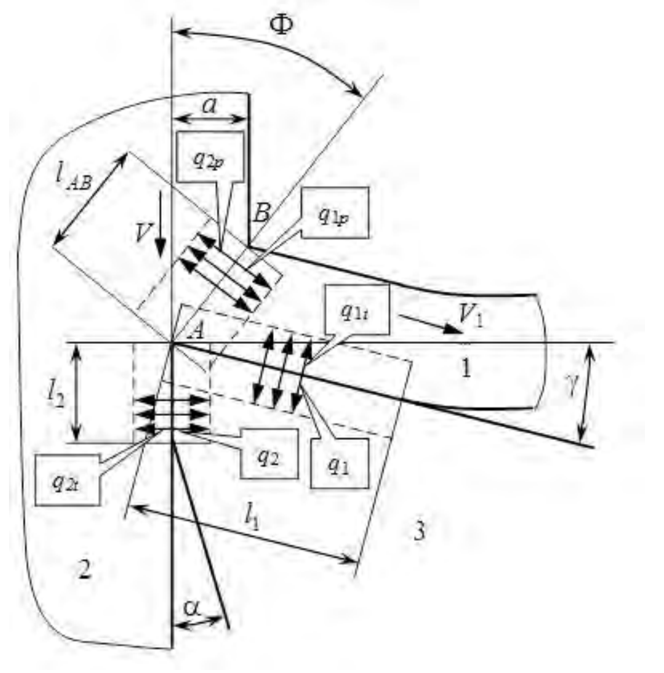

Fig. 1. Sources of thermal fields in a cutting zone

Part of temperature in a shift plane taken for chipping T_{1p} and for a detail T_{2p} is defined by the following formulas:

$$T_{1p} = T_p \, k_{ch} ; \tag{1}$$

$$T_{2p} = T_p \left(1 - k_{ch}\right), \tag{2}$$

where k_{ch} – coefficient considering part of heat transmitted to chipping [1]; T_p – temperature in a primary chipping zone (along the flow line AB),

$$T_p = \frac{k_m \, \omega \, \sigma_{ys} \sqrt{a \, V} \cos\gamma}{\left(k_m \, \lambda \sqrt{a \, V} \, \sin\Phi + \lambda \sqrt{\pi \, \omega \tan\Phi}\right) \cos(\Phi - \gamma)},$$

where σ_{ys} – yield point of a processed material; λ – heat conductivity of a processed material; ω – coefficient of heat diffusivity of a processed material, k_m – correction factor for heat-resistant alloys [2, 3].

As an example, let us define temperature T_p for the following conditions: alloy 1 – $NiCr20TiAl$; alloy 2 – $Ti1$; alloy 3 – $2Cr13$; section thickness a=0.2 mm. Fig. 2 shows the values of temperature T_p for specified materials. Fig. 2 shows that $NiCr20TiAl$ alloy has the largest temperature. This corresponds to estimated and experimental results made in works [2-4].

It is necessary to define the temperature of chipping between a tool rake and chipping T_{ch} for correct choice of temperature-dependent mechanical characteristics of processed materials σ_u, σ_{ys}, σ_y taking into account the temperature in a primary chipping zone T_{1d} defined by formula (1). It is defined by the following expression:

$$T_{ch} = \left(1 + k_{Tch}\right) T_{1p} + T_{1t} , \tag{3}$$

where k_{Tch} – coefficient considering the heating of surface layers of a chipping material taking into account technology factors [2]; T_{1t} – friction temperature on a contact area between a tool face and chipping for chipping.

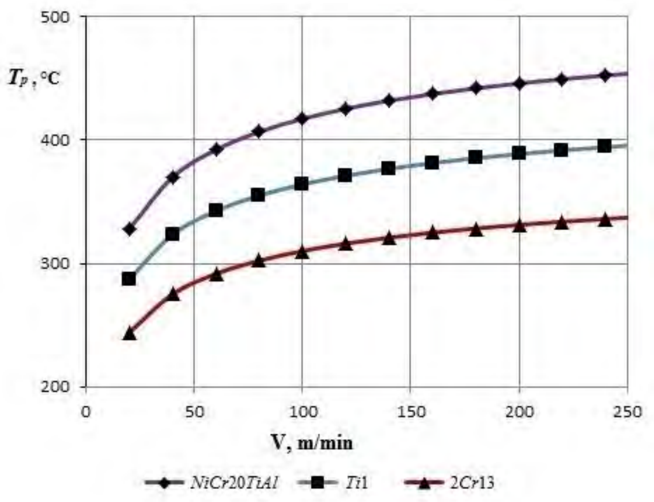

Fig. 2. Dependence of temperature in a shift plane T_p on cutting speed for processed alloys $NiCr20TiAl$, $Ti1$, $2Cr13$

Temperature T_{1t} averaged through the contact line is defined by the following expression:

$$T_{1t} = \frac{k_{T1t} \, L_{ch}}{\lambda} \sqrt{\frac{\omega \, \zeta \, l_1}{V}} q_{1t} ,$$

where k_{T1t} – reduction coefficient of units; L_{ch} – coefficient of a form of distributed heat source between a tool rake and chipping; ζ – chip shrinkage factor.

The contact line length between chipping and a tool face l_1 in relation to processing of heat-resistant alloys is well described by Abuladze's formula [3]

$$l_1 = a \zeta^{\varepsilon} \left[\zeta \left(1 - 2\operatorname{tg}\gamma\right) + \frac{1}{\cos\gamma} \right] ,$$

where ε – correction factor.

The intensity q_{1t} of a heat friction source on a contact area between a tool rake and chipping for chipping according to formula (3) is defined by the following expression [2, 3]:

$$q_{1t} = \frac{V \, F_{ch}}{b_1 \, l_1 \, \zeta} k_{q1t} ,$$

where b_1 – chipping width; $b_1 = b \, \zeta$; k_{q1t} – reduction coefficient of units; F_{ch} – friction force between a tool face and chipping.

The results obtained in works [4-10] were used to define the components of cutting forces under various processing conditions.

As an example let us define the chipping temperature T_{ch} for the following conditions: alloy 1 – $NiCr20TiAl$; alloy 2 – $Ti1$; alloy 3 – $2Cr13$; section thickness a=0.2 mm (Fig. 3). There are high temperatures in a chipping zone, which corresponds to experimental results given in works [3, 4].

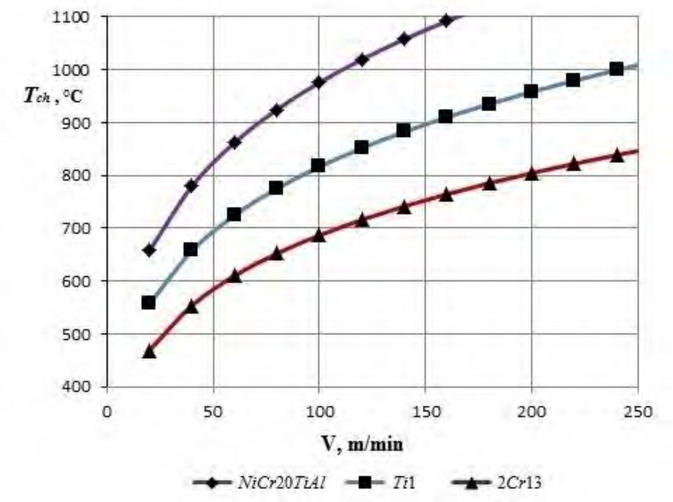

Fig. 3. Dependence of chipping temperature T_{ch} on cutting speed for processed alloys *NiCr*20*TiAl*, *Ti*1, 2*Cr*13

The temperature formed on a processed surface of a detail T_d by analogy with (3) is defined by the following expression:

$$T_d = \left(1 + k_{Tch}\right) T_{2p} f_{Td} + T_{2t}, \qquad (4)$$

where f_{Td} – function displaying the temperature distribution law on a contact area of a tool with a detail caused by the deformation heat; $f_{Td} \approx \sqrt{1+\vartheta} - \sqrt{\vartheta}$; ϑ – argument, $\vartheta = \frac{l_2}{2a} \tan \Phi$, $l_2 = h_f$, h_f – flank land of a cutting tool.

The first part in expression (4) represents temperature of a detail from a primary chipping zone. The formula (2) shows that with the increase in cutting speed it may be neglected. The friction temperature T_{2t} on a contact area between a tool clearance and a detail is defined by the following expression:

$$T_{2t} = \frac{k_{T2t}}{\lambda} \sqrt{\frac{\omega l_2}{V}} q_{2t}, \qquad (5)$$

where k_{T2t} – reduction coefficient of units.

The intensity q_{2t} of a heat friction source on a contact area between a tool clearance and a detail according to formula (5) is defined by the following expression:

$$q_{2\text{T}} = \frac{V F_d}{b \, \ell_2} k_{q2t},$$

where k_{q2t} – reduction coefficient of units; F_d – friction force between a tool clearance and a detail [4-10].

As an example let us define the chipping temperature T_d for the following conditions: alloy 1 – *NiCr*20*TiAl*; alloy 2 – *Ti*1; alloy 3 – 2*Cr*13; section thickness *a=0.2* mm; flank land h_f = 0.2 mm (Fig. 4). Fig. 4 shows rather high temperatures on a contact area between a tool clearance and a detail, which corresponds to experimental results given in works [3, 4].

Fig. 4 shows that the temperature values formed on a processed surface of a detail T_d and calculated by the formula (4) depend on a flank land volume. Let us consider the temperature T_d at variation of a flank land h_f = 0.2 … 0.8 mm for the processed alloy *NiCr*20*TiAl*. Fig. 5 shows the calculation results. The figure shows that the maximum permissible value of a flank land for the considered processed material shall not exceed 0.4 mm. Another limiting factor is the cutting speed, which at a flank land of h_f = 0.5 mm shall not exceed 120 m/min.

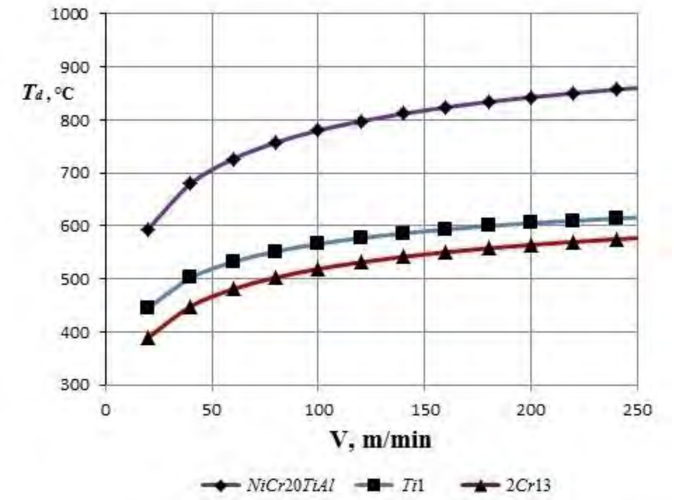

Fig. 4. Dependence of temperature T_d on a contact area between a tool clearance and a detail on the cutting speed for processed alloys *NiCr*20*TiAl*, *Ti*1, 2*Cr*13

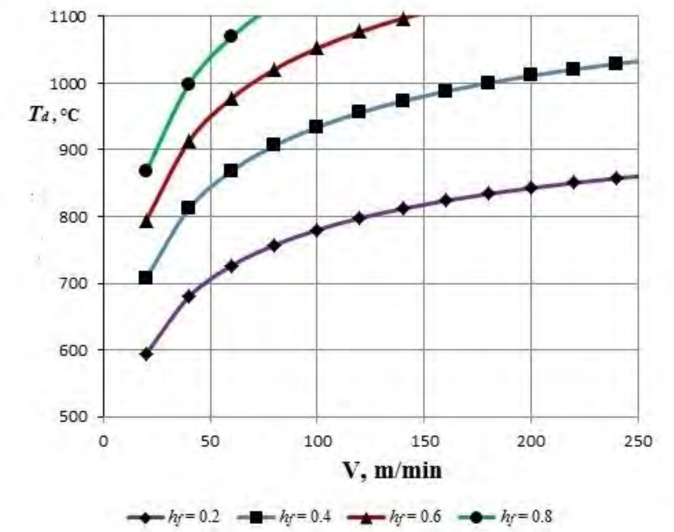

Fig. 5. Dependence of temperature T_d in a contact zone of interaction of a detail with a tool clearance on the cutting speed for the processed alloy *NiCr*20*TiAl* at variation of a flank land h_f = 0.2 … 0.8 mm

The heat source on a contact area between a tool clearance and a detail is mobile.

The time of passing the contact area with the length of $l_2 = h_f$ makes

$$\tau = \frac{l_2}{V}.$$

Within the studied cutting speed ranges the time τ changes according to the diagram presented on Fig. 6. Over time τ the temperature formed on a contact area gets into a metal surface. To assess the heat penetration let us use two comparable dimensionless groups [2]:

- relative temperature $t_h = T_h / T_d$;
- the dimensionless coordinate $H = \sqrt{\frac{V}{\omega l_2}} h$,

where h – the depth of the metal layer from the detail surface; T_h – temperature at depth h; T_d – the temperature at the surface of the detail.

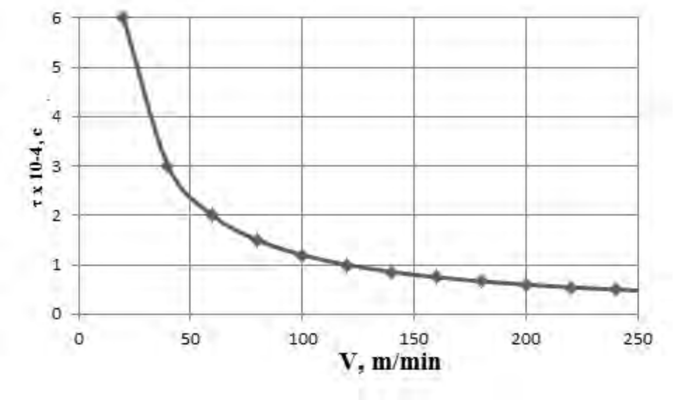

Fig. 6. Diagram of time dependence of a contact area between a tool clearance and a detail on the cutting speed

The correlation between complexes characterizes the weakening of temperature at corresponding depths of a metal surface. Let us consider the characteristic correlations:

$$H = 1.0;\ t_h = 0.4 \ \rightarrow \qquad T_h \approx 0{,}4\, T_d\ ; \tag{6}$$

$$H = 2{,}0;\ t_h = 0{,}1 \rightarrow \qquad T_h \approx 0{,}1\, \mathrm{T}_d\ ; \tag{7}$$

$$H = H_{\text{м}} = 3{,}0;\ t_h = 0{,}02 \ \rightarrow T_h \approx 0{,}02\, T_d\ . \tag{8}$$

The correlations (6)-(8) define the nature of temperature weakening in metal depth. At the same time the temperature on a surface of a processed detail is define by the formula (4). To define the maximum depth of the changed temperature let us pick the last one (8) corresponding to this depth from correlations obtained in (6)-(8). Considering the obtained groups it is possible to connect the maximum penetration depth of changed temperature $h_{\text{м}}$ with thermophysical and kinematic characteristics presented by the following correlation:

$$h_{\text{м}} = H_{\text{м}} \sqrt{\frac{\omega l_2}{V}}\ .$$

As an example let us determine depth $h_{\text{м}}$ for the following conditions: alloy 1 – *NiCr*20*TiAl*; alloy 2 – *Ti*1; alloy 3 – 2*Cr*13; section thickness a=0.2 mm; flank land $l_2 = h_f = 0.2\,\text{мм}$. Fig. 7 shows the dependence diagrams $h_{\text{м}}$ on the cutting speed for specified materials.

It is necessary to find out whether the temperature accumulates in a metal depending on rotations of a detail. For this purpose let us define time of one rotation of a detail τ_r, for example with a diameter of 60 mm, and let us compare it with time of passing the contact area τ_h. Time τ_r is three orders more than time τ_h. The detail cools down per one rotation. The temperature does not accumulate. The cutting coolant almost does not influence the temperature stresses since cutting is carried out on juvenile (clean) surfaces of a detail, which the cutting coolant cannot reach.

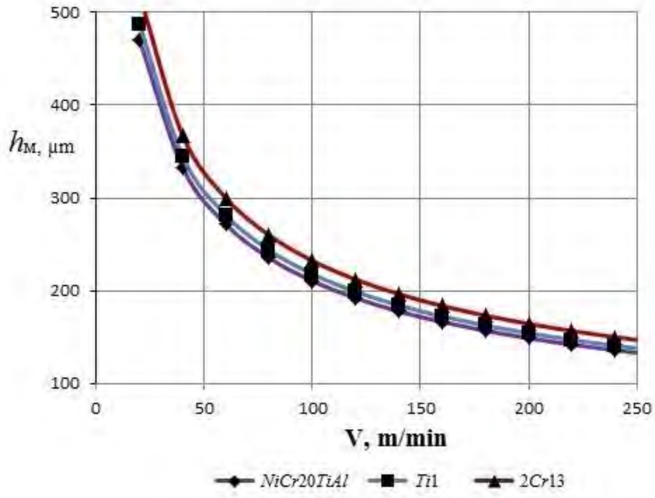

Fig. 7. Dependence of the maximum penetration of the changed temperature $h_{\text{м}}$ on the cutting speed for processed alloys *NiCr*20*TiAl*, *Ti*1, 2*Cr*13

III. Conclusion

The study results in the following conclusions:

1. The method of sources, which served the basis for model solutions, turned to be highly efficient in the study of thermophysical characteristics of heat-resistant steels and alloys.

2. The heat sources on contact areas of a tool face and chipping and a tool clearance and a detail are more intense than the heat source in a primary chipping zone along a flow line. The cutting heat makes a dominating contribution to heat release.

3. Heat is strongly distributed between sources throughout the wear of a tool. With the increase of a flank land from 0.2 mm to 0.8 mm the temperature on a contact area between a tool clearance and a detail will increase up to two times thus reaching invalid values.

4. The touch time of a tool clearance with the respective surface area of a detail has time constant of 10^{-4}c. This surface area cools down per one rotation of a detail. This leads to another important conclusion, i.e. phase-structural changes cannot be created on a detail surface for such a short period.

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