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Investigation of the properties of hardened steels during cutting based on the thermomechanical approach

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Abstract. The analysis of widely used dependencies for determining the mechanical characteristics during steel cutting is given. Based on the description of the scheme of the deformation zone when turning hardened steels, the laws of hardening and softening of the processed material are determined. It was revealed that the temperature, which leads to the localization of a part of the deformation in a narrow region of the chip formation zone, significantly affects the change in the properties of hardened steel during cutting. To describe this dependence, a thermomechanical approach is used that takes into account dynamic factors and the mutual influence of temperature and yield strength. The calculated values of shear stresses and temperatures are compared with experimental data.

1. Introduction

Determination of mechanical characteristics during cutting is the main step in the calculation of forces and temperatures during cutting. In the well-known literature [1], the hypothesis of a single flow curve for cutting and stretching, or the hypothesis of the equality of specific work during cutting and compression, was most often used to describe mechanical properties. It was also noted that as the characteristics of the resistance of materials during cutting, it is necessary to use the average tangential stresses in the chip formation zone (τ_y), which depend only on the tensile characteristics and are not dependent on other cutting conditions [2]. However, these hypotheses are valid only for cutting conditions of annealed, normalized or improved steels, since when machining hardened steels, due to a wider range of strength characteristics and, accordingly, temperatures, the use of these hypotheses is not justified and, as a rule, in calculations, leads to get erroneous results. This may be due to the fact that at higher temperatures characteristic of the treatment of hardened steels, the softening of the processed material, caused by the influence of temperature, can be more significant than when processing less strong steels. Thus, the aim of this work is to take into account the effect of temperature on the properties of hardened steels during cutting.

2. Formulation of the problem

In cutting theory, a significant amount of research has been devoted to attempts to theoretically or experimentally determine tangential stresses. In [3], it is pointed out that in order to solve this problem, it is necessary to take into account the specific loading conditions of the cutting blade.
The experimental determination of shear stresses is the subject of a large number of works by N N Zorev [4], which compare the resistance to plastic deformation during cutting with standard data obtained in tensile tests. In this case, the equation establishing the relationship between the yield stress on shear under tension and the average shear stresses during cutting (τ_y) had the following form:

$$\tau_T = A(\varepsilon_u)^m, \tag{1}$$

where ε_u – is the true shift;
m – is the coefficient of strain hardening.

However, it was experimentally established that the average tangential stresses (τ_y) in the conditional shear plane with an increase in the final true shear in the chip formation zone not only did not increase, but either significantly decreased or remained constant with an increase in the true shear.
Therefore, the author made assumptions on the independence of tangential stresses during cutting from deformation (ε_u) and on the extrapolation of the law of simple loading (1) by the value of the true shift $\varepsilon_u = 2.5$.
Later in [3] it was proposed to take into account the influence of the strain rate (103 ... 105 $s\ -1$) on tangential stresses.
Today, in most works devoted to the determination of tangential stresses during cutting, the provision on the independence of the yield strength on the strain rate and temperature is used [5, 6]. However, the experimental data of N N Zorev points to a decrease in shear stresses with increasing strain. It was noted in [2] that such a regularity can be explained by the influence of temperature. Confirmation of this was also given in the works of V A Govorukhina and G L Kufareva, devoted to turning of hardened steel ShKh15. They made an attempt to take into account the influence of speed and temperature factors on stresses during cutting by introducing correction factors determined experimentally:

$$\sigma_p = B \cdot e_i^c + \left(27 \cdot \sigma_{0.2}^{0.35} - \sigma_{0.2}\right) - \sigma_t \ , \tag{2}$$

where $B \cdot e_i^c = \sigma_i$ is the voltage obtained during the static tests at room temperature;
$27 \cdot \sigma_{0.2}^{0.35} - \sigma_{0.2}$ $-$ correction for increasing stresses from the speed factor;
$(80.4 - 0.44 \cdot \sigma_{0.2}) e_i^{0.0035_{\sigma_{0.2}}} = \sigma_t$ $-$ the magnitude of the voltage reduction due to temperature.
However, the use of dependence (2) is limited by the conditions of the experiment, since when changing the cutting conditions, it is necessary to conduct research each time to determine new correction factors.
In addition, in domestic and foreign works, hypotheses are given about the independence of tangential stresses in the chip formation zone when cutting from the strain rate and temperature due to their mutual compensation. As a compensating factor in the works of Mac−Gregor and Fisher, the temperature modified by the strain rate was used. However, this hypothesis has not received experimental confirmation.
The influence of the speed and degree of deformation on the plasticity of a material when cutting by modern science has not been studied enough. Although taking this effect into account at high stresses and temperatures characteristic of cutting conditions, especially hardened steels, can significantly increase the accuracy of existing theoretical models. So, in recent years, a thermomechanical model of material resistance to cutting has been increasingly used. An example of such a model is the defining equation (3) [7], which relates the yield strength to the temperature, deformation, and strain rate of a material during cutting.

$$\frac{\tau_p}{S_b} = \frac{dA_W}{d\varepsilon} = A\left(\frac{\varepsilon}{\varepsilon_0}\right)^m \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{k\Delta T'} exp(-B\Delta T') \ , \tag{3}$$

where $A = \left\{\sqrt{3}\left[\sqrt{3}\ln(1+\varepsilon_z\right]^m\right\}^{-1}$, $\Delta T' = A_W A_1$, $A_1 = \frac{S_b}{C_V T_{\text{ïë}}}$.
τ, ε, and S_b are the current values of the characteristics of the material and the process during cutting; τ_0, ε_0, $\dot{\varepsilon}$, S_{b0} are the values of the characteristics of the material and the process under tension (i.e., at room temperature).
Similar dependences were obtained by other scientists [8].
To determine the properties of the processed material in the zone of chip formation and on the contact surface of the cutting tool and chips during cutting in the work of M Yu Levin was proposed to use the finite element method. The accuracy of the model was determined by the method of successive approximation of the calculated and experimental cutting forces. As a result, the ratio for determining the flow stress during cutting has the following form:

$$\bar{\sigma} = K\left(e^{aT} + Ae^{b(T-T_0)^2}\right)\left(\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_R}\right)(\bar{\varepsilon})^d \,, \tag{4}$$

where $\bar{\sigma}$ is the flow stress;
$\bar{\varepsilon}$, $\dot{\bar{\varepsilon}}$, $T -$ deformation, strain rate and temperature, respectively.
The parameter $\dot{\bar{\varepsilon}}_R$ was introduced to preserve the dimension and the coefficients a, b, c, A, K, T_0 are calculated by the least squares method.
However, equations (3), (4) and similar ones were developed and used to describe the cutting conditions of non-hardened steels and did not take into account the features of processing materials with higher hardness.
To calculate stresses in the conditional shear plane, the Johnson-Cook model [9] is also widely used:

$$\sigma = \left(A + B\varepsilon_p^n\right)\left(1 + c\, ln\frac{\dot{\varepsilon}_p^n}{\dot{\varepsilon_0}}\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right), \tag{5}$$

where ε_p is the effective plastic deformation, Tm is the melting temperature, Tris room temperature, A, B, c, n, m, ε_0 are model parameters, $K_{\dot{\varepsilon}} = 1 + c\, ln\frac{\dot{\varepsilon}_p^n}{\dot{\varepsilon_0}}$ is the dynamic coefficient.
This model allows you to relate stress, strain and strain rate to temperature. However, the influence of the temperature factor is taken into account as an independent variable, and since the temperature in the chip formation zone depends on deformation and yield strength, therefore, the application of this model for cutting conditions is impossible.
Based on the analysis of the considered models, the most accurate description of the change in the properties of the material during cutting is the thermomechanical model (3). However, it requires clarification for the cutting conditions of hardened steels.
Thus, the following tasks are set in the work:

- To determine the patterns of hardening and softening when cutting hardened steels, it is necessary to describe the schematization of the deformation zone.
- Determine analytically the dependence of yield strength on deformation for cutting conditions of hardened steels.
- To compare the calculated shear stresses and temperatures with experimental data obtained by cutting hardened steel.

3. Theory

Due to the fact that turning of hardened steels is accompanied by the formation of discharge chips, according to current concepts, it is advisable to divide the chip formation zone into two deformation regions A and A '(Fig. 1) [2].
When a material is deformed in a narrow region A, its hardening cannot be significant, as a result of which the yield strength is stabilized. The converse is also true that stabilization of the yield strength ($d\tau_T/d\varepsilon_p = 0$) is a necessary condition for the localization of strains in a narrow region. Moreover, according to prevailing ideas, the boundary of these two regions (A and A') should be considered the line on which the strain-strain hardening of the material is completely compensated by temperature softening. Thus, the adopted schematization of the chip formation zone allows not only the hardening of the material in region A', but also its possible softening in this region under the influence of the deformation temperature, which depends on the final true shear $\varepsilon_{\dot{e}}$ (Fig. 2) [2].
For an analytical description of the hardening process of hardened steel in region A' (Fig. 1), we use dependence (3). Given that the yield strength can be represented as the dependence of the specific work on the strain, therefore, equation (3) can be written in the following form:

$$\frac{\tau_p}{S_b} = \frac{dA_W}{d\varepsilon_p} = AK_\varepsilon\varepsilon_p^m\left(1 + \frac{AA_1B_\tau K_\varepsilon}{1+m}\varepsilon_p^{1+m}\right)^{-1} \tag{6}$$

where K_ε and B_τ are empirical constants characterizing the influence of the strain rate and temperature on the yield strength.

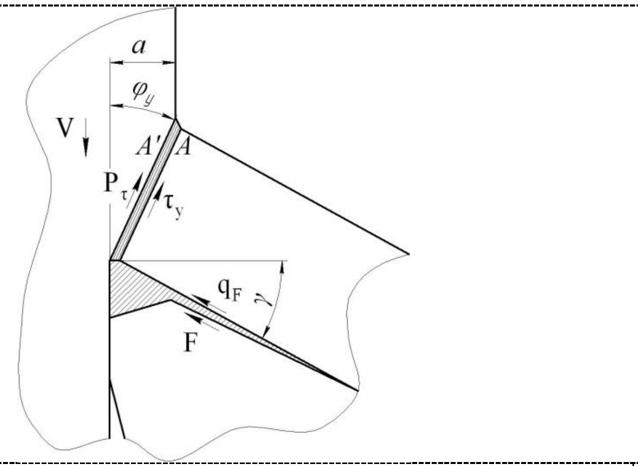

Figure 1. Scheme of the deformation zone in the plane of chip formation during the formation of discharge chips: A − is the region of large strains; A' − is the region of small strains; P_τ − is the tangent force in the conditional plane of shear; φ_y − is the angle of inclination of the conditional plane of shear; a − is the thickness of the shear layer; V − is the cutting speed.

To describe the mechanical properties during cutting at the boundary of regions A and A', due to the alignment of hardening and softening ($d\tau_T/d\varepsilon_p = 0$), we used the maximum values of yield strength ($\tilde{\tau}$) and the corresponding shear strain ($\tilde{\varepsilon}_\tau$):

$$\tilde{\varepsilon}_\tau = \left[\frac{m(1+m)}{AA_1B_\tau K_\varepsilon}\right]^{\frac{1}{1+m}} \text{ and } \frac{\tilde{\tau}}{S_b} = \frac{AK_\varepsilon\tilde{\varepsilon}_\tau^m}{1+m} \quad , \tag{7}$$

where $\tilde{\varepsilon}_\tau$, $\tilde{\tau}$ are the coordinates of the stationary point of the flow curve: the localized shift and the maximum yield stress of the processed material during cutting (Fig. 2).

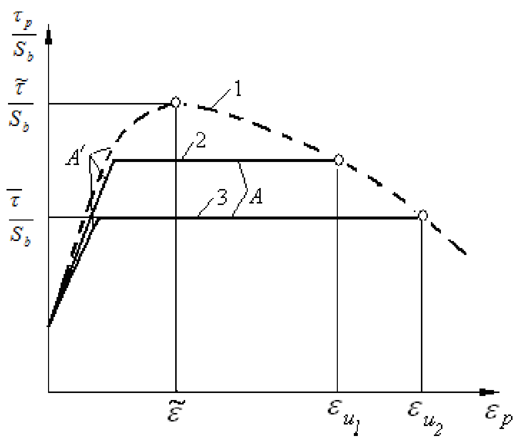

Figure 2. The dependences of the yield strength on the current true shear in the zone of chip formation: 1 − typical curve; 2, 3 − curves taking into account the localization of a part of the deformation.

Since the cutting mode and the geometrical parameters of the tool do not affect the maximum values of tangential stresses, these values can be taken as the initial mechanical characteristics of the material during cutting.
To describe the effect of temperature softening on the mechanical properties when cutting hardened steel in region A (if $\tau_p > \tilde{\tau}$), the equation is obtained:

$$\frac{\tau_p}{S_b} = \frac{\tilde{\tau}}{S_b}\left(1 - \frac{T' - T_0'}{1 - T_0'}\right), \tag{8}$$

where $T' = B_1 \cdot \frac{\tilde{\tau}}{S_b} \cdot A_1 \cdot \varepsilon_u$ is the homological strain temperature, B_1 is the coefficient that takes into account the decrease in shear stresses during strain localization under the influence of temperature.

4. Experimental results

Modeling the curve, taking into account the above schematization of the chip formation zone, showed that a change in the HB hardness from 1970 to 5000 MPa of the processed steel ShKh15 leads to an increase in the maximum tangential stresses at the boundary of regions A and A 'in the chip formation zone $\left(\frac{\tilde{\tau}}{S_b}\right)$ from 0.97 to 1.08. This is almost 1.7-1.9 times higher, respectively, than the shear yield strength determined in standard tensile tests ($S_b/\sqrt{3} = 0.577$). Moreover, due to the localization of deformations in region A (Fig. 3), the average tangential stresses $\left(\frac{\bar{\tau}}{S_b}\right)$ will be slightly lower: $\frac{\bar{\tau}}{S_b} =$ 0.79 (at HB = 1970 MPa) and $\frac{\bar{\tau}}{S_b} = 0.57$ (at HB = 5000 MPa).

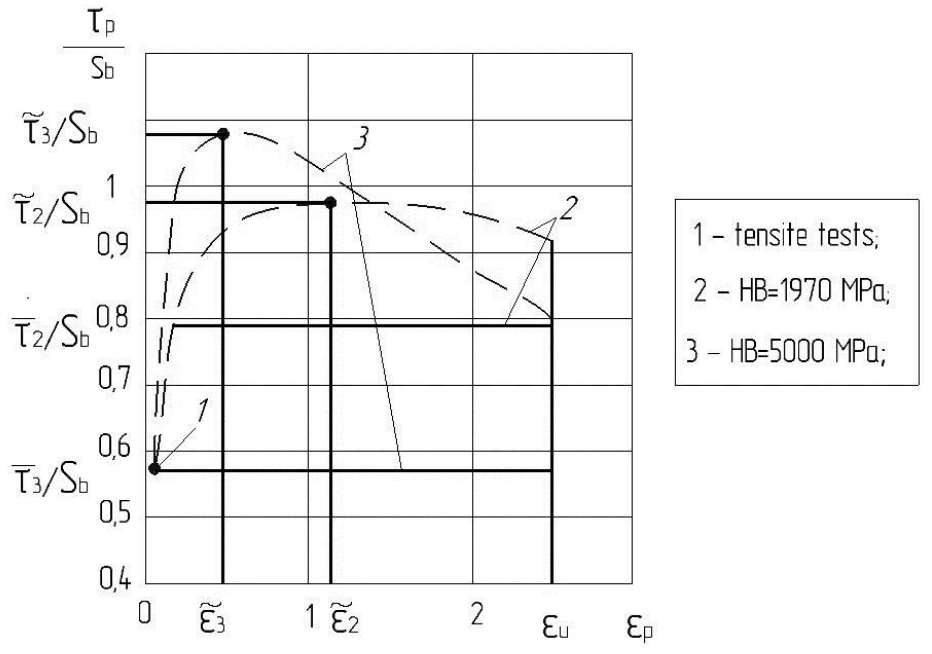

Figure 3. The dependences of the yield strength on the current true shear in the zone of chip formation: 1 – typical curve; 2, 3 – curves taking into account the localization of a part of the deformation.

The results obtained for non-hardened steel with a hardness of HB = 1970 MPa are in good agreement with the experimental data obtained by turning annealed steels [10].
To justify the decrease in the level of shear stresses in the field of chip formation with increasing hardness of steel, as well as to test the developed model, we will use the experimental data obtained when turning ShKh15 hardened steel with HB hardness from 3000 to 5000 MPa (Fig. 4). To exclude the influence of deformation on shear stresses, the corresponding experimental values $\left(\frac{\bar{\tau}}{S_b}\right)$, were chosen $\varepsilon_u = 2.5$.

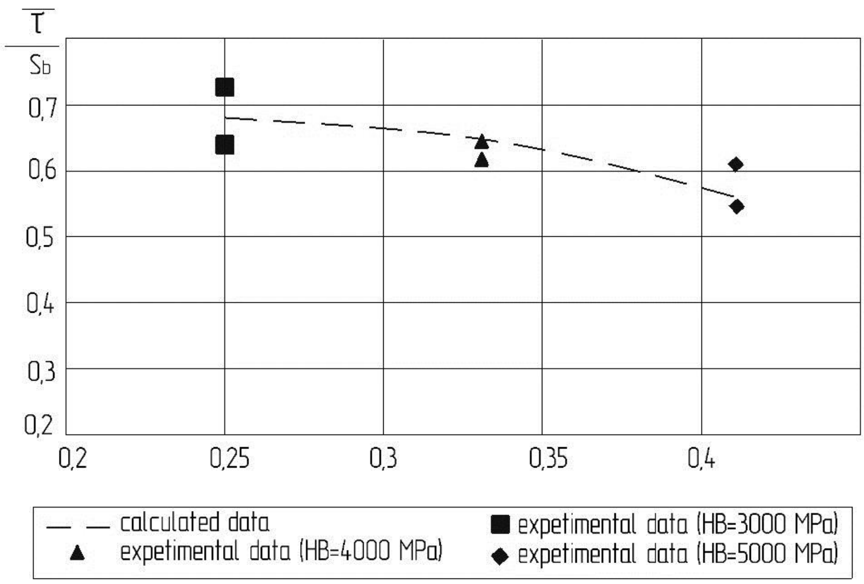

Figure 4. Comparison of average tangential stresses in the zone of chip formation when turning steel ShKh15 (t = 2 mm; S = 0.056 − 0.708 mm/rev; V = 7 − 140 m / min) cutter T15K6 (φ= 75 °; $\varphi_1 = 15^0$; $\alpha = \alpha_1$ = 8 °; γ = + 10 °; 0 °; −10 °; λ = 0 °; r = 0.3 mm).

The presented experimental data (Fig. 4) confirm the hypothesis about the influence of the temperature factor on shear stresses in the chip formation zone, while the calculation error does not exceed 10%.
Due to the fact that the material properties are used to calculate the temperatures during cutting, we will compare the temperatures calculated using the proposed model with the experimental data obtained when turning hardened steel. To calculate the temperature of the cutting tool, the well-known “TERM” procedure was used, which allows one to take into account the decrease in yield strength from temperature increase (Fig. 5) [7].

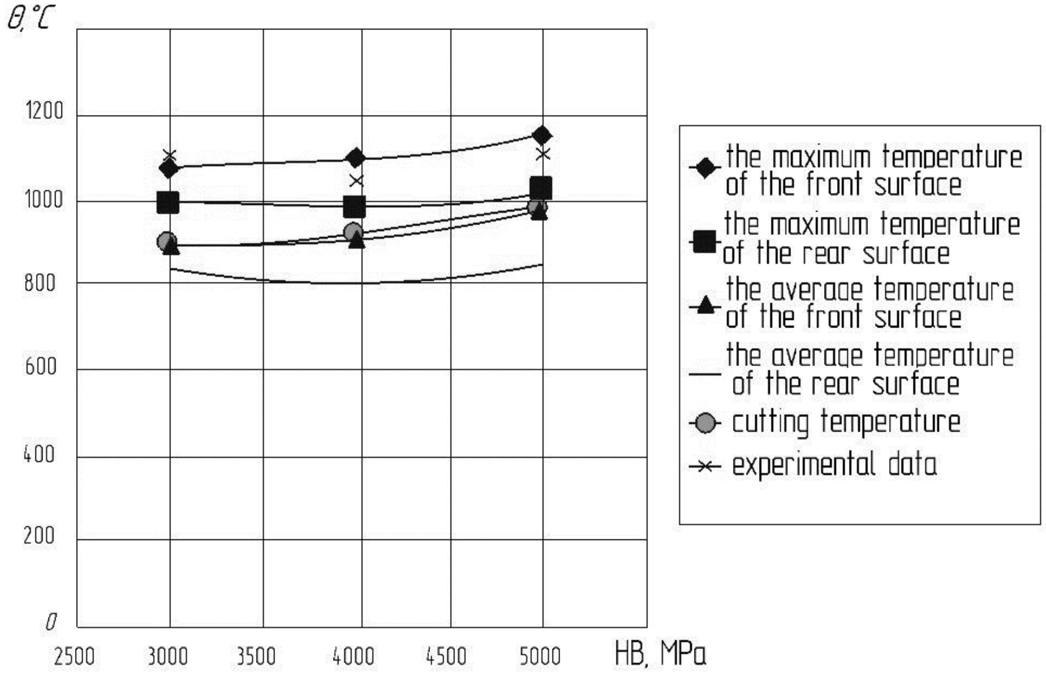

Figure 5. Comparison of temperatures during turning of hardened steel ShKh15 (t = 2 mm; S = 0.334; 0.522 mm / rev; V = 54.5 − 102 m/min) cutter T15K6 (φ = 75 °; φ_1 = 15 °; $\alpha = \alpha_1$ = 10 °; γ = 0 °; λ =0°; r = 0.3 mm; h_z = 0.1 mm).

The analysis of experimental data (Fig. 5) showed that the cutting temperature during turning of hardened steel exceeds 1040°C, although according to calculated data this temperature is in the range of 890 − 970°C. Therefore, when turning hardened steels as the temperature factor that most accurately describes the level and patterns of temperature changes with increasing hardness, it is necessary to use not the cutting temperature but the maximum temperature on the front surface. In this case, the discrepancy between the calculated maximum temperatures and the experimental data did not exceed 5%.

5. Discussion of results

Thus, when turning hardened steels with an increase in hardness, an increase in the maximum values of shear stresses $\left(\frac{\tilde{\tau}}{S_b}\right)$ of 1.7−1.9 times is observed in comparison with the yield strength for shear under tension. However, due to the localization of a part of the deformation in the chip formation zone, the level of average tangential stresses decreases significantly in comparison with the obtained values $\left(\frac{\tilde{\tau}}{S_b}\right)$ by 1.2−1.9 times under the influence of the temperature factor, which is confirmed by experimental data (Fig. 3). Consequently, the use of the hypothesis of constant shear stress widely used by many researchers for the conditions of machining hardened steels is impossible, as it will lead to significant errors in the calculation of cutting forces and temperatures.

Taking into account the influence of the temperature factor on the properties of hardened steels during cutting made it possible to increase the accuracy of calculating temperatures that turned out to be significantly higher than those observed during the treatment of non-hardened steels. In addition, the use of cutting temperature as a temperature factor in the treatment of hardened steels is not possible, since this temperature does not reflect the level of actually observed temperatures in experimental studies. It was revealed that the maximum temperature on the front surface of the cutting tool can serve as such a factor.

6. Conclusions and conclusions

- It is shown that the application of hypotheses about the possibility of spreading the law of simple loading and the constancy of specific tangential forces cannot be the basis for calculating tangential stresses (yield strengths) when cutting hardened steels.
- It was established that at large deformations characteristic of the cutting conditions of hardened steels, temperature softening prevails, and not strain hardening, which is characteristic of thermally not hardened steels.
- For the conditions of treatment of hardened steels with localization of deformation in the conventional shear plane, the dependences of the average tangential stresses necessary for calculating the temperatures during cutting are obtained.
- The developed model, taking into account the influence of temperature on the properties of the material being processed, has significantly improved the accuracy of temperature calculation during the treatment of hardened steels and determined as the temperature factor the maximum temperature on the front surface of the tool.

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