The influence of thermodynamical characteristics of high speed steels on temperature and forces values when turning construction steel

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Abstract. The article is devoted to the critical problem of studying the dependencies of temperature and cutting forces on the entropy of tool materials (high-speed steels - HSS). The high wear resistance of the cutting tool is closely related to the entropy of tool materials. However, the relationship of entropy as structural sensitive characteristic with temperature and forces during machining processes is poorly investigated. The experimental studies were carried out on the engine lathe with an infinitely variable regulation of spindle rotation frequencies, equipped with a measuring complex, allowing cutting forces and temperature recording at different cutting speeds. It has been established experimentally that at all cutting speeds in the studied range the smallest values of cutting forces and contact temperatures were characteristic for cutting tools made of HSS with high levels of thermal entropy. Thus, the thermal entropy of HSS can be used to the preliminary assessment of relative values of cutting forces and temperatures during the processing of steels which characteristics are strongly connected with wear rates and reliability of cutting tools.

1. Introduction
In modern automated production, a comparatively high proportion of cutting tools, especially small-size tools, is retained by tools, the working part of which is made of HSS. One of the main current trends of improving operating characteristics of cutting tool materials (CTMs) is to create new grades of HSS by improving their chemical composition with new alloying elements. The main channel of energy dissipation in the cutting zone during machining processes is thermal, and quantitative evaluation of the intensity of these processes can be made by temperature values estimation. The temperature values are affected by the load-speed parameters of the cutting process (cutting speed, depth, feed), the most significant of which is the cutting speed. It is the thermal factor, which is significantly dependent on cutting forces, that contributes to the increase in wear rates, and limits the cutting speed value when achieving heat resistance of tool material [1,2]. Currently, the performance properties of HSS tools, including their heat resistance, wear-resistance, and reliability, are improved by chemical-thermal treatment, deposited coatings, laser hardening methods etc. [3-5]. The relative increase of performance properties values of modified HSS tools in comparison with tools made of basic HSS grades are estimated mainly on the basis of experimental data. It is important to be able to predict a priori some operating and tribological properties of existing and newly developed HSS depending on their chemical composition by investigation of thermodynamic processes in the zone of
friction during cutting and receiving analytical dependencies for evaluation of friction and wear characteristics. The study of thermodynamic processes during friction and cutting has enabled the calculation dependence for the wear intensity to be obtained on the basis of the entropy balance equation [6]

\[
J = \left[ \frac{\int_{0}^{\infty} [P[S] - \Phi[S]] \, dx}{v \cdot S} \right] \cdot k ,
\]

where \(P[S]\) – entropy production; \(\Phi[S]\) – entropy flux; \(v\) – sliding (cutting) speed; \(S\) – original thermal entropy of the material; \(k\) – coefficient, taking into account the share of energy spent on wear.

From (1) it follows that the highest wear resistance values would be obtained for CTMs with higher values of the original thermal entropy \(S\). Thus, in the development of new HSS grades preference should be given to compositions characteristic by high levels of thermal entropy, which calculation is not difficult for heterogeneous structures of known chemical composition under the additive rule [7,8].

High-entropy CTMs also characterized by low values of absolute (relative) thermo-EMF and high surface dynamic micro hardness demonstrate better tribological characteristics and higher wear resistance in comparison with low-entropy materials [6,9-11]. They also tend to form highly effective shielding dissipative structures and show low values of friction coefficient for some of the materials being processed, including structural steels [11,12].

The aim of this work is to study the dependencies of cutting forces and temperature values in the cutting zone on cutting speed during processing work-pieces made of structural steel 45 considering the thermal entropy value of HSS as an integrated characteristic of CTM chemical composition. This study is part of a set of research into the cutting, operational and tribological properties of high-entropy CTM.

2. Materials and methods

The research was carried out on a lathe without using of cutting fluids. The exact values of the cutting speeds \(V\) were obtained using the frequency converter Mitsubishi. The spindle rotation frequencies \(n\) were controlled by the MEGEON 18005 laser tachometer with an accuracy of 0.5 rpm. To measure and record cutting force components \(P_z, P_y, P_x\) and cutting temperature \(T\) the STD.201-1 (Armenia) measuring system, equipped with the National Instruments interface unit obtaining the signal sampling frequency of 0.78 kHz, was used. The turning work-pieces of 45 structural steel (analog of steel grades 1044, 1045 – USA, 1.0503 – BRD and S45C – Japan) was made using specially made whole tools of 7 grades of HSS with different values of thermal entropy \(S\). The grade’s denomination, chemical composition and thermal entropy \(S\) of the HSS specimens are represented in the table 1.

| №  | Grade   | Chemical composition          | Thermal entropy \(S\), J·mol\(^{-1}\)·K\(^{-1}\) |
|----|---------|-------------------------------|---------------------------------------------|
| 1  | R6M3    | W(6%)+Mo(3%)+Fe               | 26.86                                       |
| 2  | R6M5    | W(6%)+Mo(5%)+Fe               | 27.26                                       |
| 3  | R6M4F4  | W(6%)+Mo(4%)+V(4%)+Fe         | 27.46                                       |
| 4  | R8M3F4  | W(8%)+Mo(3%)+V(4%)+Fe         | 27.53                                       |
| 5  | R18     | W(18%)+Fe                     | 28.04                                       |
| 6  | EP658   | W(6%)+V(2%)+Co(8%)+Mo(5%)+Fe | 30.60                                       |
| 7  | EP657   | W(12%)+V(2%)+Co(8%)+Mo(3%)+Fe | 30.78                                       |

The linear dimensions and the cutting part geometry of the HSS specimens are presented on figure 1. Cutting depth \(r=0.5\) mm, feed \(s=0.15\) mm·rev\(^{-1}\).
Figure 1. The linear dimensions and the cutting part geometry of the HSS specimens.

The cutting temperature $T$ was measured using the natural thermocouple method. Preliminary tarring was made by heating each of the seven “HSS - Steel 45” thermocouples and corrective coefficients were obtained to determine the temperature values $T$ in the cutting zone based on the relative thermo-EMF values recorded by the measuring complex. The statistical processing of the data was carried out by an algorithm composed of standard MathCAD functions for analysis of variance (ANOVA) using the methodology [13].

3. Results and discussion

Comparison of cutting forces for HSS of different grades was made by the average values of $P_{z_{avg}}$, $P_{y_{avg}}$, $P_{x_{avg}}$ without taking into account the initial and final cutting stages (figure 2).

Figure 2. Cutting forces components $P_z, P_y, P_x$ variations in time $\tau$ when turning by R18 tool ($S=28.04 \text{ J mol}^{-1} \cdot \text{K}^{-1}$), cutting speed $V=50.3 \text{ m min}^{-1}$.

Figure 3 (a), (b), (c), (d) shows the dependencies of the cutting forces and temperature in the cutting zone on the cutting speed. It is seen that the lowest averages of $P_z$, $P_y$, $P_x$ were recorded in the case of high-entropy HSS tools. Moreover, with the increase of the cutting speed value component
$P_{z\text{avg}}$ for high entropy HSS tools also increases, while for low entropy HSS tools there is a tendency to decreasing.

![Figure 3](image-url)

**Figure 3.** The dependences of $P_{z\text{avg}}$ (a), $P_{y\text{avg}}$ (b), $P_{x\text{avg}}$ (c) and contact zone temperature $T_{\text{avg}}$ (d) on cutting speed $V$ when turning steel 45 by HSS tools of different grades: 1 – R6M3; 2 – R6M5; 3 – R6M4F4; 4 – R8M3F4; 5 – R18; 6 – EP658; 7 – EP657.

The cutting force components $P_{y\text{avg}}$ and $P_{x\text{avg}}$ for all investigated HSS grades tend to grow with increase of cutting speed $V$. The high-entropy HSS are also characterized by lower temperature values $T$ in the contact zone at all cutting speeds $V$ of studied range (figure 3, (d)).

The presented data are well consistent with results of previous investigations of tribological properties of HSS specimens of the same grades under conditions of friction on structural steels without lubricant. Thus, as a result of tribological tests, when the levels of sliding speed and normal load were close to those characteristic to machining processes, lower friction coefficients, temperatures and wear intensity rates were recorded for high-entropy HSS specimens [6,10]. The same dependence of tribological characteristics on the HSS entropy was observed as a result of tests performed on tribometre which implemented the scheme of friction "pin on disc" at comparatively low pressure values. In this case, formation of dissipative shielding structures of considerable thickness, contributing to the separation of rubbing surfaces and acting as dry lubricant has been recorded for the specimens (pins) made of high-entropy HSS grades [12].
4. Conclusions
As a result of the study it has been established experimentally that at all cutting speeds in the studied range the smallest values of cutting forces and contact temperatures were characteristic for cutting tools made of HSS with high levels of thermal entropy. Thus, when choosing CTM for structural steels machining, and in the development of new HSS grades preference should be given to compositions characteristic by high levels of thermal entropy as obtaining better tribological characteristics and higher wear resistance together with potentially higher cutting speed and productivity values in comparison with low-entropy materials.

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