

Study increase the mechanical characteristics of tool materials by cryogenic treatment

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Abstract. In this work, the hypothesis of taking into account a specific thermoEMF to determine the degree of hardening of the cutting tool by cryogenic hardening is put forward, which is the most convenient and important value from the point of view of information content. As a result of studies of improving the mechanical characteristics of instrumental materials by cryogenic treatment, the values of the absolute and specific values of thermo emf were revealed depending on the temperature of three instrumental materials obtained by tarrying them together with platinum. The values of temperatures at the maximum values of the specific thermo emf, have been obtained. It was found that deep cooling of the metal increases the degree of ordering of its structure and increases the vibrational energy of the crystal lattice. The results of the study showed that the resistance of the cryogenic cutting tool increases by up to three times, this positively affects the energy efficiency of the use of such a tool in production. The reduction of energy costs is expressed in the reduction of kilowatt-hours associated with the costs of sharpening the tool and can reach up to 30% of the total amount of electricity consumed.

1 Introduction

Researchers [6] presented methods of hardening of cutting tools that are used for additional processing of ready-to-use tools, such as cryogenic treatment, which is not included in the list of recommended hardening methods [6]. There is an opinion [7] that cryogenic treatment, in particular in nitrogen, the boiling point of which is -195.8 °C, cannot be recommended for use as a special method of hardening. Studies on the effect of cryogenic treatment on the durability of drills, carried out at the Vilnius plant, showed [8] that:

- 1) the processing of finished high-quality drills made of steels S6-5-2S and S18-0-1 with liquid nitrogen does not have a tangible effect on the wear of cutting elements;
- 2) the processing of finished high-speed drills made of S6-5-2S steel with liquid nitrogen does not significantly increase the durability of drills with defects in mechanical heat treatment.

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In [8] it is shown that "third-party methods of treatment with liquid nitrogen" did not present any rigorous scientific hypothesis explaining the physical essence of the process of increasing the durability of a cutting tool immersed in liquid nitrogen.

However, [8] shows that the liquid nitrogen treatment did not obtain any rigorous scientific hypothesis explaining the physical nature of the process of increased stamina resistance of a low temperature treated cutting tool. At the same time, many studies emphasize the similarity of the structure of the cutting part material and stable hardness before and after treatment with liquid nitrogen.

P.P. Petrosyan conducted a fundamental study [9] of heat treatment of steel with cold. It is shown to them that cold treatment of S18-0-1 type steel swordsmen increases their resistance in 17,8 times, although decay of residual austenite can be accomplished by multiple tempering in fast-cutting steels; it is believed that with the correct heat treatment of these steels, the need for cold treatment no need, but the above example [9] convincingly shows the desirability of deep cooling for these steels as well, and mainly when the geometry of the article makes the heat treatment process difficult. "In addition, P.P. Petrosian research suggests that the treatment of cemented steel with cold before grinding completely eliminated cracking led to a 50% cheaper product. "Some researchers believe that the correct conduct of the normal heat treatment of fast-cutting steel (quenching and multiple tempering) perfectly ensures that the limits of quality are obtained under operating conditions and that cold treatment is only a correction of the irregularities that can be observed during the heat treatment of these steels. This point of view cannot be considered correct, if only because with the introduction of deep cooling, the number of tempering can be reduced to only one or two, and the tempering following cooling is carried out at a lower temperature (400-450 C), which ensures the preservation of higher hardness of martensite, and therefore increases the resistance of the tool as a whole"[1].

Studies [10, 11] show that cooling below 0 °C Celsius resumes martensitic conversion of residual austenite. Hardness at the same time increases by 0.5-2 HRC. And the more it is, the more austenite the hardened steel had when cooled to 15-20 °C. It is also stated in [10, 11] that cryogenic treatment is sufficient to be carried out with cooling up to - 78 °C (in a mixture of dry ice with gasoline) or up to - 60 (-70) OS in refrigeration units with exposure, which provides cooling of the cutting tool throughout the section.

However, it is necessary to bear in mind the following. These works dealt with the cryogenic processing of steels. The author [6] discovered an increase in the efficiency of solid alloy tools as a result of cryogenic processing, which requires a scientific explanation. In addition, opponents of the method object when it comes to liquid nitrogen. Thus, studies are needed over a wide range of negative temperatures to identify the need for liquid nitrogen or other cryogenic treatment media.

As shown above, on pages of technical literature there is no consensus on use of cryogenic processing (or "processing's by cold", "processing's by deep cold", "deep cooling", etc.) for increase in the cutting properties (hardening) of the cutting tool. For steels, this method is explained by the fact that for most of them the point M, the end of martensitic transformations lies below 0 °C [1], and its position varies depending on the chemical composition of the steels in the range -55... - 120 °C. In particular, [6] for steels: C105W1 - 60 °C, SK1 - 70 °C, 100Cr6 - 90 °C, 20Cr4 - 100 °C, 105WCr6 - 110 °C, S 18 1-2-5 - 70 °C, S6-5-2S - 100 °C (DIN). Moreover, in [6] it is shown that cooling below point M, does not lead to additional martensitic transformations.

As for hard alloys, that is, studies [6] of their hardening. And if quenching allows you to increase the cutting properties of hard alloys, apparently, processes similar to those that occur during quenching of steels are observed in them. Therefore, in cryogenic treatment in alloys, processes similar to those occurring in the treatment of steels should occur. If it turns out that solid alloys improve physical and mechanical properties during cryogenic

treatment, it will be necessary to determine the temperature (medium) for such treatment. The same applies to fast-cutting steel S6-5-2S, and cutting ceramics WOK60.

In industry, liquefied gases are used to obtain cryogenic temperatures: methane (boiling point $-161, 5\text{ }^{\circ}\text{C}$), oxygen [$-183\text{ }^{\circ}\text{C}$] argon ($-186\text{ }^{\circ}\text{C}$), nitrogen ($-195.8\text{ }^{\circ}\text{C}$). However, methane and oxygen are explosive, and liquid nitrogen is cheaper than argon. In addition, nitrogen is used along with other refrigerants to obtain higher cryogenic temperatures, particularly in refrigeration compartments.

In general, it should be assumed that cryogenic treatment, affecting defects in the crystal structure of instrumental materials, contributes to a decrease in the thermal activation of vacancies and the release of dislocations to the surface, which can lead to structural changes in materials with a corresponding improvement in their physical and mechanical characteristics, which leads to an increase in their cutting properties. This is a working hypothesis. Thus, appropriate experimental studies of fast-cutting steel, hard alloys, and cutting ceramics WOK60 are needed, after cooling into a temperature in the vicinity of $-195.8\text{ }^{\circ}\text{C}$, to find the optimal cryogenic temperature and explain the processes occurring in instrumental materials during cryogenic processing.

2 Materials and Methods

In this work, studies were carried out on hardness, microhardness, and thermoEMF after holding the plates S6-5-2S, hard alloys HG30 and HT01, and cutting ceramics WOK60 at various cryogenic temperatures in the range under consideration. Studies have found that each of the plates of a certain instrumental material has a spread of the values of these parameters, which can exceed for different vertices 3... 5%. Within one vertex, the spread is much smaller. Testing of cutting inserts was carried out with turning of casing drill pipes for couplings from carbonaceous steels of grades 25CrMo4, 36CrNiMo4, Ck45 (DIN, WNr), hardness NV255, yield strength = 637 MPa and impact viscosity KCV = 490 kJ/m² on a lathe using special equipment.

The test revealed that the resistance of a tool equipped with cutting plates S6-5-2S, HG30, HT01, and cutting ceramics WOK60 after cryogenic treatment increased by 1.09... 1.18 times. At the same time, cryogenic treatment of the plates was carried out with temperatures (218... 168) K⁰. The determination of other mechanical characteristics, such as flexural strength, impact toughness requires special samples from which the properties of materials can be evaluated only in general. In other words, they cannot characterize the state of the local zones of the cutting inserts, i.e., hardness and microhardness are most suitable for this purpose. Such a physical characteristic as a coercive force also reflects mainly the density of the material as a whole. ThermoEMF can characterize the local zone, which is the vertex of a polyhedral plate, very definitely.

Figures 1...4 show the values of the test parameters depending on the cryogenic temperatures at which the plates of instrumental materials were held. The initial values are hardness, microhardness, and thermoEMF of standard plates HT01, HG30 (DIN, WNr) and cutting ceramics WOK60 and the same in shape, which have undergone standard thermal treatment, steel plates S6-5-2S; on schedules values of initial parameters at T are specified = 293 K⁰ (the note: here and there is lower than the Kelvin temperature of symbol K⁰). Moreover, the thermal EMF was fixed both during the calibration of the plates paired with the plate (Figure 3), and during the cutting of casing drill pipes made of steel Ck45 and 32CrMo12 (Figure 4). The analysis of results of researches allows to draw a conclusion that the hardness of S6-5-2S steel increases most intensively in the temperature range (218...168) K⁰, it will be coordinated with given above to data on other steels. For hard alloys and cutting ceramics WOK60, a smoother increase in hardness is observed in the range of the analysed temperatures (Figure 1).

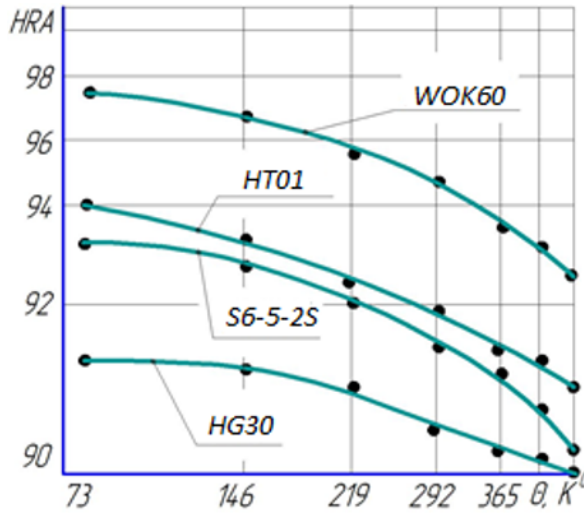


Fig. 1. Dependencies of hardness of tool materials on cryogenic treatment temperature

The microhardness (Figure 2) of plates made of hard alloys, cutting ceramics WOK60, and fast-cutting steel S6-5-2S increases accordingly to hardness, however, in the temperature range (168...77) K⁰ the intensity of its growth, like hardness, drops somewhat. The thermal EMF (Figures 3 and 4) decreases with a decrease in the cryogenic treatment temperature, having a minimum value at the boiling point of liquid nitrogen (77 K⁰).

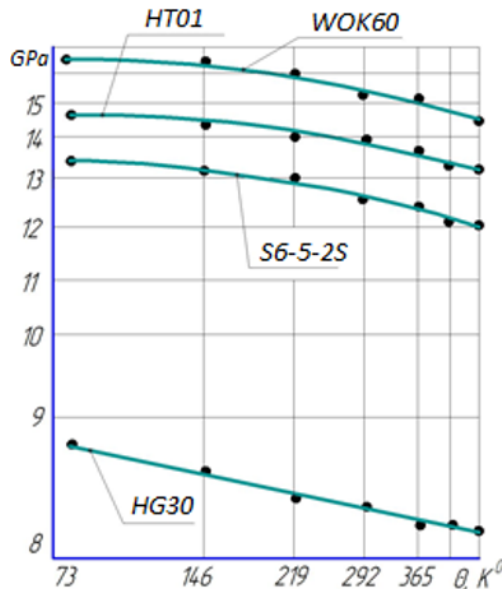


Fig. 2. Dependencies of microhardness of hard alloy plates HG30, HT01, cutting ceramics WOK60, and fast-cutting steel S6-5-2S, on the cryogenic treatment temperature

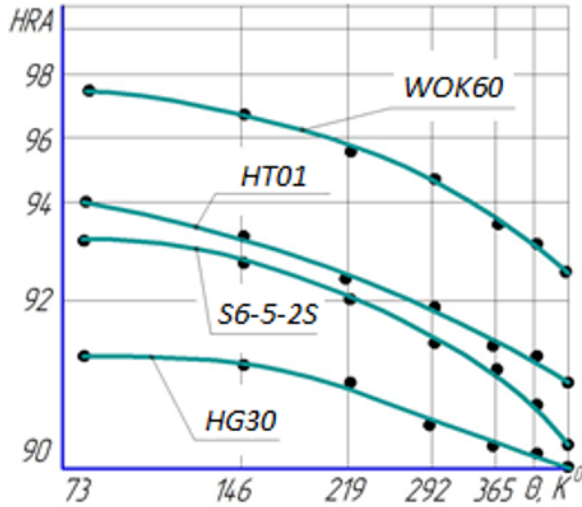


Fig. 3. Dependence of thermoEMF on cryogenic treatment temperatures during calibration of materials with platinum: WOK60, HG30, and HT01 = 873 K⁰; S6-5-2S = 673 K⁰ [1]

These experimental studies make it possible to conclude that it is necessary to use liquid nitrogen as a cryogenic medium since as a result of holding in it, the mechanical characteristics of thermoEMF are also maximally reduced. Such a change in the parameters under consideration should lead to an increase in the operability of the cutting tool. Furthermore, as shown above, the use of liquid nitrogen as a cryogenic medium is economically and technologically advantageous.

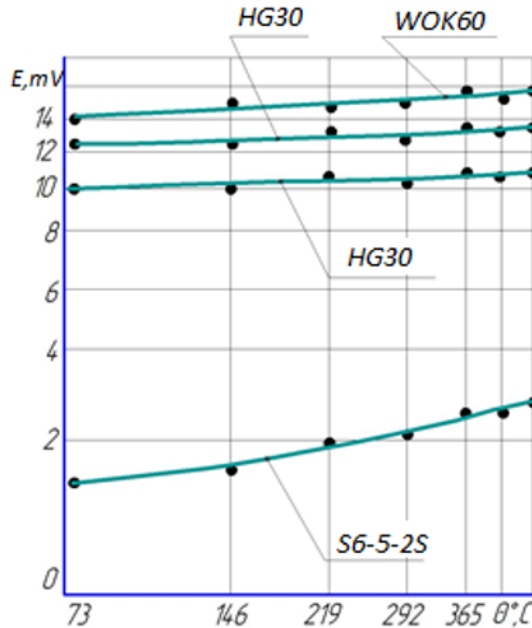


Fig. 4. Dependencies of thermoEMF on cryogenic treatment temperature obtained during turning of steels Ck45 and 32CrMo12. Cutting speed of HG30, HT01 and cutting ceramics VOK-60 - 66 m/min; S6-5-2S - 34.2 m/min, feed 0.21 mm/v, cutting depth 0.25 mm equal

2.1 Specific thermoEMF and Debye temperature

The thermoEMF method is used to explain the improvement of mechanical characteristics of tool materials after cryogenic treatment since it is known [2, 3, 18 – 20] that the change in thermoEMF can be fixed very accurately. Table 1 shows the values of absolute (E) and specific (a) thermoEMF depending on the temperature of three instrumental materials, obtained during their calibration in tandem with platinum. Index 1 denotes values of tested parameters before cryogenic treatment, index 2 - after cryogenic treatment. After cryogenic treatment, a decrease in thermoEMF is seen, which is an indirect confirmation of the proposed hypothesis. For further, more in-depth confirmation of the hypothesis put forward, the specific thermoEMF is considered, which is the most convenient and important value from informativity. At the end of the table, the temperature values at maximum values of specific thermoEMF are presented and the ratios of these temperatures, which are necessary for the future.

Table 1. Dependence of absolute (E, mV) and specific (a, mV/K) thermoEMF on temperature (θ , K⁰) of " S6-5-2S - Pt" pair

θ	313	393	473	553	633	673	753	833
E ₁	0,25	0,74	1,3	1,74	2,44	2,57	2,77	2,98
E ₂	0,18	0,57	1,0	1,49	1,9	2,04	2,18	2,37
$a_1 \times 10^{-4}$	7,99	18,8	27,5	31,5	38,5	38,2	36,8	35,8
$a_2 \times 10^{-4}$	5,75	14,5	21,1	26,9	30,0	30,3	28,8	28,4

Table 2. Dependence of absolute and specific thermoEMF on " HT01 - Pt" steam temperature

θ	313	433	553	673	793	913	1033	1153
E ₁	0,6	0,9	1,5	2,0	2,5	2,7	2,8	3,1
E ₂	0,4	0,7	1,2	1,6	2,2	2,3	2,4	2,6
$a_1 \times 10^{-3}$	1,92	2,08	2,71	2,97	3,15	2,96	2,71	2,69
$a_2 \times 10^{-3}$	1,28	1,62	2,17	2,38	2,77	2,52	2,32	2,25

$$\theta_1 = 753 \text{ K}^0, \theta_2 = 793 \text{ K}^0, \theta_{2D} = 1,026 \times \theta_{1D}$$

Table 3. Dependence of absolute and specific thermoEMF on " HG30 - Pt" steam temperature

θ	353	473	593	693	793	913	1033	1153
E ₁	1,3	2,7	4,2	5,2	5,8	6,5	6,8	7,0
E ₂	1,2	2,5	4,0	4,88	5,55	6,35	6,7	6,85
$a_1 \times 10^{-3}$	3,68	5,71	7,08	7,43	7,26	7,12	6,58	6,07
$a_2 \times 10^{-3}$	3,4	5,25	6,74	7,14	7,0	6,95	6,58	5,94

$$\theta_1 = 693 \text{ K}^0, \theta_2 = 713 \text{ K}^0, \theta_{2D} = 1,04 \times \theta_{1D}$$

It is known [2, 15 – 17] that in general the thermoEMF for a chain consisting of different metals is expressed by the formula:

$$E = \int_{\theta_1}^{\theta_2} a \times d\theta, \tag{1}$$

where a - specific thermoEMF, V/K, θ - current temperature K^0 .

When studying the temperature dependence of thermoEMF, it should be borne in mind that for metals there are two fundamentally different temperature regions separated by the Debye characteristic temperature, which is found on the ratio (2-5)

$$\theta_D = \frac{h \times \omega_m}{\mathfrak{R}}; \tag{2}$$

where h and \mathfrak{R} Planck and Boltzmann constants, respectively;

ω_m - the maximum frequency of elastic oscillations of the crystal lattice of the metal, depending on the number of atoms and molecules in the corresponding volume and the average speed of sound propagation in the metal.

At $\theta \gg \theta_D$ the same time, (high temperatures) the metal can be considered from classical positions; at $\theta \ll \theta_D$ (low temperatures) - quantum case; at $\theta = \theta_D$ - a transition region in which the classical and quantum behavior of the metal [2 – 10] is manifested to one degree or another. For most solids, the Debye temperature is about 10^2 K, that is, the metals in the cutting treatment are at temperatures corresponding to the most difficult, transition region. According to the studies of B. G. Livshitz [11, 12 – 15], the specific thermoEMF consists of two additive parts, the values of which can be of the same order but have different temperature dependence.

$$a_1 \sim a = a_1 + a_2, \tag{3}$$

Here, the first term is due to the assumption of the elasticity of electron scattering

$$a_1 \sim \frac{\theta}{e \times E_F}, \tag{4}$$

where e - is the charge of the electron, E_F - is Fermi's energy.

The first term is explained by the hypothesis of a phonon-electron interaction and at high temperatures has a temperature dependence

$$a_{21} \sim \frac{\theta_D}{e \times D}, \tag{5}$$

at low temperatures

$$a_{22} \sim \frac{\theta^n}{e \times D_D^n}, \tag{6}$$

where n is a measure of the degree that is determined by the Fermi-surface type; at $n = 2$ - open Fermi - a surface; at $n = 3$ - the closed Fermi - a surface.

In the transitional area, all three terms must obviously be taken into account.

Enter dimensionless value

$$X = \frac{\theta}{\theta_D}, \tag{7}$$

and corresponding proportionality factors A, B, and C.

Record for Transition Area

$$a = A_x + B_x^{-1} + C_x^n; \text{ where } A \sim \frac{\theta}{e \times E_F}, B \sim \frac{1}{e}; C \sim \frac{1}{e}; \tag{8}$$

This ratio can explain the decrease in thermoEMF after cryogenic metal treatment. The basis of this explanation is the physical hypothesis: with deep cooling of the metal, the degree of ordering of its structure increases, and the vibration energy of the crystal lattice increases. This means increasing and therefore. Qualitative analysis of dependence $a = a(\theta)$ supports this hypothesis. The Debye temperature for iron has a value of 467 K, which corresponds to the descending branch of the curve $a(\theta)$, located to the left of the point with the minimum a_{\min} value (Figure 5).

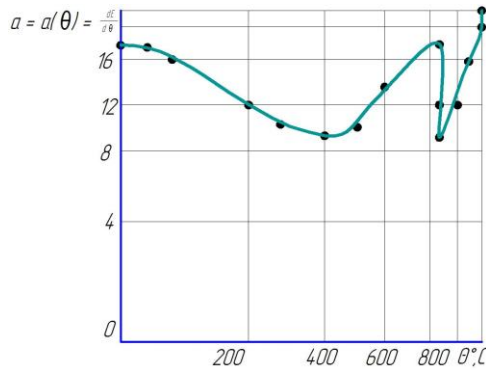


Fig. 5. ThermoEMF of thermocouple Fe - Pt up to 1500 °C

The constancy in some cases of the thermoEMF value after cryogenic treatment can be explained by assuming that for such materials the Debye characteristic temperature and the temperature corresponding to a_{\min} are very close.

The following are the results of experimental studies to determine the change in Debye characteristic temperature as a result of cryogenic treatment of instrumental materials based on the analysis of the dependence of specific thermoEMF on temperature - $a(\theta)$. Figure 6 shows, as an example, for clarity, the experimentally obtained thermoEMF specific temperature relationships for the HT03-platinum alloy pair. Both dependencies have a clearly expressed maximum at different personal temperatures: for curve 1 at $\theta_1 = 833 \text{ K}^\circ$; for curve 2 at $\theta_2 = 873 \text{ K}^\circ$. This circumstance is used to detect the shift of the Debye characteristic temperature θ_D .

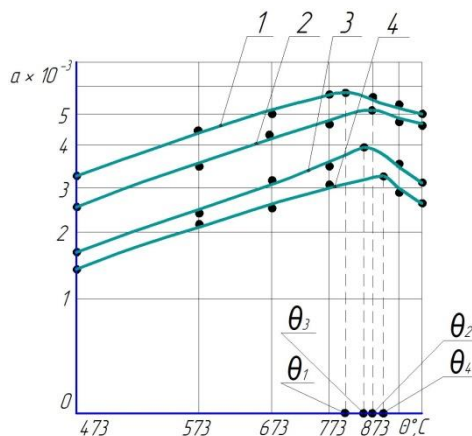


Fig. 6. Dependencies of specific thermoEMF on the temperature of pairs of alloys " HT01 - Pt" and "WOK60 - Pt": 1 - alloy " HT01 - Pt" to cryogenic treatment; 2 - alloy " HT01 - Pt" after cryogenic treatment; 3 - "WOK60 - Pt" before cryogenic treatment; 4 - "WOK60 - Pt" after cryogenic treatment

As shown above, the analytical dependence of the specific thermoEMF has the form (8). We investigate it at the extreme:

$$a' = A + (-1)Bx^{-2} + n \times cx^{n-1} = 0; \tag{9}$$

$$\text{or } x^{n+1} + \frac{A}{n \times c} \times x^2 - \frac{B}{n \times c} = 0.$$

Equation (9), depending on the index p, can be biquadrate or cubic. In our case, since there is only one extremum, equation (9) has one real root. With natural physical constraints on coefficients A, B, and C, this is possible only for the cubic equation. So $n = 2$ and equation (9) takes the form

$$x^3 + \frac{A}{2 \times C} \times x^2 - \frac{B}{2 \times C} = 0. \tag{10}$$

We substitute in this equation the expression for the coefficients A, B and C

$$A = \frac{K_1}{e \times E_F} \times \theta_D; \quad B = \frac{K_2}{e}; \quad C = \frac{K_3}{e}; \tag{11}$$

where K_1, K_2, K_3 are proportionality coefficients.

Let's also substitute the value get

$$y^3 = \frac{a}{\theta} \times y - \frac{\beta}{\theta^3} = 0. \tag{12}$$

$$\text{where } y = \frac{1}{\theta_D}; \quad a = \frac{k_1}{2 \times k_2 \times E_F}; \quad \beta = \frac{k_2}{2 \times k_3}.$$

When substituting for equation (12) the temperatures and, which account for the maxima on the curves, you can solve this equation with respect to the y value, the inverse of the Debye temperature. Solving equation (12) we calculate the value

$$Q = \frac{a^3}{270^3} + \frac{\beta^2}{4 \times \theta^6}. \tag{13}$$

This relationship shows that $\theta > 0$. This means that equation (12) has one real and two imaginary roots. We find the only real root according to the Cardan formula [2...5]

$$y = \sqrt{\frac{\beta}{2 \times \theta^3}} + \sqrt{\frac{a^3}{27 \times \theta^3} + \frac{\beta^2}{4 \times \theta^6}} + \sqrt{\frac{\beta}{2 \times \theta^3} - \sqrt{\frac{a^3}{27 \times \theta^3} + \frac{\beta^2}{4 \times \theta^6}}}; \tag{14}$$

or

$$y = \frac{1}{\theta} \times \left[\sqrt{\frac{\beta}{2} + \sqrt{\frac{a^3 \times \theta^3}{27} + \frac{\beta^2}{4}}} + \sqrt{\frac{\beta}{2} - \sqrt{\frac{a^3 \times \theta^3}{27} + \frac{\beta^2}{4}}} \right]; \tag{15}$$

Given the small E_F for electrons in the metal, it is believed that at any reasonable values of the proportionality coefficients $K_1, K_2,$ and K_3 inequality is fulfilled $a \gg \beta$. In this case, the expression in square brackets on the right side of formula (15) will be proportional to $\theta^{0.5}$ and therefore $y \sim \frac{1}{\theta^{0.5}}$. We emphasize that if in equation (15) you immediately neglect the term containing, then you get a similar result.

$$y = \sqrt{\frac{a}{\theta}}. \tag{16}$$

Most important is the following ratio $\theta_D \sim \theta^{0.5}$.

Thus,

$$\frac{\theta_{1D}}{\theta_{2D}} = \left(\frac{\theta_1}{\theta_2} \right)^{0.5}. \tag{17}$$

Substituting numerical temperature values into equation (17) and we get, for example, for the pair "HT03 - Pt." For other combinations of instrumental materials with platinum, similar relations are given at the end of tables 1 - 3.

3 Results

The results obtained on the increase in Debye temperature during cryogenic processing of instrumental materials confirm the validity of the proposed hypothesis, namely, the consideration of specific thermoEMF, as the most convenient and important value from the point of view of informativity. Experimentally obtained dependencies of specific thermoEMF on temperature for the pair "alloy HT03 - platinum." Both dependencies have a distinct maximum at different temperatures: for curve 1 at $\theta_1 = 833$ K; for curve 2 at $\theta_2 = 873$ K⁰. This circumstance is used to detect the shift of the Debye characteristic temperature θ_D . Experimental studies make it possible to conclude that it is necessary to use liquid nitrogen as a cryogenic medium, since as a result of exposure, mechanical characteristics are maximally increased in it, and thermoEMF is also maximally reduced. Such a change in the parameters under consideration should lead to an increase in the operability of the cutting tool. Besides, as shown above, the use of liquid nitrogen as the cryogenic environment is expedient from the economic and energy-efficient point of view as after cryogenic processing the wear resistance of the tool increases, less electric power when cutting in connection with the application of the rational modes of cutting is spent ($V = 34...67$ m/min; $S = 0.07... 0.21$ mm/r; $t = 0.25... 1, 0$ mm). In addition, the time for turning the cutting tool is reduced, which also saves electrical energy, as the resistance of a cutting tool equipped with hard alloy plates and cutting ceramics from 20 min to 50... 66 min increases, which as a result, electricity savings will be 30% on average from the total number of working equipment in the workshop.

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