

## Calculation of stored deformation energy in the surface layer of an item after machining

V F Bezyazychny<sup>1</sup>, M Szczerek<sup>2</sup>, M A Prokofiev<sup>1</sup>, M V Timofeyev<sup>1</sup>, A V Filippova<sup>1</sup>

<sup>1</sup> Rybinsk State Aviation Technical University named after P. A. Solovyov, 53, Pushkin St., Rybinsk, 152934, Russia.

<sup>2</sup> Technologies National Research Institute, 6/10 Pulashiego ul., Radom, 26 – 600, Poland.

E-mail: [tehnology@rsatu.ru](mailto:tehnology@rsatu.ru)

**Abstract.** This paper contains the research results from calculation of stored deformation energy in the surface layer of a sample with considerations for material hardening under deformation, i.e., change in its microhardness. A dependency was obtained describing changes in the stored deformation energy in the surface layer as a function of temperature. A dependence of interdislocational interaction parameter on temperature has been found out; the latter being a characteristic of the amount of energy stored in the surface layer. Correction of the calculated surface layer stored energy from cutting for temperature is performed by taking into account the dependency of the shear modulus of the processed surface material in the cutting zone on temperature, where the cutting zone depends on the processing condition (cutting mode and cutting tool geometry).

### 1. Introduction.

It is known, that dislocations in material lead to changes in interatomic interaction that leads to changes of the initial temperature of phase change, diffusive and other characteristics of the material, having a direct influence over the process of structural and phase changes and formation of stress-deformed state of the processed item [1, 5-7, 9-15]. Presence of the dislocation in the crystalline structure of material manifests in increased internal (stored) energy of the system.

M.A. Prokofiev has proposed a mathematical model that allows for calculation of the stored deformation energy  $W_{\text{spec}}$  (J/m<sup>3</sup>) from the parameter of the material's deformation flow curve,

$$W_{\text{yA}} = \frac{Q}{\alpha^2 G} (\sigma - \sigma_{0.2})^2, \quad (1)$$

where  $Q$  is the proportionality factor,  $Q = 0.5 - 1$ ;  $G$  is the shear modulus of the item's material, Pa;  $\alpha$  is the parameter of interdislocation interaction;  $\sigma$  is a stress necessary for movement of mobile dislocations, Pa;  $\sigma_{0.2}$  is the flow stress of the material, Pa.

Currently, unfortunately, there are no exact recommendations guiding the selection of the interdislocation interaction parameter for given materials when calculating the stored deformation energy with the formula (1), especially so for high temperature values. Thus, an objective was set to



determine the dependency of the interdislocation interaction parameter  $\alpha$  on temperature in the surface layer of material  $T$ .

## 2. Research Operation

V.M. Greshnov obtained an empiric dependence of the parameter  $\alpha$  on temperature for steel grades 10kp, 20kp, 20G2R and 38KhGNM for non-cutting shaping of metals [4]

$$\alpha = 0,159 \exp\left(\frac{100}{T}\right), \quad (2)$$

where  $T$  is the material temperature of the item, K.

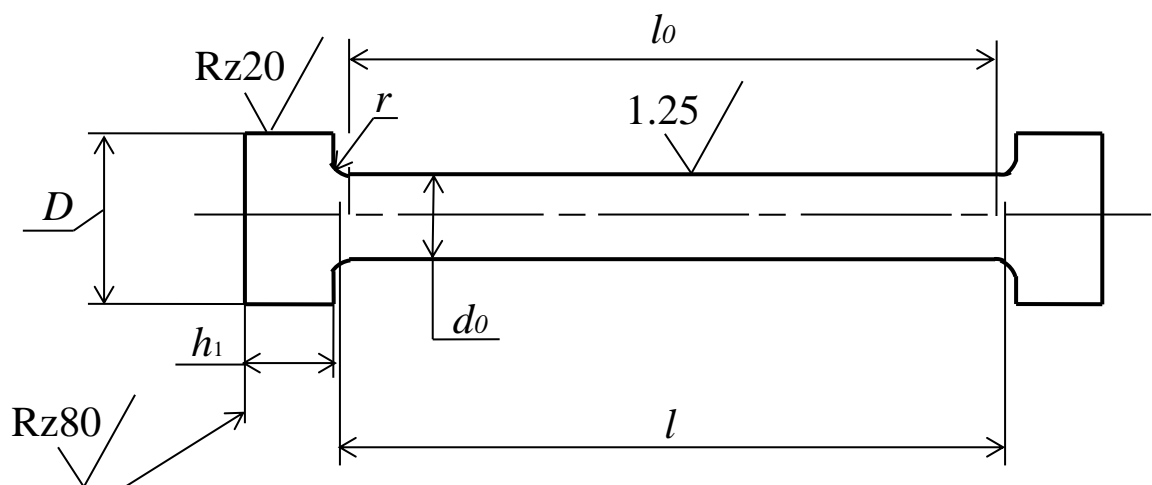
The formula (2) shows, that with increased temperature, the dislocation interaction parameter  $\alpha$  decreases. It may be explained by energy spent by dislocation for overcoming various obstacles being diminishing with increased temperature due to increased mobility of atoms [2]. Calculations for steels at 293K gives the value of the parameter  $\alpha = 0.224$ .

The task of studying the dependency of the dislocation interaction parameter  $\alpha$  on the temperature factor for other grades of material is of interest. A possibility to calculate the parameter  $\alpha$  and, as a result, the value of the stored deformation energy will allow extending the range of studied materials and revealing new regularities connecting the internal energy with temperature and elasticity modulus of various groups of materials being processed.

The authors has conducted experiments to study the temperature dependence of the interdislocation interaction factor and confirm the hypothesis of a common physical mechanism of absorption and dissipation of the plastic deformation, according to which a ratio of the stored material deformation energy (the energy of crystalline lattice defects) to the energy spent for deformation (to create those same defects) is a constant for the second stage of plastic deformation of metals and is equal to approximately 10% (7%...12%) of the energy spent [2].

The given definition of the hypothesis contains no information on the process of affecting the material, as it holds for elementary deformation processes of compression, tension and twist that inevitably accompany various types of metal processing with non-cutting shaping, cutting with edge tools and abrasive cutting.

For a more detailed consideration of this presumption, static tensile testing was performed at cylindrical samples manufactured in accordance with GOST 1497-84 of Grade 45 steel (Figure 1) using a universal tensile machine IR 5047-50 complete with an electronic dynamometer. Preliminary, each of the samples underwent annealing at 850°C for stress relief.



**Figure 1.** A sample for tensile testing

It is interesting to study the material under both normal conditions (i.e., at a temperature of 20°C), and under increased temperatures corresponding to various types of surface layer processing (300...750 °C). It would allow considering the issue of temperature factor influence onto the value of interdislocation interaction parameter  $\alpha$  and formation of internal deformation energy when submitting the sample to tension testing. Dimensions of the samples and processing modes are given in Table 1.

**Table 1.** Dimensions of the samples and processing modes of tensile testing

Sample no.	$l$ , mm	$l_0$ , mm	$d_0$ , mm	$F_0$ , mm	$V$ , mm/min	$\Theta$ , °C
3	60	84	5.84	26.786	1	20
4	65	62	5.82	26.603	5	20
5	65	62	5.93	27.618	5	20
6	65	62	5.86	26.97	10	20
7	65	62	5.87	27.062	5	20
8	65	62	5.87	27.062	5	20
9	65	62	5.79	26.329	5	20
<b>10</b>	<b>65</b>	<b>62</b>	<b>5.76</b>	<b>26.057</b>	<b>5</b>	<b>20</b>
11	65	62	5.76	26.057	5	20
12	65	62	5.76	26.057	5	300
<b>14</b>	<b>65</b>	<b>62</b>	<b>5.94</b>	<b>27.711</b>	<b>5</b>	<b>300 (1.5 hour.)</b>
15	65	62	5.89	27.247	5	500 (1 hour.)
16	65	62	5.93	27.618	5	300 (1 hour 20 minutes)
<b>17</b>	<b>65</b>	<b>62</b>	<b>5.96</b>	<b>27.898</b>	<b>5</b>	<b>500 (1.5 hour.)</b>
18	65	62	5.98	28.086	5	20
19	65	62	5.79	26.329	5	20
20	65	62	5.74	25.876	5	20
21	65	62	5.74	25.876	5	300
22	65	62	5.69	25.428	5	500
<b>23</b>	<b>65</b>	<b>62</b>	<b>5.77</b>	<b>26.148</b>	<b>5</b>	<b>750</b>
24	65	62	5.77	26.148	50	20
25	65	62	5.77	26.148	100	20
26	65	62	5.74	25.876	250	20
27	65	62	5.74	25.876	500	20
<b>28</b>	<b>65</b>	<b>62</b>	<b>5.74</b>	<b>25.876</b>	<b>250</b>	<b>500</b>

*Legend:*  $l$  is the operating length of the sample, mm;  $l_0$  is the initial design length of the sample, mm;  $d_0$  is the initial diameter of the sample, mm;  $F_0$  is the initial cross-section area of the sample, mm;  $V$  is the deformation rate, mm/min;  $\Theta$  is the time of exposure in a furnace to obtain uniform heating of the sample throughout its cross-section, °C.

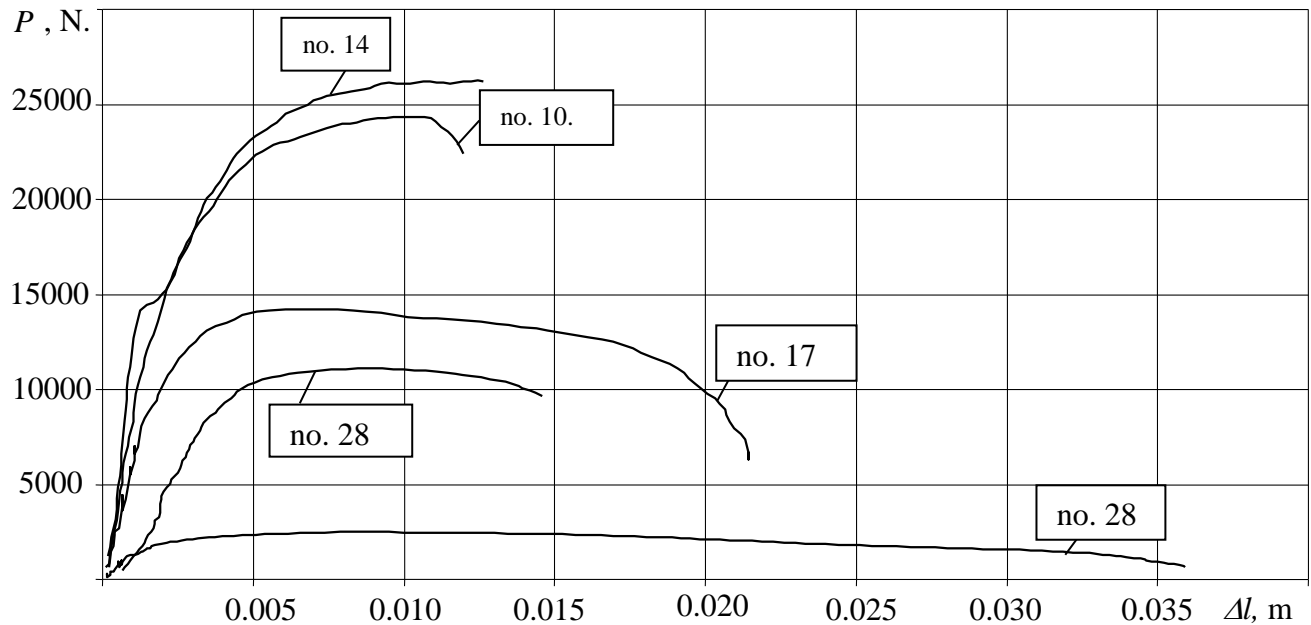
For the tensile testing, samples 10, 14, 17, 23, 28 were selected from the Table 1; they have various thermal condition of testing, while sample no. 13 is a witness sample that was not subjected to the tensile testing (Table 2).

**Table 2.** Tensile test results

Sample no.	$l$ , mm	$l_0$ , mm	$l_k$ , mm	$d_0$ , mm	$d_k$ , mm	$F_0$ , mm	$F_k$ , mm <sup>2</sup>	$V$ , mm/min	$\Theta$ , °C
10	65	62	72.573	5.76	4.76	26.057	17.795	5	20
14	65	62	84	5.94	4	27.711	12.566	5	300 (1.5 hrs)
17	65	62	89.5	5.96	2	27.898	3.142	5	500 (1.5 hrs)
23	65	62	101	5.77	2	26.148	3.142	5	750
28	65	62	78.5	5.74	3	25.876	7.069	250	500
13	-	62	-	5.75	-	22.480	-	-	-

*Legend:*  $l_k$  is the final calculated length of the sample, mm;  $d_k$  is the sample diameter after breakage, mm;  $F_k$  is the cross-section area of the sample after breakage, mm<sup>2</sup>;  $V$  is the deformation rate, mm/min.

Cross plot showing the dependence of force  $P$  and lengthening  $\Delta l$ , m for the selected samples is given in Figure 2.



**Figure 2.** A plot showing the dependence of  $\Delta l$  on applied force  $P$

To determine the hardening created as a result of the force action, the microhardness was measured. For that end, thin sections were made using the TegraPol-11 grinding and polishing machine and fine suspensions. The microhardness of the surface layer of the polished samples was determined with the Durascan 20 automatic hardness meter on the Vickers scale.

The experimental conditions used the previously obtained dependency to determine the values of the deformation energy stored in the surface layer of the item ( $W$ , J) applied to the surface layer of the sample:

$$W = \frac{\pi d^2 \cdot L \cdot Q}{4 \cdot \alpha^2 G} \int_0^H [0.32(HV - HV_0)]^2 \cdot dH, \quad (3)$$

where  $W$  is the value of stored deformation energy, J;  $L$  is the surface length of the studied section of the sample, m;  $HV_0$  is the initial microhardness of the material, Pa;  $HV$  is the microhardness of the material after treatment  $H$ , Pa;  $d$  is a diameter of the studied section of the sample, m;  $(HV - HV_0)$  is the hardening of the material as per Figure 3.

Formula (3) was used to determine the absolute value of the stored energy, at that, for sample no. 10 from previous research on Grade 45 steel under normal conditions [4] it was assumed that  $\alpha = 0.224$ . For the rest of the samples, the value of the parameter  $\alpha$  was calculated from the hypothesis that  $W/A_p \approx 10\%$ . The results are given in Table 4, where it is evident, that the values of the interdislocation interaction parameter decrease as the temperature increases. The value of total deformation energy  $A_p$  was determined from the plots showing the dependence of lengthening  $\Delta l$ , m on the applied force  $P$  (Figure 2) as the value of area under the respective curve.

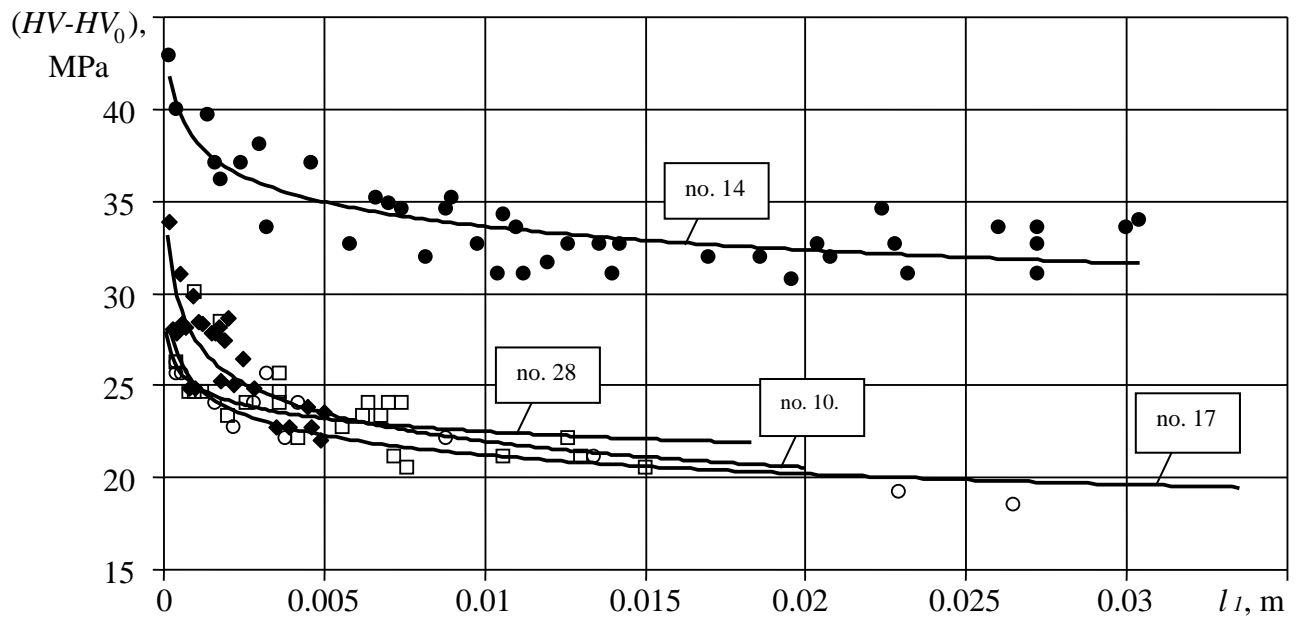
It should be noted, that sample no. 28 had the deformation rate different from that of others, and thus, for the sake of veracity of the experiment, it has been removed from the rank of the studied samples. Besides, the sample no. 23 did not attain breakage during tension at high temperatures (750 °C) while its microhardness is close to that of the witness sample no. 13.

From the computational data (Table 3), the following mathematical dependency was obtained

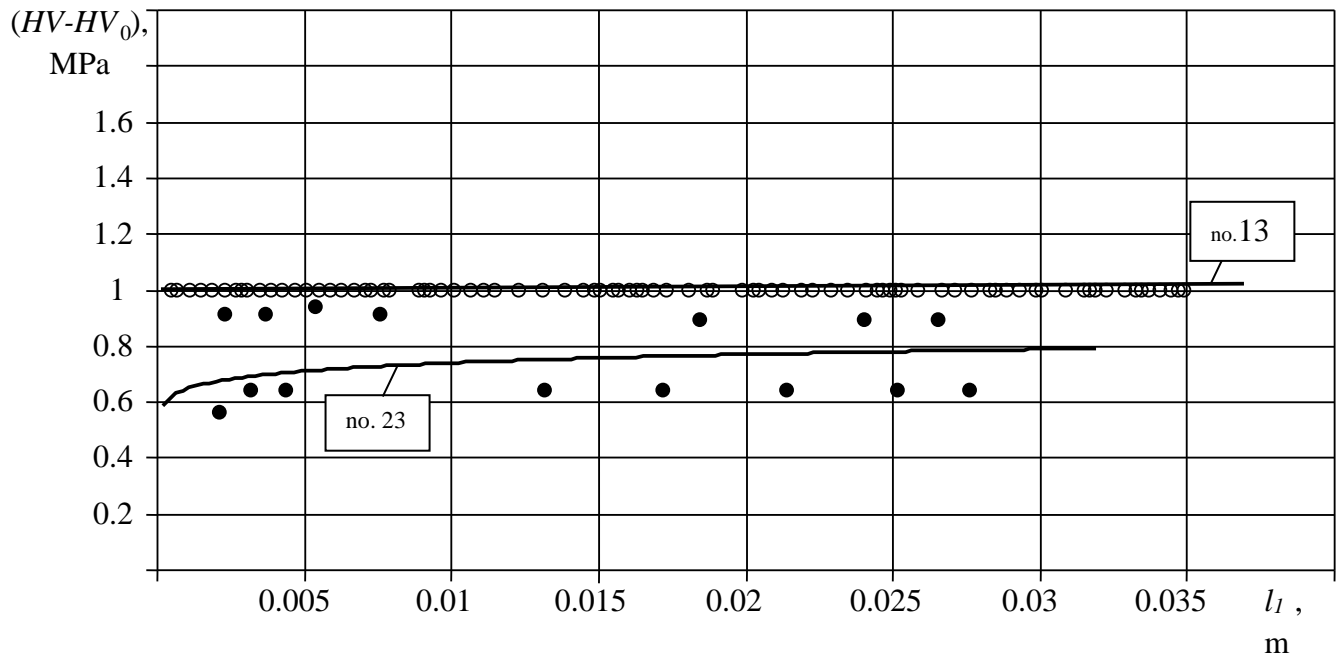
$$\alpha = 0,285T^{-0.08} \quad (4)$$

**Table 3.** Calculated values of the factor  $\alpha$

Sample no.	$W/A_p, \%$	$T, ^\circ\text{C}$	$\alpha$
10	10	20	0.22
14		300	0.19
17		500	0.16



a)



b)

**Figure 3.** Plots (a, b) showing the change in material hardening along the length of the sample (start of the measurement at  $l_l=0$  corresponds to the middle of the contraction where the breakage took place).  $l_l$  is the distance along the length of the sample from the breakage point; a) is for samples 10, 14, 17, 18; b) is for samples 13, 23.

### 3. Discussion.

Dependence (4) shows, that energy spent by dislocation for overcoming various obstacles is diminishing with increased temperature due to increased mobility of atoms [9]. At a temperature of 20°C, the values of factor  $\alpha = 0.22$ , which coincides with previous research on the same material under normal conditions [4]; at temperatures 300...500°C, characteristic of various types of surface layer processing, the value of  $\alpha = 0.19...0.161$ .

The formula for determination of the energy stored in the surface layer include the value of shear modulus  $G$ , which also depends on temperature. At that, it is known, that the main elastic characteristics of materials: shear modulus  $G$ , Young's modulus  $E$  and Poisson's ratio  $\mu$  are interconnected with the equation

$$G = \frac{E}{2(1 + \mu)}. \quad (5)$$

In its turn, the ratio between the modulus of elasticity before and after the processing has the following form, as taken from previous research [1, 3]:

$$\frac{E_{\text{офр}}}{E_{\text{ucx}}} = \frac{C \cdot A^K}{E_{\text{ucx}}},$$

where  $E_{\text{proc}}$  and  $E_{\text{init}}$  are the values of the modulus of elasticity of the surface layer of item's material after the processing and its initial value;  $A$  is the energy criterion of the cutting process [8];  $C$  and  $K$  are the values depending on the properties of the processed material [1]. The values of  $C$  and  $K$  are given in Table 4.

The value of energy criterion of the cutting process  $A$  before the processing is calculated with formula devised by Prof. S.S. Silin [8]:

$$A = \frac{a_1 b_1 (c\rho)_g \theta}{P_z}$$

where  $(c\rho)_g$  is the specific volumetric heat capacity of the processed material, J/m<sup>3</sup>K;  $\theta$  is the temperature in the cutting zone, °K;  $P_z$  is the cutting force, N;  $a_1$  and  $b_1$  are thickness and width of the cross section of cut.

**Table 4.** Factors  $C$  and  $K$  depending on the processed material and processing method

Processed material group	$C, 1 \cdot 10^3$		$K$	
	Lathe turning	Milling	Lathe turning	Milling
Nickel heat-resisting alloys	165	182	-0.08	-0.08
Structural steels	166	197	-0.010	-0.07
Titanium alloys	88	100	-0.11	-0.15

Taking into account the thermal dependence of the the factor  $\alpha$  and having determined the shear modulus  $G$  with the formula (4) accounting for the properties of the processed material and energy criterion  $A$ , and substituting its value into the formula(3), we obtain the dependence of the stored deformation energy  $W_{\text{spec}}$  on the deformation temperature and processing condition of the studied surface.

#### 4. Conclusion.

Thus, studies of samples under normal conditions (that is, under the temperature of 20°C) and under increased temperatures (300...750 °C), confirm the influence of the thermal factor on the value of the interdislocation interaction parameter  $\alpha$  and onto formation of internal deformation energy during the tensile testing of the samples. When the temperature is increased, the interdislocation interaction parameter  $\alpha$  decreases, which is explained by increased mobility of atoms and thus reduced energy that the dislocation shall spend to overcome obstacles. The presuppositions on the nature of changes in the stored energy ratio in the total deformation energy is confirmed on the basis of the calculation methodology for finding internal deformation energy depending on various factors.

#### 5. Acknowledgment.

The work has been complete with financial assistance from the Ministry of Education and Science of the Russian Federation, contract no. 02.G25.31.0156, dated December 1, 2015 in execution of the decree no. 218 of the Government of Russia.

#### References

- [1] Bezyazychny V F 2012 *Method of Similarity in Engineering technology* (Moscow: Mashinostroyeniye)
- [2] Bezyazychny V F, Prokofief M A, Vinogradova N V 2015 Studying the influence of process conditions of machining onto stored deformation energy in the surface layer of items. *Annals of Perm National Research Polytechnic University. Aerospace Industry* **4(43)** 131-144
- [3] Vodolagin A L 2002 *Determining the endurance strength of heavy duty parts of gas turbine engines after processing with edge tools. Dissertation. Candidate degree in Engineering Sciences* (Rybinsk)
- [4] Greshnov V M, Lavrinenko Y A, Napalkov A V 1999 Predicting failure of metals in cold plastic deformation. Report 1. Approximate model of plastic deformation and failure of metals. *Issues in Durability* **1** 76 – 85
- [5] Babichev A P, Motrenko P D, Kostenkov S A et al. 2011 *Tooling for machining in granulated*

- mediums* (Rostov-on-Don: Don State Technical University Press)
- [6] Maksarov V V, Kosheleva E V 2016 Increasing accuracy and quality of machining items of titanium and titanium allows with preliminary plastic deformation. *Quality and Life* **3** 61-65
  - [7] Maksarov V V, Kosheleva E V, Vazhenin A Y 2017 Increasing the quality of machining items of titanium and titanium allows with preliminary plastic deformation. *Annals of Rybinsk State Aviation Technical University named after P. A. Solovyov* **1(40)** 276-281
  - [8] Silin S S 1979 *Method of Similarities in Cutting of Materials*. (Moscow: Mashinostroyeniye)
  - [9] Diao Xiaoxue, Xing Xiasan 1990 Low energy dislocation structure in deformed metals. *Chin J. Mater. Sci. Technol* **6** 338-344
  - [10] Maksarov V V, Krasnyy V A, Krasnyy, Olt J J 2016 Increase of wear and fretting resistance of mining machinery parts with regular roughness patters. (Annals of DAAAM and Proceedings of the International DAAAM Symposium)
  - [11] Maksarov V V, Krasnyy V A 2017 The formation of surface roughness of piston rings for the purpose of improving the adhesion of wear resistant coating. *Key Engineering Materials* **736** 73-78
  - [12] MITRA TAHERI, HASSO WEILAND, ANTHONY ROLLETT 2006 A Method of Measuring Stored Energy Macroscopically Using Statistically Stored Dislocations in Commercial Purity Aluminum. *METALLURGICAL AND MATERIALS TRANSACTIONS A* **37A** 19-25
  - [13] Oliferuk W, Maj M 2010 Identification of energy storage rate components. Theoretical and experimental approach. *Journal of Physics: Conference Series* **240** 012144 doi:10.1088/1742-6596/240/1/012144
  - [14] Rajmohan N, Hayakawa Y, Szpunar J A, Root J H 2000 COMPARISON BETWEEN ORIENTATION-DEPENDENT STORED ENERGY OF COLD ROLLED AND STRESS RELIEVED INTERSTITIAL FREE STEEL. *JCPDS-International Centre for Diffraction Data 2000, Advances in X-ray Analysis* **42** 460-463
  - [15] Feng Yan, Hongwang Zhang 2012 Evaluation of Stored Energy from Microstructure of Multi-component Nanostructured Cu. *J. Mater. Sci. Technol.* **2012** 289-293