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TECHNOLOGICAL OPPORTUNITIES FOR INCREASING A BEARING SURFACE OF FLAT PARTS MADE FROM VT22 ALLOY DURING PENDULUM GRINDING

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ABSTRACT

Application of digital technology allowed to analyze a bearing surface of flat parts made from VT22 alloy during grinding by high porous wheels (HPW): CBN30 (B76, B126, B151) 100 OV K27 – KF40 and (37C, 39C) 46 I12 VP produced by Norton company. A pseudo-regular macrorelief with straight-through cavities was identified on the surfaces of parts; the cavities are located along their length, and the intensity of the formation of cavities is concentrated in the zone of cutting into HPW with transversal feed. After ending of transversal movement its zone of contact with HPW is rapidly decreasing reaching zero. That strengthens the formation of a bearing surface of parts without connecting cavities on a surface, which are correlated with a transversal movement. Among CBN HPW the largest bearing surface was demonstrated by fine grain tools, and among Norton HPW – grains 37C. For the increase of a bearing surface of parts it is necessary to decrease the cutting depth t in the end of a path. The best precision was demonstrated by Norton HPW: 37C at t =0.005 mm, 39C at t =0.01 mm.

Keywords: bearing surface, grinding, titanium alloy, statistics, measures of position, dispersion.

1. INTRODUCTION

Titanium alloys have a unique combination of properties: high specific strength, corrosion resistance in various media and heat resistance [1]. They are demanded in aerospace engineering, gas-pumping equipment, chemical equipment and ship building. All types of titanium alloys, especially high-strength alloys ($\sigma_в > 1000$ MPa), have one technological disadvantage - low machinability by tools made from traditional abrasives (electrocorundum, silicon carbide) of standard porosity: (6-7)-th structures. For that reason, the specific weight of grinding during the production of titanium parts at the moment is still much lower as compared with steel ones. That fact negatively influences technological progress in the mentioned branches of machine building.

Titanium alloy VT22 is two-phase ($\alpha+\beta$). The presence of β-stabilizers in the volume of 11.8% allows to carry out effective thermal processing (tempering, aging), after which it becomes a part of a group of high strength alloys with the worst grinding parameters. Those problems are related to intensive clogging of a work surface of abrasive tools with standard porosity and its adhesion interaction with a material of a workpiece [1-4]. The first phenomenon is related to the low anti-friction properties of titanium, which has a low wear resistance and big tendency to seizure during friction. Thin oxide film on a surface of titanium easily destructs, as it is more brittle than a lower material. Its embrittlement is caused by the diffusion of hydrogen, oxygen and nitrogen at temperatures of grinding, starting from 400-600°C [4]. That fact increases the adhesion component of the coefficient of friction, which depends on adhesion interaction and the coefficient of strengthening of a formed connection under load [5]. Efficient measures of improvement of machinability of titanium alloys by grinding are the following: the use of inert, wear-resistance abrasive grains and HPW; creation of reaction media in a cutting zone, which facilitates the passivation of metal, and, therefore, the decrease of its interaction with abrasives. Application of special liquid coolant is an efficient measure for the decrease of clogging of abrasive tools [3, 6-7]. However, with small volume of grinding titanium parts the special liquid coolants inhibit its centralized preparation at a production facility. That fact requires additional economic justification of an application in each case. In our opinion, more prospective directions for the improvement of grindability of parts from titanium alloys are the two mentioned above.

According to the results of studies [3, 4, 6-10] it was established that during grinding of titanium workpieces by traditional abrasives black and green silicon carbides have an advantage. It is related to the fact that titanium more intensively loses electrons to atoms of aluminum in corundum, which increases adhesion wear. Thus, during grinding of VT22 silicon carbide exceeds wear resistance of corundum materials up to two times. The black and green silicon carbide grains do not significantly differ in chemical composition and physical properties. Their selection for grinding of titanium parts is, generally, related to the results by the surface microrelief. However, selection of grains appeared to be correlating with marks of titanium alloy that requires individual approach for each specific type of the alloy. The abrasive materials, the atoms of which do not receive electrons of titanium and, thus, minimize adhesion, are cubic boron nitride (CBN) and diamond [4].

Formation of large pores in HPW with grains of CBN provides good placement of chips and facilitates additional cooling of processed workpieces due to better penetration of lubricoolant in zone of cutting and soaking of a ceramic body of wheel with it. As a result, clogging of

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HPW, the temperature and power of grinding are decreased 1.5-2 times [4, 9].

Synthesis of CBN allowed to more effectively grind titanium alloys. However, it also leads to kinematic transfer of topography of a working surface of HPW from CBN to a processed surface, which influences its roughnesses and rippling [9-15].

For the analysis of a real condition of parts' surface various methods of diagnostics are used. A method for the evaluation of a bearing surface by photography through a microscope with contrast specification of a contact zone is known [16]. Study of a surface is carried out in reflected polarized light and requires visual comparison of contours of spots of main colors. Area of a single spot is defined in micrometers. It causes troubles for comparison of parts with varied scale, which are represented with varied scale of magnification. The study [17] discussed the method for search of 3D coordinates of a surface by means of scanning and digital photography. At that, there are inaccuracies, which are related, first of all, to the deviations of a measured surface from perpendicularity relatively to a scanning device. In the study [18] it is proposed to apply a flatbed scanner and analyze images using plane of hues of gray tone. It is not recommended to use that methodology for grinding of workpieces, which have tendency for blueing and burns in heating. New generation of equipment is based on the production of holographic image of an object in optical and X-Ray ranges. Undoubtedly, they allow studying processes of treatment in 3D and identified topography of a surface of parts, which is based on module-geometrical approach [19]. Instrumentality for the creation of that kind of devices is limited by complexity and expensiveness.

A prospective direction of diagnostics of a surface is so-called digital mapping, because standard parameters of roughness and form accuracy are not enough for characterizing the contact pair of parts for the evaluation of cutting capabilities of wheels. Selection of HPW with various abrasive materials and depth of grinding using criteria of a bearing surface of flat parts made from titanium alloy VT22 with implementation of innovative parameter [20] is the topic of the presented study, which is aimed at the expanding of understanding of a surface formation.

2. METHODOLOGY OF THE EXPERIMENT

Equipment, shape and dimensions of HPW, as well as the parameters of regime of pendulum grinding, are presented in Table-1.

Table-1. Basic parameters of the full-scale experiment.

Machine	Grains	Shape and dimensions of HPW	Technological parameters*				
			v_w, m/s	s_1, m/min	s_{cr}, mm/double pass	t, mm ($j=1;2$)	z, mm
3E711V	*CBN*30	1*A*1 200×20×76×5 mm [21]	28	6	4	0.005 (1)	0.1
3G71M	37*C*, 39*C*	01 250×20×76 mm [22]	35			0.010 (2)	

Note: * - v_w - speed of cutting, s_1 - longitudinal feed, s_{cr} - transversal feed, *t* - depth of cutting, *z* - production allowance.

In what follows we will discuss in details the certain conditions of the experiment, which allow understanding its main points. Down movement of a spindle with HPW at a depth *t* was stated in the moment, when a workpiece came to the leftmost position in relation to the operator, in the beginning of the technological transfer and in the cutting of the allowance. It must be remembered that at a machine HPW rotates clockwise, and feed s_{cr}, was specified for double pass. In that situation movement of a longitudinal table from left to right in terms of functionality is considered as a working movement in limits of moving of a workpiece in a transversal direction for a value of s_{cr}. Then, the opposite movement of the table in the initial position is spark-out pass. The remained portion of a part by width of HPW, which in the end of the grinding doesn't exceed 16 mm, also works in the mode of multiple spark out according to the scheme of down grinding. The object of the study are specimens of titanium alloy VT22 ($\sigma_{UST} = 1200$ MPa, $\delta_E = 8-12\%$, E = 115 GPa) with sizes $B\times L\times H$ = 40×40×50 mm, which were connected to the machine table by means of clamp arms. The grinding was carried out along the plane $B\times L$ without additional spark-out passes in its classical treatment. The applied liquid lubricant is 5% emulsion Akvol-6 (TU 0258-024-00148845-98), which is supplied by sprinkling on the part in volume of 7–10 l/min. The volume of duplicating repeats is n=10. Before each experiment $\vartheta = \overline{1;10}$ HPW was set by a dressing diamond. Varied conditions of grinding are reflected by code "i, j, r, ϑ" in the output parameter of the process – $y_{ijr\vartheta}$, which has large in formativeness for multiple recording. Characteristics of HPW are specified by code $i = \overline{1;5}$: 1 – CBN30 B76 100 OV K27–KF40; 2 – CBN30 B126 100 OV K27–KF40; 3 -

CBN30 B151 100 OV K27–KF40; 4 – 37C 46 I12 VP; 5 - 39C 46 I12 VP. The wheels $i=\overline{1;3}$ are produced by JSC "Scientific and Production Complex "Abrasives and Grinding" (Saint-Petersburg) [21, 23]. Grain size in them varied from *B*76 (200/230) to *B*151 (100/120); sizes of grains in meshes are presented in brackets. Wheels 37*C*, 39*C* ($i=4;5$) are produced by *Norton* company [22], which uses various abrasive materials: 37*C* – black silicon carbide; 39*C* – green silicon carbide. As it can be seen from Table 1, the index $j=1;2$ reflects the previously accepted depth of cut *t*: 1 – 0.005 mm, 2 – 0.010 mm (basic). For the evaluation of precision of the process we used the measures of dispersion $r=\overline{1;3}$: 1 - standard deviations $(SD)_{ij}$; 2 – ranges R_{ij}; 3 – quartile width QW_{ij}, which are dealt with in details below during the discussion of statistical methods.

Taking into account the stochastic nature of grinding, we consider the obtained observations as random variable (RV). We evaluate them with application of statistical approaches; for that at the first stage of the study we represent them as independent sets $i=\overline{1;5}$, $j=1;2$:

$$\{y_{ij\vartheta}\},\ \vartheta=\overline{1;10}. \quad (1)$$

Theoretical statistics include two directions: parametric and non-parametric (in particular, rank). Characteristics of one-dimensional distribution for (1) are [24-27]: means $\overline{y_i}=y_{i\bullet}$, standard deviations $(SD)_{ij}$, ranges $R_{ij}=|y_{\max}-y_{\min}|_{ij}$ - for the first direction; median $\widetilde{y}_{ij}$, quartile width $QW_{ij}=|y_{0.75}-y_{0.25}|_{ij}$ – for rank characteristics. The first frequency of one-dimensional distribution characterizes measure of position of RV (reference value), the further – their measures of dispersion (precision). Difference between $y_{ij\bullet}$ and $\widetilde{y}_{ij}$ indicates that probability density of a distribution curve is characterized by asymmetry (skewness), which is approximately calculated using the expression:

$$As_{ij}=\left[3(y_{\bullet}-\widetilde{y})/SD\right]_{ij},\ i=\overline{1;5},\ j=1;2. \quad (2)$$

Each method of statistics has its own area of rational application taking into account features of the obtained (1). In engineering applications the most widely used are parametric techniques, at that, without proper justification. Actually, for that method it is necessary that (1) met the requirements of normality and, which is especially important, uniformity of deviation dispersions of distributions. In the case of the presence of deviations among the mentioned restrictions, it is reasonable to use the rank method, which is not related to a specific family of dispersions and doesn't use its properties.

Testing (1) of the uniformity of dispersions $(SD)^2_{ij}$, i.e. the acceptance of null-hypothesis (H_o), were carried out using three groups of criteria ($q=\overline{1;3}$): 1 - Hartley, Cochran, Bartlett (in software *Statistica* 6.1.478.0 they are presented as a single group), 2 - Levene, 3 - Braun-Forsyth. Condition of uniformity of dispersion is fulfilment of the inequalities:

$$\alpha_{ijq}<0.05 \quad (3)$$

for variables $i=\overline{1;5}$ and fixed $j=1;2$, $q=\overline{1;3}$, where α_{ijq} – calculated level of significance.

Due to probabilistic nature of hypotheses of solution f_o in favor of H_o can differ, but in the end they must meet the requirement: $f_o\in[2;3]$.

For verification of H_o in regard to normality of distributions (1) we used Shapiro-Wilk statistics, which was tested for each variable i and j, on the condition of fulfilment the inequalities:

$$\alpha_{ij}>0.5. \quad (4)$$

In any case the interpretation (1) is carried out by means of two consequent procedures. First, on the basis of one-dimensional dispersion analysis (ODA) at 5% level significance of difference of the experimental means and median $i=\overline{1;5}$ for fixed $j=1;2$ without specification of concrete i is identified. At confirmation of the proposed hypothesis the final stage of ODA is carried out with implementation of multivariative comparison tests of reference values $\hat{y}_{ij\bullet}$ or $m\hat{y}_{ij}$, $i=\overline{1;5}$, $j=1;2$, which differ significantly at 5% level.

For quantitative evaluation of a bearing area of a plane we carried out monitoring of a grinding operation by means of digital mapping. The developed method of diagnostics allows considering characteristics of topographical structure of a surface. For the numerical description of load-bearing plane we proposed the innovative parameter – relative bearing part of a plane, which theoretical justification is presented in [20]:

$$t_{fM}=\frac{1}{n}\left[\sum_{\vartheta=1}^{n}\left(1-\frac{F_C}{F_\Sigma}\right)\right]\times 100\%, \quad (5)$$

where f - depth of a cavity, which correspond to thickness of fraction of indicator-filler; F_Σ - total area of projection; F_C - area of projections of cavities.

At the first stage of digital mapping of processed surfaces the aim was to obtain the color image file with numerical parameters of pixels, which reflect tonal picture.

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For that we used the paint method, which is convenient for the indication of cavities of macro roughness. The main point of the method is that a layer of oil-base paint "Red lake" (TU 2331-023-05751640–2007) with sizes of particles up to 2 μm is applied on a ground surface by means of a rubber roller. Prior to it the paint was diluted with industrial-purpose oil in order to achieve the required density of color. Excesses of the applied paint were removed from the studied surface until it stopped to transfer to a flatness reference, which is sliding on it; the reference was calibration ruler ShP-2-400 (TU 2-034-806-76, accuracy class 2).

The studied object was photographed in macrography mode with focal length of 250 mm; for imaging we used *Nikon D* 3100 digital camera with *CMOS* and 14.2 megapixels mounted on a tripod. Macrography mode had the following parameters: *ISO* 400 sensitivity, maximum aperture *f*/3.5-5.6 and image resolution of 4608×3072 pixels. The imaging was carried out with artificial light, which was provided by a set of studio lamps Smartum with 5500º*K* source through diffusers. It allowed to avoid possible half-shades. Each elementary area of a surface: plateau, protrusion, cavity etc. was reflected in digital image in a form of a pixel with of a certain color. The image was saved in a form of *JPEG* file with parameters, which allowed to provide the most contrast representation of a surface. Pixels of an image, which differed from hues of red color, were marked out using digital processing. The image was converted in a color image with limited number of bit $K \leq 16$, which are sufficient for genesis of a surface. At that not painted areas of the studied surface become one of standard colors of white and painted - hues, which are close to a color of possible 16 colors, except white. The quantitative ratio of pixels of red color to others remained the same as the ratio of red hues to iron-grey in the source file. That file was converted by means of a special software for processing of raster images into a table of frequencies of pixels, which were coded in *HTML* and *RGB* codes; after that the values were saved in *txt* file.

According to standard *HTML* code standard colors of red, which reflected the presence of cavities, were identified. Information of digital mapping of surface allows transforming (1) taking into account (5) to the form of [20]:

$$t_{fM} = \frac{1}{n}\left[\sum_{\vartheta=1}^{n}\left(1 - \frac{\sum P_{red}}{\sum P_k}\right)\right] \times 100\%,$$

where t_{fM} – reference values (mean, median) for all (1); $\sum P_k$, $\sum P_{red}$ – respectively, number of pixels for all colors at $K \leq 16$ and red spectrum for each $\vartheta = \overline{1; n}$.

In further from t_{fM} we compiled sequences, in which we searched one-dimensional distribution of frequencies. Taking into account the aforementioned we evaluated shift of medians along relatively average by means of median coefficient with $i = \overline{1;5}$ and $j = 1;2$:

$$K\mathit{м}_{ij} = (\tilde{t}_{fM} / t_{fM\bullet})_{ij}, \tag{6}$$

$$\hat{K}\mathit{м}_{ij} = (m\hat{t}_{fM} / \hat{t}_{fM\bullet})_{ij}. \tag{7}$$

Evaluation of cutting capabilities of HPW $i = \overline{2;5}$ in regard to the basic tool CBN30 B76 100 OV K27 – KF40 (*i=1*) is carried out for both characteristics of one-dimensional distribution of frequencies (1) with simultaneous $i = \overline{1;5}$ and $j = 1;2$ [24-27]:

$$K_{(i)j} = (\tilde{t}_{fM(i)} / t_{fM(1)})_j, \tag{8}$$

$$\hat{K}_{(i)j} = (m\hat{t}_{fM(i)} / m\hat{t}_{fM(1)})_j, \tag{9}$$

$$K_{ST(i)j1} = SD_{(1)j} / SD_{(i)j}, \tag{10}$$

$$K_{ST(i)j2} = R_{(1)j} / R_{(i)j}, \tag{11}$$

$$K_{ST(i)j3} = \mathrm{Q}W_{(1)j} / \mathrm{Q}W_{(i)j}. \tag{12}$$

The influence of the depth of cut t_j, $j = 1;2$ for the basic $t_2 = 0.01$ mm at a bearing surface of parts was presented in a reduced form by coefficients:

$$\hat{K}_{i(1)} = (m\tilde{t}_{fMi(1)} / m\hat{t}_{fMi(2)})_j, \tag{13}$$

$$K_{STi(1)3} = \mathrm{Q}W_{i(2)} / \mathrm{Q}W_{i(1)}. \tag{14}$$

In (8) - (14) the index in parentheses represents variable conditions of grinding.

3. RESULTS AND DISCUSSIONS

Figure 1 presents images of the ground surface of a part, in which two zones are marked out: 1 - cavities of macroroughness, 2 - smoother zone, which forms a bearing part of a surface. Qualitative analysis of the photograph, which is presented in Figure-1, b, demonstrated that the topogram shows pseudo-regular macrorelief with alternating protrusions and cavities, which are directed along the vector s_1, The step of location of cavities is similar to feed s_{cr} . Therefore, kinematics of the grinding process defines formation of systematic inaccuracies of forms, and a surface has "cast" of a cutting surface of HPW, which was created during grinding of a specimen $\vartheta = 7$ with depth of $t = 0.01$ mm in time of opposite spark-out pass. Transversal movement of the carriage with the workpiece is reflected by the arrow s_{cr}. Thus, cutting of the workpiece in the cutting zone starts from the right side, and exit from the contact with HPW is from the opposite left side. As it is known, boundaries of contact zones with an adjacent part concentrate in the zones of protrusions 2 (Figure-1, b). For the specimen $\vartheta = 7$ mean of the bearing surface was $\bar{t}_{fM(1;2;7)}$ = 47.687%. The value of the supporting area was calculated using (5) with implementation of mean pixels (Table-2), in which cavities are formed by means of colors $K = \overline{4;6}$.

Table-2. Frequency distribution of pixels of each color during grinding of a specimen ϑ = 7 by the wheel CBN30 B76 100 OV K27 – KF40 at t =0.01 mm.

Color $K = \overline{1;7}$	Number of pixels	*RGB* code	*HTML* code
1	2 513	(0,0,0)	#000000 black
2	10	(0,0,128)	#000080 navy
3	3	(0,128,128)	#008080 teal
4	1 801 688	(128,0,0)	#800000 maroon
5	175 481	(128,0,128)	#800080 purple
6	89 212	(128,128,0)	#808000 olive
7	1 881 209	(128,128,128)	#808080 fractal

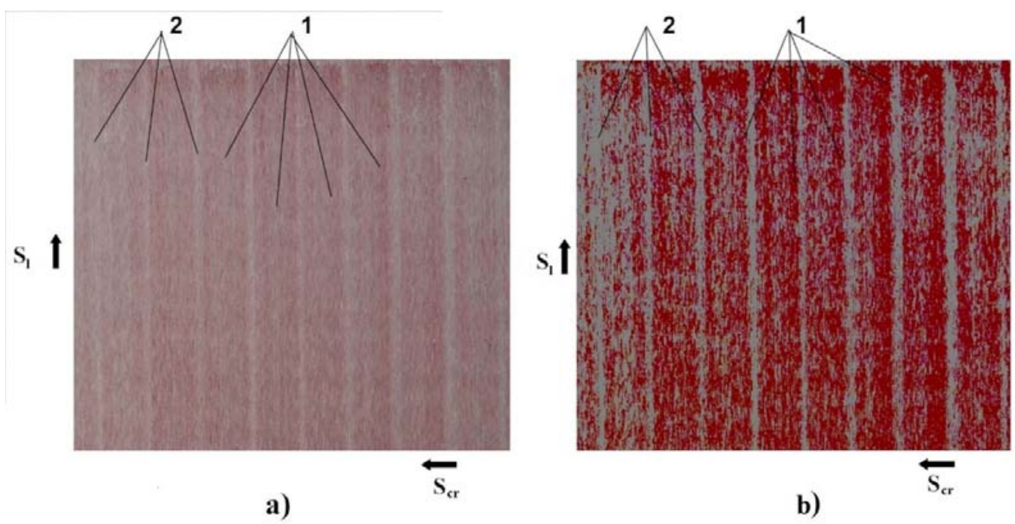

Figure-1. Images of a surface of a part ϑ = 7, ground by HPW CBN30 B76 100 OV K27 – KF40, at a depth of $t = 0.01$ mm: a – source image, b – image with 16-bit color.

The increase (5) leads to the decrease of deviations from flatness of the connected surfaces. In the framework of the carried out study that problem is partially solved by means of grinding of titanium parts using a wheel made from grains *CBN*30 and 37*C* with a lesser depth $t = 0.005$ mm (Figure-2). According to (5) supporting area of contact increased to the following levels: $\bar{t}_{fM(1;1;7)}$=55.556% - for grinding with HPW CBN30 B76 100 OV K27 – KF40; $\bar{t}_{fM(4;1;7)}$= 63.778% - for HPW 37*C* 46 I12 VP. As it can be seen from Figure 2, in both cases of grinding the ratio of protrusions and cavities of surface changed in favor of the later. Pseudo-regular nature of the whole surface is less explicit, especially, for grains 37*C*, which have lower wear-resistance. Cavities cross the surface along the full length of the workpiece. They are cold commuting cavities. That kind of surface has high dripping leakage due to the difference of pressure of hydraulic fluid [28]. From another point of view, pseudo-regular profile in the course of operation is capable to hold and transport lubricant, which excludes the so-called film deficiency. According to the data of the study [5], this is especially topical for steel parts with $R_a 0.04 - 0.16$. In our case the roughness of titanium parts is higher $(R_a 0.32 - 0.63)$; however, titanium has a higher coefficient of friction and requires more lubricant, as compared to steel parts, in order to increase the antiscuff resistance of rubbing surfaces.

From Figures 1 and 2 it can be seen that parts of surfaces where a workpiece is losing contact with HPW (left side of a surface) have a smoother relief, and protrusions in the range $B = (2 - 4)\,s_{\text{п}}$. are dominating. At these parts of HPW the work is finished in conditions of classical spark out for both variants of longitudinal feed of a Table 1.

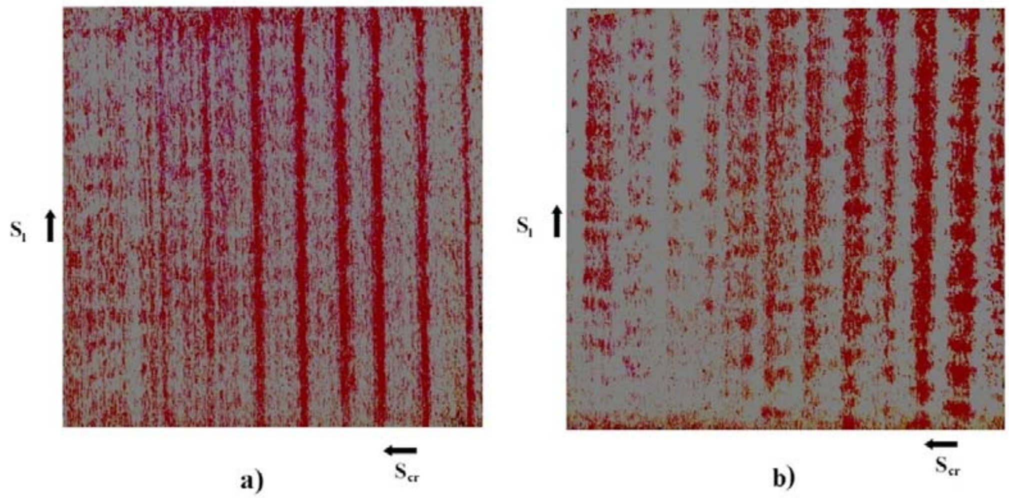

Figure-2. Topograms of macrorelief of a surface after grinding by HPW CBN30 B76 (a) and 37C (b) with depth of cutting t = 0.005 mm.

However, the efficiency of the process of sparkout, which is accompanied by the decrease of cavities, depends on elastic negative allowance in the section "part – HPW". With lower negative allowance (for example, for $t = 0.005$ mm) a process of leveling of a surface starts to manifest itself at an earlier stage with B=4 s_{cr} (Figure-2), as compared to higher negative allowance (Figure-1, b). The results of the presented study showed that the discussed part of a surface has increased microhardness, because the cycle of grinding ends in conditions of the decrease of thermal influence on the part.

For the selection of a statistical method we tested the output parameters of grinding using (3) and (4). Table 3 presents the results of the testing (1) with an aim to find uniformity of dispersions. The results of the testing (1) for uniformity of distributions show that the nature of variant $(SD)_{ij}^2$ with the variable $i = \overline{1;5}$ and fixed $j = 1;2$ depends on the excepted cutting depth. In the case of grinding with the minimum t=0.005 mm H_o according to (3) were rejected for all statistical methods $q = \overline{1;3}$.

Table-3. Verification of uniformity of dispersion for the relative supporting part of the surface.

Criterion $(q = \overline{1;3})$	α_{ij}		**Acceptance of H_o by (3)**	
	$j = 1$	$j = 2$	$j = 1$	$j = 2$
Hartley, Cochran, Bartlett (1)	0.567622	0.183888	-	+
Levene (1)	0.412934	0.080001	-	+
Braun-Forsyth (3)	0.432594	0.257694	-	-

With increase of depth to $t = 0.01$ mm H_o are accepted at $f_o = 2$ in conditions of error of the second kind. Probably, cutting of operation allowance at t = 0.01 mm leads to the increase of elastic negative allowance in the technological segment "HPW-workpiece", which leads to the decrease of α in (3) in 2-4 times and increases the randomness of dispersion $(SD)_{i2}^2$.

The results of the testing (1) with an aim to find the normality of distribution of HPW $i = \overline{1;5}$ at two depths of cutting are showed in Table-4; for better clearness Figure-3 presents histograms of quality of surface at two depths t_j, $j = 1;2$, which are obtained during grinding by basic HPW CBN30 B76 100 OV K27 – KF40.

Table-4. Testing (1) for normality of distributions of H_o by (4).

HPW ($i=\overline{1;5}$)	Calculated level α_{ij}		Accepted $H_{o(ij)}$ by (4)	
	$t=0.005$ mm ($j=1$)	$t=0.010$ mm ($j=2$)	$t=0.005$ mm ($j=1$)	$t=0.010$ mm ($j=2$)
$CBN30B76$ (1)	0.6410	0.7738	+	+
$CBN30B126$ (2)	0.6065	0.1673	+	-
$CBN30B151$ (3)	0.5424	0.2550	+	-
$37C\,46$ (4)	0.4779	0.6579	-	+
$37C\,46$ (5)	0.4468	0.0947	-	-

As it can be seen from the Table-4, laws of distribution of (5) depend not only on characteristics of HPW, but also on the depth t to the larger extent. In the course of the grinding of parts made of VT22 by nitride-boron HPW $i=\overline{1;3}$ with a depth of $t=0.005$ mm 100% normal distribution of reference

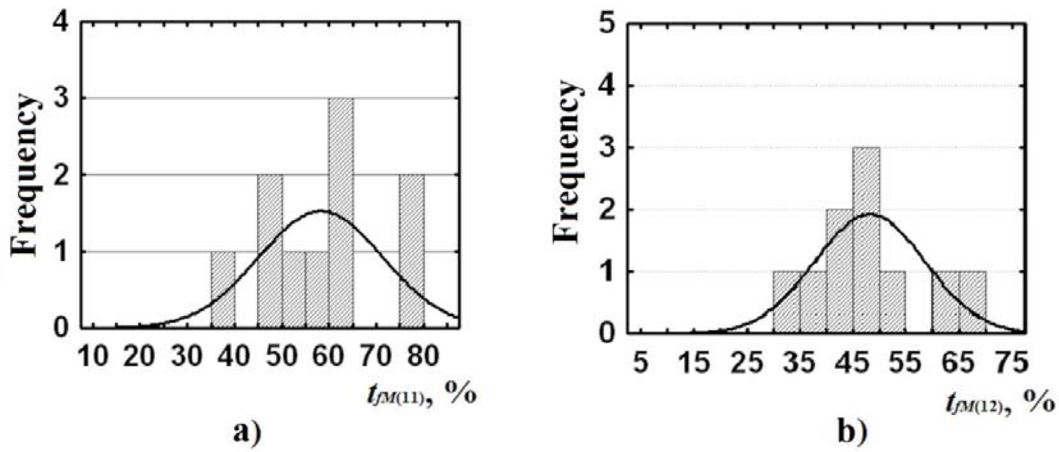

Figure-3. Histograms of quality of the surface with applied curves of normal distribution during grinding of parts by the wheel CBN30 B76 100 OV K27 – KF40 with depths of cut of 0.005 (a) and 0.010 mm (b).

surface was provided. *Norton* ($i=4;5$) wheels showed insignificant deviations from curves of normal density. With the increase of t to 0.010 mm the number of cases of grinding with normal distribution (5) decreased from 3 to 2 and only one basic HPW $i=1$ with both t_j, $j=1;2$ provided the normality of distribution (5). For that HPW Figure 1 shows histograms of distribution of quality for both depths of cutting with applied curves of normal distribution. The obtained information allows to specify two mechanisms: limits of sweep R_{11} at work with $t=0.005$ mm increase their analogue at $t=0.01$ mm for (5-10)% by a bearing surface, which is advantageous for operability of joints; the increase of number of parts in certain ranges t_{fM} requires the increase of repeated tests.

Restrictions of RV from the point of parametric technique are not fully provided. That explains the selection of the rank method for interpretation (1) as the priority method.

Table-5 presents experimental and expected measures of position for the parameter t_{fMij} and coefficients (6) – (9) during grinding with both depths t_j, $j=1;2$. As it is known, for the increase of the reliability of joints of parts it is desirable that (1) has negative excess, which provides the inequalities $(\tilde{y} > y_{\bullet})_{ij}$ with the like i, j. As it can be seen from the Table-5 that situation occurred during grinding of parts made from VT2 by tools *CBN*30 with grain sizes *B*76 and *B*151 for both depths of grinding: 0.005 mm - K_{M11} = 1.014, K_{M31} = 1.012; 0.010 mm – K_{M12} = 1.009, K_{M32} =1.115, as well as HPW 37*C* ($i=4$) with $t=0.005$ mm – K_{M41}=1.026. The histograms presented in Figure-3 correspond to negative asymmetry (2). According to the expected medians, which are final evaluations of measures of position, coefficients (7), more than 1, changed by

HPW: $i = 2;4;5$ – at $t = 0.005$ mm; $i = 2;3$ - at $t = 0.01$ mm. That fact indicates that it is reasonable to carry out the second state of the multivariate analysis of measures of positions.

Table-5. Influence of the wheels characteristics on measures of position of the bearing surface and coefficients (6)-(9).

t_j, $j = 1;2$	**Wheel** $i = \overline{1;5}$	t_{fMij}, %				K_{Mi} **(6)**	$\hat{K}_{Mi}$ **(7)**	K_i **(8)**	$\hat{K}_i$ **(9)**
		$y_{i\bullet}$	$\tilde{y}_i$	$\hat{y}_{i\bullet}$	$m\hat{y}_i$				
0.005 (1)	1	58.026	58.849	58.373	54.420	1.014	0.932	1.000	1.000
	2	30.679	29.676	33.064	34.567	0.967	1.045	0.504	0.635
	3	56.552	57.227	58.373	54.420	1.012	0.932	0.972	1.000
	4	60.543	62.145	58.373	59.407	1.026	1.018	1.056	1.092
	5	40.219	39.459	37.834	46.303	0.981	1.224	0.671	0.851
0.010 (2)	1	48.021	48.456	46.289	46.258	1.009	0.999	1.000	1.000
	2	23.618	20.089	27.011	27.786	0.851	1.029	0.415	0.601
	3	45.712	50.968	45.380	46.258	1.115	1.019	1.052	1.000
	4	50.594	50.125	46.744	46.258	0.991	0.990	1.034	1.000
	5	37.191	35.483	41.604	41.024	0.954	0.986	0.732	0.887
Note: Wheels i: 1 – CBN30 B76 100 OV K27 – KF40, 2 – CBN30 B126 100 OV K27 – KF40, 3 – CBN30 B151 100 OV K27 – KF40, 4 – 37C 46 I12 VP, 5 – 39C 46 I12 VP.									

According to (9) during grinding of parts made by VT22 with depth of $t = 0.005$ mm, the largest bearing surface is predicted for HPW 37C 46 I12 VP ($\hat{K}_{41}$ = 1.092) and the lowest is for HPW *CBN*30 *B*126. At the second position there are HPW *CBN*30 with grain sizes of *B*76 and *B*151 (respectively with $i = 1;3$). With increase of t to 0.010 mm the noted mechanism, in general, remained there positions: for HPW $i = 2$ completely, and HPW $i = 1;3;4$ – medians $m\hat{t}_{fM(i2)}$ are predicted by general mean, which leads to (9) equals unit.

According to (13) the predicted measures of positions for the parameter $m\hat{t}_{fM(i1)}$ at $t = 0.005$ mm increased their expected analogues at $t = 0.01$ mm 1.13-1.24 times. It was established that the largest effect on the increase of the parameter $m\hat{t}_{fM}$ with the decrease of $t \in [0.010;\ 0.005]$ mm is for HPW *CBN*30 *B*126 (i=2), which had the worst results by t_{fM} at both t_j, $j = 1;2$. In the same conditions *Norton* HPW with grains of green silicon carbide ($i = 5$) predicted the lowest effect (1.13 times).

The final evaluation of precision of HPW was carried out by QW_{ij}. Parallel reduced measures of position: $(SD,\ R)_{ij}$ of Gauss rival have auxiliary nature and are reduced in order to identify their ineffectiveness at "another field" [25]. The results by QW_{ij} (Table-6) are necessary to compare with data on descriptive statistics for non-parametric method (Figure-4), on which the real position is presented along coordinate axis $(\tilde{y}, R, QW)_{ij}$, $i = \overline{1;5}$, $j = 1;2$. From the Table 6 it can be seen that $t = 0.005$ mm the lowest quartile width QW_{41} is predicted for HPW 37*C* $(i = 4)$, and for $t = 0.005$ mm – for HPW 39*C* ($i = 5$). From the Figure 4 it can be clearly seen that percentiles $\left| y_{0.75} - y_{0.25} \right|_{41}$ for the wheel 37*C* actually provide for 50% of the ground parts the highest bearing surface, and the upper boundary of their range $y_{\max(41)}$ is slightly smaller than for HPW *CBN*30 *B*76. The less advantageous situation occurred for HPW 39*C* ($i = 5$) for grinding in the same conditions. As it can be seen from Figure-4, due to positive excess for (5) during grinding with HPW 39*C* ($i = 5$) median and QW_{52} are located lower than the center of distribution. The said for 50% of ground parts decreased value of a bearing surface as compared to HPW $i = 1;4$. At that percentile $y_{0.75(52)}$ for HPW *Norton* 39*C* is shifter as compared to $y_{0.25(i,2)}$, $i = 1;4$ for wheels *CBN*30 *B*76 and 37*C*. Thus, more than 50% of parts ground by HPW *Norton* 39*C*, at $QW_{52} = 7.521\%$ has lower bearing surface as compared with parts after grinding by HPW $i = 1;4$, which has larger QW, correspondingly, 9.852 и 12.556%.

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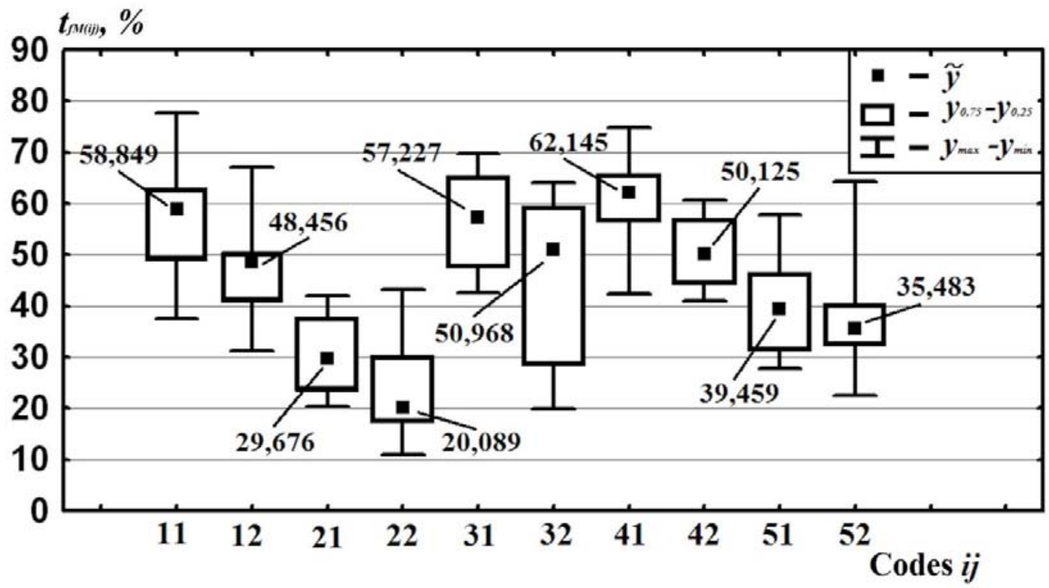

Figure-4. Descriptive statistics characterizing influence of wheels $\boldsymbol{i=\overline{1;5}}$ on the parameter $\boldsymbol{t}_{\boldsymbol{fM(ij)}}$ during grinding with depths 0.005 $\boldsymbol{(j=1)}$ and 0.01 mm $\boldsymbol{(j=2)}$.

Table-6. Evaluation of cutting capability of the wheels by measures of dispersion (5).

t_j, $j=1;2$	**wheel** $i=\overline{1;5}$	$\boldsymbol{SD_{ij}}$	$\boldsymbol{R_{ij}}$	$\mathbf{QW_{ij}}$	$\mathbf{K_{st(i)j1}}$ **(10)**	$\mathbf{K_{st(i)j2}}$ **(11)**	$\mathbf{K_{st(i)j2}}$ **(12)**
		%					
0.005 (1)	1	13.073	40.007	13.940	1.000	1.000	1.000
	2	7.621	21.549	14.422	1.715	1.857	0.967
	3	9.673	27.178	17.480	1.352	1.472	0.797
	4	8.588	32.528	8.767	1.522	1.230	1.590
	5	10.043	29.938	14.789	1.302	1.336	0.943
0.010 (2)	1	10.375	35.963	9.852	1.000	1.000	1.000
	2	9.626	32.222	12.483	1.078	1.116	0.789
	3	15.967	44.138	30.697	0.650	0.815	0.321
	4	6.918	19.642	12.556	1.500	1.831	0.785
	5	11.234	41.659	7.521	0.924	0.863	1.310
Note: Wheels i: 1 – CBN30 B76 100 OV K27 – KF40, 2 – CBN30 B126 100 OV K27 – KF40, 3 – CBN30 B151 100 OV K27 – KF40, 4 – 37C 46 I12 VP, 5 – 39C 46 I12 VP.							

As the result, HPW $i=5$ with bigger depth of grinding by number of parts of high quality by topography of surface surpasses only cutting capabilities of HPW *CBN*30 *B*126 with QW_{22} = 12.483%. The analyzed situation, which appeared in the course of grinding of parts made from VT22 by the wheel *Norton* 39*C* ($i=5$) with the largest depth t, definitely indicates that formal usage of measures of dispersion for non-parametric method can lead to methodological errors. In order to exclude those errors it is necessary to thoroughly analyze the asymmetry of distributions (2), which clearly illustrate descriptive characteristics. The obtained non-parametric evaluation of precision of formation of a bearing part of a surface with analogues from normal theory is of interest. At that, it should be noted that precise measures of dispersion in parametric method are standard deviations (1). According to those estimations the biggest repeatability of the process was provided by HPW: *CBN*30 *B*126 at $t=0.005$ mm and *Norton* 37*C* ($i=4$) at $t=0.010$ mm. Predictions of ranges conformed with those evaluations. It is clear that parametric estimations of stability of HPW operation considerably differ from rank method by QW. It allows considering them inadequate at "another field".

4. CONCLUSIONS

a) The study proved the efficiency of the application of the innovative parameter for the determination of a bearing area of macrogeometry of flat parts made from alloy VT22 with application of digital technologies.

b) It was established that the topography of surface of parts is characterized by anisotropy. The pseudo-regular macrorelief with cavities along the longitudinal feed is most explicitly shown in the right side along the width of the parts, from which they were cut in HPW at the final pass for cutting of the operation allowance. In the end of the pass at the left side of the part communicative cavities are virtually invisible.

c) Grinding of the parts made from VT22 by nitride-boron wheels strengthens the formation of pseudo-regular macrorelief of the surface as compared with HPW *Norton* with grains 37*C* and 39*C* due to a larger wear-resistance of cubic boron nitride and difficulties in setting of wheels.

d) In the conditions of violations of normality of distributions application of rank method instead of more well-known parametric analysis provided the increase of reliability of evaluation of the parameter t_{fM} by measures of the position (medians) and dispersion (QW).

e) It was established that for the depth of cutting of $t = 0.005$ mm the largest medians $m\,\hat{t}_{fM}$ = 54.42% were predicted for grinding with HPW CBN30 B151 100 OV K27 - KF40, and with $t = 0.01$ mm - HPW $i = 1;3;4$, among of which there is HPW $i = 3$ and also the aforementioned tool, which was predicted the best with the lowest depth of cutting.

f) By the precision of formation of parameter t_{fM} the best results by QW were predicted for HPW: 37C 46 I12 VP – at $t = 0.005$ mm; 39C 46 I12 VP – at $t = 0.01$ mm.

g) In the case of decrease of t from 0.01 to 0.005 mm the predicted medians of the parameter t_{fM} increased 1.13-1.24 times, that's why the final passes during cutting of the allowance must be carried out with decreased depth of cutting.

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