Surface Quality Multicriteria Optimization of Flat Parts from 06Cr14Ni6Cu2MoVaTi-SH Steel While Grinding by Varigrain High Porosity CBN Wheels

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Abstract. The grinding of flat parts from 06Cr14Ni6Cu2MoVaTi-SH high-strength corrosion-resistant steel was made by the highly porous wheel (HPW) of CBN30 (B76, B107, B126, V151) 100 OVK27-KF40 (GOST R 53922-2010, GOST R 53923-2010). As input variables for fuzzy logic modeling in the Matlab the following description of the surface quality is chosen: the microrelief parameters (GOST 25142-82) – $R_{a1}$, $R_{max1}$ in the cross-feed direction, $S_{max2}$ in the length feed direction, flatness deviation (GOST 24642-81) are introduced with the $EFE_{max}$, $EFE_{a}$, and $EFE_{q}$; microhardness $HV$. Every parameter at the model input is presented with position measures (medians) and scattering measures (quartile latitude). The Matlab modeling has shown that the best quality of the part surfaces is provided with HPW CBN30 B151 during the multicriteria optimization.

1. Introduction
The grinding is used at the final stage of the manufacturing of high load critical parts. Its effectiveness is estimated by a great number of factors, among which there is roughness, form error, microhardness and etc. relating to surface engineering [1]. Most of them are introduced with some correlated specified attributes. These attributes are difficult to be estimated qualitatively and with high accuracy. Thus, it seems to be impossible to describe physical analogs and their experimental ones are of particular character having a limited area of application. That is why it is settled to use fuzzy logic making it possible to analyze a large number of grinding variables and cover a wide range of process specification.

The fuzzy logic is a perspective trend of the cybernetics development suggested and elaborated by L. A. Zadeh [2]. He suggested using words and phrases for linguistic variables and inaccurate reasoning. As a result, the content, meaning of the information and processing logic is passed in the form of probability for problem solving that cannot be described exactly, specifically in engineering, like automatic control, diagnostics, artificial intelligence and etc. In this regard the fuzzy logic is equivalent to the fuzzy-set theory $A_1$, i.e. the classes with fuzzy boundaries, presented with the ordered
couple package made of the elements $y_i$ of the universal sets $\{y_i\}$ and corresponding grade of membership $\mu_A(y_i)$:

$$ A_i = \{ (y_i, \mu_A(y_i)) | y_i \in \{y_i\} \} , \quad v=\overline{1,n}. $$

The purpose of the present article is to study the interrelation between roughness, microhardness and flatness deviation of the surface of corrosion-resistant steel parts 06Cr14Ni6Cu2MoVaTi-SH (EP817-SH) with the help of the theory of fuzzy reasoning and the search for optimization parameters improving the quality of the part surfaces with pendulum grinding of the highly porous wheel (HPW) from the grains of cubic boron nitride (CBN).

## 2. Experimental technique

To implement the concept of fuzzy logic some grinding experimental data are used. The verification nature tests are carried out under the following constant conditions: flat surface grinding machine 3E711V; 1A1 wheels dimensioned of 200×20×76×5 mm (GOST R 53923-2010). The process-dependent parameters are cutting speed $v_w = 28 $ m/s, longitudinal feed $s_l = 6 $ m/min, cross-feed $s_c = 4 $ mm/double stroke, cutting depth $t=0.01 $ mm, operational allowance $z = 0.1 $ mm. The lubricant coolant 5% Akvoil-6 emulsion (TU 0258-024-0014842-98), is supplied flowing on the workpiece in the amount of 7-10 l/min; the number of duplicating tests is in (1) – $n = 30$. The test subject is forms of steel 06Cr14Ni6Cu2MoVaTi-SH with mechanical properties: $\sigma_{ust} = 1310-1400 $ MPa, $\sigma_{0.2} = 1210-1240 $ MPa, $\delta=12-14\%$, $\psi=57-60\%$ - and the dimension of $B\times L\times H = 60\times 60\times 60 $ mm, ground butt end $B\times L$. The index $i = 1; 4$ reflects the characteristics of HPW: 1-CBN30 B76 100 OV27-KF40; 2-CBN30 B107 100 OV27-KF40; 3-CBN30 B126 100 OV27-KF40; 4-CBN30 B151 100 OV27-KF40 (GOST R 53922-2010, GOST R 53923-2010), in which only the size of CBN grains (grain) from B76 (200/230) up to B151 (100/120), where in the brackets the grain is indicated in mesh. The parameters of surface roughness (GOST 25142-82): $R_a, R_z, R_{max}, S\mu S_m$ are measured with the profilograph-profilometer of 252 type produced by «Caliber» in two mutually orthogonal directions $i = 1; 2$ : correspondingly according to the vectors $s_l (R_{a1}, R_{z1}, R_{max1} \text{ and etc.})$ and $s_c (R_{a2}, R_{z2}, R_{max2} \text{ and etc.})$. The measuring of microhardness was made with the device PMT-3 under the condition of loading 1,96 H, the indenter lowering rate of 0,15 mm/s, the persistence time under load of 10-15s. The methods of searching for the attributes of flatness deviation (GOST 24642-81) such as the maximum $EFE_{max}$, arithmetic mean $EFE_a$, quadratic mean $EFE_a$ are discussed in the article [4].

The specificity of the grinding is that the cutting capacity of the HPW cannot be possibly imagined as a determined value during the edge cutting machining. The above mentioned is condition by the fact that the abrasive grain in the tools have an arbitrary shape, chaotic arrangement in the bonded, the difference in height in radial axis and a different number of operating grain and cutting edges per unit area of its contact with the entry into the workpiece. This makes it possible to examine the observation of random variables (RV) and estimate their behaviour on the base of probability-theoretic approaches. In this case the experimental data presentation is supposed to be given in the form of independent sets $l = \overline{1; k}$:

$$ \{ y_{\nu} \}, \quad v = \overline{1; 30}, $$

where $v$ is a number of replicate tests.

The statistical methods are divided into two groups: parametric and nonparametric, specifically rank ones. Each of them has «its own field» [3] for the effective use. In the first case it is necessary to ensure the fulfillment of the two constraints imposed on RV: homogeneity of variance of deviation and normalcy of distribution. The discussed grinding requirements are often violated to any extent that can be accompanied by a considerable bias of estimator, confidence bounds and factors [3]. In such a situation it is reasonable to use a nonparametric method that is not connected with a certain family of distributions and does not use its properties. RV are estimated by the following univariate frequency allocation [5-6], GOST R 5725-2-2012:

- position measures (reference values)
averages \( \bar{y}_i = y_i \),

medians \( \tilde{y}_i \),

- scattering measures (precision)
  deviation standards \( SD_i \), the swing \( R_i = (y_{max} - y_{min})_i \),
  quartile latitudes \( QL_i = (y_{0.75} - y_{0.25})_i \).

From the theoretical statistics it is known that a parametric method is based on the univariate frequency allocation (2), (4), (5), and the rank statistics is related to (3), (6). The acceptance of the null-hypothesis \( (H_0) \) by the homogeneity of variance of deviation and the normalcy of distribution is discussed in [5; 7]. To decrease labor content of the statistical calculations the software Statistica 6.1.478.0. is used in the research work.

The implementation of the fuzzy logic modeling for (2)-(6) is carried out in the MATLAB using a special bump pack of Fuzzy Logic Toolbox. The latter has a simple and well-engineered interface making it possible to easily design and diagnose fuzzy models [8-12]. For the assessment of the parts surface roughness quality Harrington’s desirability function \( d \) is used [13]. In its construction there is an idea of natural value conversion of individual response into a dimensionless desirability or preference scale being related to psychophysical ones. Its purpose is to set up compatibility between physical and psychological parameters. The physical parameters are thought to be some possible responses characterizing the functioning of the object under study. Experimentally assigning the desirability scale is the identifying of the compliance between the received surface quality values and their desirability assessment.

3. Research results and their discussion
Searching for HPW in the MATLAB the stress has been made on the reduction of the position measures and the scattering of the quality parameters excepting the reference value \( HV \). The microhardness should be maintained at the top level. As for microasperity it is a priori known that the most high level parameters are positioned in the cross-feed direction (\( R_{a1} \), \( R_{max} \) and etc.) and the step-by-step ones such as \( S_2 \) and especially \( S_{m2} \) are located along the vector \( s_1 \). As far as reference lengths of the profile \( t_p \) are concerned, it is known that, if a profile section level is constant, they do not depend on the grinding conditions [1]. Hence, they are excluded from the multicriteria optimization of grinding. Therefore, all of the above taken into account the process optimization according to the surface microgeometry is made with three parameters \( R_{a1} \), \( R_{max} \) and \( S_{m2} \) being the most important ensuring reliability and durability of machines.

The testing (1) on the homogeneity of variance of deviation is conducted according to three groups of criteria: Hartley, Cochren, Barlett (in the software they are united into one package); Levene; Brown-Forsythe. It showed that \( H_0 \) concerning the homogeneity (1) at 5% level of importance is accepted at all parameters. Much worse are the results of the normalcy of distribution testing according to Shapiro-Wilk criterion (Table 1), for which \( H_0 \) is accepted carrying out the inequality: \( \alpha_i > 0.5 \), where \( \alpha_i \) is acceptance reliability \( H_0 \) for the grinding parameters: \( (R_{a}, R_{max}, S_{m2}, EFE_{max}, EFE_{a}, EFE_{q}, HV) \), \( l = 1; 4 \). As is clear from Table 1, the normal distributions are found

| Parameter | Calculated significance level \( \alpha_i \) with variables \( l = 1; 4 \) |
|-----------|---------------------------------|
| \( Ra \)   | 0.0100 0.0175 0.2897 0.0184     |
| \( R_{max} \) | 0.1324 0.0239 0.7746 0.9949     |
| \( S_{m2} \) | 0.00005 0.0827 0.0551 0.0129    |
| \( EFE_{max} \) | 0.0584 0.2144 0.0028 0.0412     |
only in the two underlined cases out of 28 analyzed. Under the conditions of the normalcy of
distribution violation (1) it is reasonable to use the rank statistics method with its one-dimensional
distribution of frequencies (3) and (6). Modeling in the MATLAB the input data are assumed to be the
parameters given in Table 2.

| Quality parameters | \( EFE_a \) | \( EFE_q \) | \( HV \) |
|--------------------|-------------|-------------|--------|
| \( R_{a1} \), \( \mu m \) | 0.0635 | 0.0562 | 0.0270 |
| \( R_{\max} \), \( \mu m \) | 0.0864 | 0.1359 | 0.0077 |
| \( S_{m2} \), \( \mu m \) | 0.0112 | 0.0115 | 0.0462 |
| \( EFE_{\max} \), \( \mu m \) | 0.0112 | 0.0451 | 0.4736 |
| \( EFE_{al} \), \( \mu m \) | 0.0686 | 0.0462 | 0.4736 |
| \( EFE_{ql} \), \( \mu m \) | 0.0451 | 0.4736 | 0.4736 |
| \( HV \), MPa | 0.0270 | 0.0462 | 0.4736 |

Note. Wheels CBN30 100 OVK27-KF40: 1- B76, 2-B107, 3-B126, 4-B151

The methods of statistics do not permit to fully evaluate the quality of the ground surface, while the
microgeometry and precision of the parts form can be assessed by three characteristics for every
parameter. Meanwhile, every variable is additionally presented by position measures and scattering.
The above mentioned is even related to the parameter of \( HV \). The statistical methods can only
separately predict according to microhardness which HPW is better by reference values or which one
is better under the precision of its forming. Having regard to the above the method of fuzzy logic is
used making it possible to create an expert system of wheel classification in accordance with all the
researched parameters. At the model input the attributes \( (R_{a1}, \ R_{\max}, \ S_{m2}, \ EFE_{\max}, \ EFE_{al}, \ EFE_{ql}, \ HV) \), \( l = 1; 4 \) simultaneously satisfying (3) and (6) are sent. The
output of the model is the assessment of the surface quality for every HPW.

| Wheel \( l \) | Surface roughness | Flatness deviation | Microhardness |
|-------------|-------------------|--------------------|--------------|
| \( R_{a1} \) | \( R_{\max} \) | \( S_{m2} \) | \( EFE_{\max} \) | \( EFE_{al} \) | \( EFE_{ql} \) | \( HV \) |
| 1 | 0.500 | 0.499 | 0.823 | 0.827 | 0.870 | 0.870 | 0.825 |
| 2 | 0.656 | 0.827 | 0.173 | 0.173 | 0.130 | 0.132 | 0.173 |
| 3 | 0.175 | 0.174 | 0.541 | 0.620 | 0.367 | 0.473 | 0.500 |
| 4 | 0.809 | 0.821 | 0.821 | 0.797 | 0.827 | 0.820 | 0.787 |

Note. Grain \( l \): 1- B76, 2-B107, 3-B126, 4-B151

The received input attributes are given in Table 3 and estimated with desirability function \( d \) [13].
According to the results shown in Table 3 a general model for HPW grain choice, \( i = 1; \ldots, n \), is developed in the conditions of synchronous position measures and scattering decreasing by all parameters of the surface roughness and flatness deviation. The model consists of four variables: three of them are input and one is output (Figure 1). Every input variable value is represented by a numerical range \([0; 1]\) and its layout into three classes is shown in Table 4. From the analysis of the input parameters the microhardness is excluded, as it is represented by one attribute.

![Figure 1. The system of complex assessment of the parts quality parameters in accordance with all parameters of the surface roughness and flatness deviation](image)

| Type of assessment | Input parameters |
|--------------------|------------------|
| Linguistic         | bad              | middle            | good              |
| Numerical          | \([0.1; 0.5]\)    | \([0.1; 0.5; 0.5; 0.9]\) | \([0.5; 0.9]\)    |

Table 4. Input parameters researching for HPW grain according to complex quality assessment of ground steel parts 06Cr14Ni6Cu2MoVaTi-SH

The membership function of «Output» input variable is presented by five classes of ground parts quality as in Table 5 and Figure 2.

![Figure 2. The membership function for the variable «Output» solving the problem of the search for the HPW optimum grain according to the complex assessment of the surface roughness and flatness deviation](image)
Table 5. Parameter of «Output» searching for HPW optimum grain according to complex quality assessment of ground parts

| Type of assessment | Input parameters |
|-------------------|-----------------|
| Linguistic        | Very bad        | bad | satisfactory | good | very good |
| Numeric $d$       | [0; 0.2)        | [0.2; 0.37) | [0.37; 0.63) | [0.63; 0.8) | [0.8; 1] |

The rules of fuzzy reasoning for the developed system include $N = 3 \times 3 \times 3 = 27$ of possible combinations of output parameters. In Table 6 there are the fuzzy rules for the system of parts surface quality classification. In the batch of Fuzzy Logic Toolbox there is a graphic interface simplifying the user’s view of the rules of reasoning (Rule Viewer). Using the graphic format all possible reductions are shown, that makes it possible to forecast an output variable - Output. Every change of parts feature is displayed in the view of the output rules changing it accordingly.

Table 6. Fuzzy rules of parts classification system

| Variant | $R_{d1}(EFE_{max})$ | $R_{max1}(EFE_{a})$ | $S_{md}(EFE_{q})$ | Output |
|---------|---------------------|---------------------|-------------------|--------|
| 1       | good                | good                | good              | very good |
| 2       | good                | good                | middle            | very good |
| 3       | good                | good                | bad               | good   |
| 4       | good                | middle              | good              | very good |
| 5       | good                | middle              | middle            | good   |
| 6       | good                | middle              | bad               | satisfactory |
| 7       | good                | bad                 | good              | good   |
| 8       | good                | bad                 | middle            | satisfactory |
| 9       | good                | bad                 | bad               | bad    |
| 10      | middle              | good                | good              | good   |
| 11      | middle              | middle              | middle            | good   |
| 12      | middle              | good                | bad               | satisfactory |
| 13      | middle              | middle              | good              | good   |
| 14      | middle              | middle              | middle            | satisfactory |
| 15      | middle              | middle              | bad               | bad    |
| 16      | middle              | bad                 | good              | satisfactory |
| 17      | middle              | bad                 | middle            | bad    |
| 18      | middle              | bad                 | bad               | very bad |
| 19      | bad                 | good                | good              | good   |
| 20      | bad                 | good                | middle            | satisfactory |
| 21      | bad                 | good                | bad               | bad    |
| 22      | bad                 | middle              | good              | satisfactory |
| 23      | bad                 | middle              | middle            | bad    |
| 24      | bad                 | middle              | bad               | very bad |
| 25      | bad                 | bad                 | good              | bad    |
The received results of the HPW grain influence on the complex assessment of the parts surface microrelief of corrosion-resistant steel 06Cr14Ni6Cu2MoVaTi-SH are presented in Table 7.

The results in Table 7 show that the HPW with the maximum grain of B151 increasingly satisfy reducing the surface roughness, according to flatness deviation and microhardness the best HPW is the one with the lowest grain of B76.

**Table 7. HPW grain influence on complex assessment of surface roughness, flatness deviation and microhardness**

| Grain (l = 1; 4) | By surface roughness | By flatness deviation | By microhardness |
|------------------|----------------------|-----------------------|------------------|
|                  | d        | Output | d        | Output | d        | Output |
| B76 (1)          | 0.676    | Good   | 0.872    | Very good | 0.825    | Very good |
| B107 (2)         | 0.566    | Satisfactory  | 0.114    | Very bad  | 0.173    | Very bad  |
| B126 (3)         | 0.184    | Very bad  | 0.425    | Satisfactory | 0.500    | Satisfactory  |
| B151 (4)         | 0.820    | Very good  | 0.822    | Very good  | 0.787    | Good |

The finite problem of the research is the look for the optimum grain between HPW $l = 1; 4$, that would minimize the position measures for the surface roughness and flatness deviation at the same time, the microhardness would reach its maximum. In this respect the precision of all quality parameters should be the largest, i.e. their measures of dispersion should be minimized. With this in mind, a model of four variables is generated: three of them are input and one is output (Figure. 3). The values of every input variable fit the output ones shown in Table 7.

**Figure. 3.** The system of complex assessment of parts quality parameters

The results of HPW grain influence on the complex assessment of parts surface quality of corrosion-resistant steel 06Cr14Ni6Cu2MoVaTi-SH are given in Table 8.
### Table 8. HPW grain influence on complex assessment of parts surface quality

| Grain ($l = I; 4$) | $d$   | Output   |
|-------------------|-------|----------|
| B76 (1)           | 0.7959| good     |
| B107 (2)          | 0.1613| very bad |
| B126 (3)          | 0.3034| bad      |
| B151 (4)          | 0.8234| very good|

The fuzzy logic modeling helped us determine that the HPW with the grain of B151 to the fullest extent ensures the multicriterion quality optimization of part surfaces. The received data have been similar to those ones foreseen at the first stage of the investigation. The multicriterion optimization of HPW features is very important during robust design of grinding operations, that should be carried out with the help of the best basic tooling. This will optimize all target process functions with much more effectiveness.

### 4. Conclusion

1. The surface roughness, microhardness and flatness deviations are important factors estimating the microrelief of part surfaces. They are characterized by a great number of standardized parameters assessed by the position and scattering measures. This complicates the choice of optimum characteristics of the wheels using the statistical methods.

2. In conditions where homoscedasticity and normalcy of distribution of the experimental data are violated, to realize the fuzzy logic it is reasonable to consider nonparametric assessment of the position and scattering measures, to which medians $\tilde{y}_l$ and quartile latitude $QL_l$ relate.

3. As a result of the fuzzy logic modeling in the MATLAB it is found that HPW CBN30 B151 100 OVK27-KF40 during grinding parts from 06Cr14Ni6Cu2MoVaTi-SH steel ensure the best quality of the surface according to the complex quality assessment of the ground parts. The use of the wheels increase the efficiency of the robust design of grinding operations, as the search for the basic models of the multiple variance analysis is fulfilled with the tools of the optimum features.

4. The modeling results can be used in local grinding problem solving. For example, to choose the optimal wheel grain by surface roughness, flatness deviation or microhardness. It has been established that the HPW with the greatest grain of B151 reduces all surface roughness and the HPW with the lowest grain of B76 has advantages of flatness deviation and microhardness.

### References

[1] Suslov A G, Bezyazichny V F, Panfilov Y V et al. 2008 Surface Engineering details Mechanical Engineering (Mashinostroyenie) (Moscow) 320.

[2] Zadeh L A 1988 Fuzzy logic IEEE Transactions on Computers 21 4 83–93.

[3] Hollander M and Wolfe D A 1999 Nonparametric statistical methods, Second Edition Wiley-Interscience 787.

[4] Soler Ya I and Nguyen V L 2015 Selection of synthesis corundum Crain in Grinding flat parts from hardened steel 30ChGSA the macrogeometry criterion Applied mechanics and material 788 95-101.

[5] Zaks L 1976 Statistical estimation (Statisticheskoye otsenivanie) // Transl. from German M.: Statistika. 598.

[6] Willer D and Chambers D 2009 Statistical process management (Statisticheskoye upravlenie protsesami) // Transl. from English M.: Alpina Business Books 469.

[7] Soler Ya I and Kazimirov D Yu 2010 Selecting abrasive wheels for the plane grinding of airplane parts of the basis surface roughness Russian engineering research.30 3 251-261.
[8] Ali Y M and Zhang L C 1999 Surface roughness prediction of ground components using a fuzzy logic approach Journal of Materials Processing Technology 561–568.
[9] Ali Y M and Zhang L C 2004 fuzzy model for predicting burns in surface grinding of steel Int J Mach Tool Manu 44 563.
[10] Vyatchenin D A 2004 Fuzzy methods of automatic classification UP Technoprint (Minsk) 219.
[11] Kofman A 1982 Introduction to the theory of fuzzy sets M. Radio and communication (Radio i svyaz) 432.
[12] Leonenkov A V 2005 Fuzzy modeling in MATLAB and FuzzyTech BXV-Petersburg (St. Petersburg) 736.
[13] Harrington E C 1965 The desirability function // Industrial Quality Control Industrial Quality Control 21 494-498.