Influence of characteristics of abrasive wheels on surface qualities of high-speed plates HS10-4-3-10 at flat grinding

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Abstract. The article presents the results of the influence of characteristics abrasive wheel on the surface qualities of high-speed plates HS10-4-3-10 at flat grinding with using statistical method and fuzzy logic simulation. Parameters of surface quality were estimated according by: microrelief Ra, Rmax, Sm; accuracy form EFEmax, EFEm; microhardness HV, for each parameter is represented by median and quartile latitude. Results of fuzzy logic simulation can use for selection of based elements of the wheel characteristic, to optimize each parameter of surface quality. Optimal abrasive wheel by all parameters in the greatest measure responses predicted as follows: 25AF46K10V5-P03, 5NQ46I6VS3 and 5SG60K12VXP with the maximum values of the desirability function. Receiving results will be used for optimization of grinding process according by theory of experimental design.

1. Introduction
The grinding process has some features. First of all, the cutting capacities of abrasive tool does not seem possible to characterize the deterministic value, because of the rest of the blade machining processes. As is known, abrasive grains have an arbitrary shape, chaotic arrangement in a bundle, different heights in the radial direction. On this basis, they are divided into cutting, pressing and non-working. Subsequently, the grains differ in the amount of edges, cutting-point angle and radius of there curvature. In the first approximation, the microroughnesses of the part is considered a "mould" of the working surface of the abrasive tool. The high speed and intensity of the heat source cause structural-phase transformations in the surface layer of high-speed cutting plates (HSCPs) [1, 2], leading to a decrease in the resistance of precast cutting tools.

High-speed cutting steel HS10-4-3-10 has an increased tendency to decarburization, reduced toughness, increased wear resistance, reduced grindability. They destine for the manufacture of tools used in the processing of high-strength stainless and heat-resistant steels, alloys and improved alloy steels in conditions of increased heating of the cutting edge: gear-cutting tools, milling and shaped tools, countersinks, taps. Table 1 show chemical composition in % of material weight and steel grades of different standards of HS10-4-3-10 [3].

The problem of grinding process is multi-purpose. It is provided for prediction, increasing of efficiency process, optimization of adaptive control and other methods of the product life of abrasive wheel: manufacturing, working conditions, repair and adjustment processes... For each of them there are special requirements to identify the quality (accuracy form, local of parameters, operational efficiency) of the objects involved [1].
The purpose of current paper is to selecting the optimal abrasive wheel on a surface topography while the surface grinding high-speed cutting steel HS10-4-3-10 using statistical method and fuzzy logic simulation for increasing of the efficiency of grinding process.

2. Materials and methods

The procedure is organically divided into stages: The natural experiment and analysis data of experiment using statistical methods and fuzzy logic simulation.

2.1. Experiment

The experiments were conducted by the periphery of abrasive wheels: abrasive wheels standard porosity - standard porosity, most often the 6th structure; highly porous wheels - 10 - 12th structures. The removal of the operating allowance corresponded to a pendulum scheme without standard grooming at the end of the grinding cycle. Following unchanged conditions were adopted: surface grinding machine 3G71M; the subject of experiment - grinding of plates HS10; the characteristic of wheels area 3G71M; the subject of experiment - surface grinding high-speed cutting steel HS10-4-3-10 (HV_{initial}=7200 mPa) with the size 40x60 mm; abrasive wheels in below part; technological parameters: speed of wheel – v_{w}=35 m/s, cutting deep t=0.015 mm, the operating allowance z=0.15 mm, longitudinal feed s_{c}=7 m/min, cross-feed s_{c}=1 mm/double stroke; cutting fluids – 5% lubrication of emulsion Akvol-6 (TU 0258-024-00148845-98) with speed of flow 7-10 l/min.

The characteristic of wheels area \( i = 1;16 \) contain the following information by GOST P52381-2005 (GOST – Russian State Standard), GOST P52587-2006 and catalogs [4, 5]:

- Standard-porous wheels of different manufacturers (\( i = 1;5 \)): 1–5A46L10VAX, 2–EKE46K3V (corporations Abrasives Corundum, Germany); 3–5NQ46I6VS3 (Norton Vitrium); 4–92A/25AF46L6V20, 5–34AF60K6V5 (Russia).
- High-porous wheels of Norton company (\( i = 6;9 \)): 6–5SG46K12VXP, 7–5SG46I12VXP, 8–5SG60K12VXP, 9–TGX80I12VCF5 (Altos);
- High-porous wheels of Russian production (\( i = 10;16 \)): 10–25AF46M12V5-ПО, 11–25AF46M12V5-ПО3, 12–25AF46M10V5-ПО, 13–25AF46M10V5-ПО3, 14–25AF46K10V5-ПО3, 15–25AF60M10V5-ПО, 16–25AF46L10V5-КФ35;

In round Norton Vitrium \( i = 3 \), as high-porous wheels \( i = 6;8 \), number 5 means, betwenness seeds NQ (Norton Quantum) and usual aluminum oxide SG couched in parity. In Russian standard-porous wheel \( i = 4 \) this condition was realized for the seeds 92A and 25A. In the round Altos (\( i = 9 \)) to seeds TGX were added grain material of sintercorundum SG in parity. Marking of rounds \( i = 4;5;10;16 \) are in following link [5], although there is a letter F before the number of grain. To the greatest extent, the designations of characteristics differ for wheels from monocorundum \( i = 1 \); 2, in which the marking of grains depends on method of making a round: 5A (\( i = 1 \)) is pressurized, EKE (\( i = 2 \)) is cast. The designation of the other constituents of the characteristics of the wheel \( i = 1 \) coincides, to the greatest
extent with the Russian, except of the structure. In Russian instruments, the numbers of structures are 10; 12 - belong to the highly porous, but the wheel 5A - 10th structure is classified open, and (13 - 20) - the according to the catalog [4] are considered highly porous. In the cast tool i = 2, index "K" indicates the average structure and the number "3" indicates the hardness "soft".

Parameters of the surface quality of the HSCPs were selected: the greatest roughness, specifically – $R_{ai}$, $R_{maxi}$ and $S_{mi}$; accuracy form – $EFE_{maxi}$ and $EFE_{ai}$; microhardness $HV_i$. Characteristic of parameters and the method of their measurement are given in [2, 6, 7].

2.2. Statistical methods and fuzzy logic simulation
The cutting capacities of abrasive tool are considered variable values. For the interpretation of observations probability-theoretical approaches are used [2, 8-9]. Reduction of the labor intensity of statistical computations is achieved by using of software products, in particular, Statistica 10. In forced of analysis of the experimental data:

$$\{y_{ijv}\}, \ i = \overline{1;16}, \ j = \overline{1;6}, \ v = \overline{1;30},$$

(1)

where $j$ – number of parameters, $v$ – number of measurement for each parameter. It is possible to lead with the involvement of parametric (average $y_{ij}$, standard deviations $SD_{ij}$ and ranges $R_{ij}=y_{maxij}-y_{minij}$) and nonparametric (median $y_{ij}$ and quartile latitude $Q_{ij}=|y_{0.75}-y_{0.25}|$) statistical methods. Each of them has "its own field" [8] for effective exertion in technical applications. For the parametric method, it is necessary that all Eq. (1) possess the properties of homogeneity of variance deviation and normality of distributions. Otherwise, the exact criteria of this method lose their reliability and can lead to the adoption of incorrect statistical decisions. In a similar situation, it is more expedient to use ranking statisticians which are not related to any family of distributions and do not use its properties.

The choice of statistical methods is described in [8, 9]. Throughout of this study, we confine ourselves to stating that the procedure for interpreting Eq. (1) has been reduced to one stage as follow: a one-dimensional variance analysis for detecting a significant difference between the levels of measures positions without their nominal search.

The theory of fuzzy logic simulation opens up new possibilities in classification problems, optimal conditions and optimal process of manufacturing which in contrast to traditional statistical methods and allows using the more adaptable methods to represent the initial data of structure [10, 11]. Fuzzy logic simulation is equivalent to theory of fuzzy sets $A_{ij}$ which classes with diffuse boundaries represented by sets of ordered pairs, composed of elements $y_{ijv}$ of universals sets $\{y_{ijv}\}$ and the corresponding of membership $\mu_{A_{ij}}(y_{ijv})$:

$$A_{ij} = \{(y_{ijv}, \mu_{A_{ij}}(y_{ijv}))| y_{ijv} \in \{y_{ijv}\}\},$$

(2)

where $\mu_{A_{ij}}(y_{ijv})$ is the characteristic functions that indicate the degree of membership $y_{ijv}$ of fuzzy sets $A_{ij}$.

The desirability function (d) of fuzzy system was proposed by Harrington which is determined by the expression [10, 11]:

$$d = \frac{\sum_{n=1}^{s} z_n S_n(u)}{\sum_{n=1}^{s} S_n(z_n)}, \ u = \overline{1; s}$$

(3)

where $s$ - is the number of functions belonging to the output term in the base rule; $z_n$ - output value of the system corresponding to the rule having membership function; $S_n, S_n(z_n)$ - the value of the membership function of the term, equal to truth degree of sub-clause of this rule.

The simulation process the fuzzy logic in the Matlab environment, was used a special Fuzzy Logic Toolbox extension package.
3. Results and Discussions

The results of the experiment according to median (med.) and QL after statistical processing (Table 2) are considered input variables for modeling topography of the surface of HSCPs HS10-4-3-10 in the fuzzy logic simulation.

**Table 2. Input variables for the simulation of cutting capacities of wheels in the fuzzy logic toolbox**

| Wheel | \( R_{ai}, \mu m \) | \( R_{maxi}, \mu m \) | \( S_{mi}, \mu m \) | \( EFE_{maxi}, \mu m \) | \( EFE_{ai}, \mu m \) | \( HV_{i}, \text{mPa} \) |
|-------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
|       | med. | QL | med. | QL | med. | QL | med. | QL | med. | QL |
| 1     | 0.056 | 0.015 | 0.363 | 0.071 | 56.22 | 14.00 | 16.00 | 2.75 | 11.42 | 2.50 | 5824.95 | 734.35 |
| 2     | 0.060 | 0.012 | 0.408 | 0.100 | 60.19 | 19.81 | 15.00 | 1.00 | 9.38 | 1.25 | 8568.03 | 1654.71 |
| 3     | 0.049 | 0.023 | 0.329 | 0.153 | 50.64 | 9.72 | 15.00 | 1.75 | 11.29 | 0.83 | 8895.90 | 882.68 |
| 4     | 0.065 | 0.025 | 0.395 | 0.109 | 42.18 | 13.86 | 15.00 | 1.00 | 11.17 | 2.88 | 7190.38 | 933.58 |
| 5     | 0.057 | 0.014 | 0.347 | 0.088 | 46.22 | 13.30 | 17.00 | 3.75 | 12.46 | 2.69 | 6863.94 | 596.74 |
| 6     | 0.047 | 0.017 | 0.307 | 0.129 | 57.05 | 17.97 | 15.00 | 3.00 | 11.46 | 1.90 | 7747.19 | 615.91 |
| 7     | 0.050 | 0.018 | 0.353 | 0.138 | 50.30 | 18.88 | 18.00 | 2.75 | 12.00 | 3.54 | 7918.75 | 620.63 |
| 8     | 0.048 | 0.020 | 0.347 | 0.126 | 53.29 | 32.20 | 14.00 | 5.25 | 8.75 | 2.13 | 8033.13 | 486.09 |
| 9     | 0.055 | 0.019 | 0.367 | 0.111 | 48.96 | 21.87 | 16.00 | 6.25 | 10.25 | 5.88 | 6002.68 | 1424.52 |
| 10    | 0.070 | 0.030 | 0.463 | 0.204 | 79.28 | 33.17 | 12.00 | 2.75 | 7.75 | 1.51 | 9445.00 | 896.80 |
| 11    | 0.080 | 0.020 | 0.510 | 0.143 | 50.59 | 22.88 | 18.00 | 4.75 | 10.42 | 2.35 | 7861.56 | 817.97 |
| 12    | 0.080 | 0.040 | 0.550 | 0.249 | 67.78 | 33.21 | 12.50 | 3.00 | 7.75 | 1.98 | 10553.73 | 1294.39 |
| 13    | 0.095 | 0.133 | 0.675 | 0.709 | 73.15 | 32.86 | 16.50 | 4.75 | 9.75 | 3.69 | 9092.63 | 811.40 |
| 14    | 0.079 | 0.021 | 0.511 | 0.133 | 65.12 | 22.32 | 12.00 | 1.00 | 9.17 | 1.88 | 8376.25 | 714.85 |
| 15    | 0.080 | 0.030 | 0.550 | 0.222 | 68.53 | 32.76 | 14.75 | 6.88 | 8.17 | 4.97 | 7487.75 | 501.53 |
| 16    | 0.120 | 0.150 | 0.820 | 0.923 | 66.22 | 35.69 | 18.00 | 6.00 | 11.54 | 3.60 | 7416.25 | 776.81 |

As the Table 2 shows, the cutting capacities of wheels are the most correlated with the heights of microroughnesses. In particular, their growth from the median \( R_{maxi}(0.32) \) for the Norton wheel \((i=6)\) to 0.82(1.0) \( \mu m \) for the high-porous wheels 25AF6L10V5-KF35 \((i=16)\) was noted. Here categorical values are placed in parentheses (GOST 2789-73). We have a deterioration of the topography of the surface by the greatest roughness of six categorical values. At the same time, for the analyzed instruments parameter \( R_{ai}(med.) \) increased from 0.047(0.05) to 0.12(0.125) \( \mu m \), respectively for five categorical values. Concerning the average step irregularities \( S_{mi} \) in the longitudinal direction, it is worth noting the wheels \( i=4; 5; 9 \) that made it possible to obtain them within the limits of categorical value not more 50 \( \mu m \). At the same time, steps increasing to \( S_{mi} \), \( i=10; 13 \) to categorical value 80 \( \mu m \), on three values from the regulated series (GOST 2789-73). In the design documentation, the state of the surface of the HSCPs are often regulated by parameter \( R_{a} \). On this parameter, Norton wheels \( i=3; 6; 8 \) are undisputed leaders, which are providing a micron categorical value 0.05 \( \mu m \). The choice of the optimum characteristics of the abrasive tool by this parameter \( R_{a} \) allows reducing the number of transitions in the developed grinding operation or increasing it productivity while maintaining the roughness. In similar conditions, cutting capacities of wheels increased the accuracy of the HSCPs form by one qualifier value (GOST 24643-81) and microhardness of their surface increased by 1.6-1.8 times. In both cases, the best results showed wheels \( i=12; 16 \). Even, by taking into account medians, it is difficult to choose a wheel that would ensure the best state of the topography of the HSCP surface. If the analysis includes QL, then this problem cannot be realized on basis of statistical methods.

Table 3 presents the results of the first stage of fuzzy logic simulation for each parameter by the wheel; they were estimated by the attributes of medians and QL:

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*Table 3: Results of the first stage of fuzzy logic simulation for each parameter by the wheel.*

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For each parameter, the best result by attributes median and QL is predicted wheels: \( Ra - i=1, 2, 5, 6; R_{max} - i=1, 2, 5; S_m - i=3, 4; EFE_{max} - i= 2, 4; EFE_a - i=2, 3 \) and HV – \( i=8, 15 \);

From table 3 it is established that when grinding HSCPs HS10-4-3-10 recommend using abrasive wheels with characteristics: hardness \( K \), grain size F60, number of porous 12.

**Table 3.** The results of fuzzy logic on the differential estimation of cutting capacities of wheels

| Wheel | \( d_s(R_{a1}) \) | \( d_s(R_{max}) \) | \( d_s(S_m) \) | \( d_s(EFE_{max}) \) | \( d_s(EFE_a) \) | \( d_s(HV) \) |
|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1     | 0.848           | 0.828           | 0.531           | 0.602           | 0.581           | 0.401           |
| 2     | 0.860           | 0.793           | 0.500           | 0.856           | 0.773           | 0.210           |
| 3     | 0.767           | 0.681           | 0.687           | 0.745           | 0.840           | 0.513           |
| 4     | 0.724           | 0.776           | 0.644           | 0.856           | 0.545           | 0.501           |
| 5     | 0.855           | 0.796           | 0.545           | 0.533           | 0.532           | 0.661           |
| 6     | 0.843           | 0.701           | 0.501           | 0.578           | 0.661           | 0.653           |
| 7     | 0.829           | 0.716           | 0.506           | 0.557           | 0.506           | 0.648           |
| 8     | 0.807           | 0.733           | 0.442           | 0.528           | 0.629           | 0.826           |
| 9     | 0.805           | 0.765           | 0.513           | 0.527           | 0.500           | 0.202           |
| 10    | 0.673           | 0.628           | 0.324           | 0.602           | 0.722           | 0.559           |
| 11    | 0.809           | 0.722           | 0.505           | 0.409           | 0.599           | 0.513           |
| 12    | 0.568           | 0.574           | 0.407           | 0.578           | 0.650           | 0.746           |
| 13    | 0.332           | 0.500           | 0.420           | 0.526           | 0.510           | 0.523           |
| 14    | 0.795           | 0.790           | 0.500           | 0.857           | 0.666           | 0.556           |
| 15    | 0.673           | 0.605           | 0.423           | 0.516           | 0.504           | 0.806           |
| 16    | 0.121           | 0.287           | 0.291           | 0.497           | 0.511           | 0.525           |

As it can be seen from table 3 for selecting abrasive wheel which ensuring all quality parameters is difficult. Solving this problem needs to do the second stage of fuzzy logic simulation. The value for each variables input to be in the numerical interval \([0; 1]\) with linguistic estimation: \([0; 0.5]\) – Bad; \([0; 0.5; 0.5; 0.9]\) – Middle and \([0.5; 0.9]\) – Good. The desirability function of output (integral estimation) including 4 estimates with numerical intervals and linguistic: \([0; 0.37]\) – Low; \([0.37; 0.63]\) – Normal; \([0.63; 0.80]\) – Good and \([0.8; 1.0]\) – High.

**Table 4.** The influence of characteristics of wheels on the complex evaluation of surface quality of HSCPs

| Wheel (i) | \( d_s \) | Output (class)                        |
|----------|----------|---------------------------------------|
| 5A46L10VAX (1) | 0.57 | Normal Cutting Capacities               |
| EKE46K3V (2)   | 0.68 | Good Cutting Capacities                |
| 5NQ46I6VS3 (3) | 0.72 | Good Cutting Capacities                |
| 92A/25AF46L6V20 (4) | 0.67 | Good Cutting Capacities                |
| 3AF660K6V5 (5) | 0.57 | Normal Cutting Capacities 1            |
| 5S64612VXP (6) | 0.65 | Good Cutting Capacities                |
| 5S6412VXP (7) | 0.58 | Normal Cutting Capacities              |
| 5S6612VXP (8) | 0.72 | Good Cutting Capacities                |
| TGX8012VCF5 (9) | 0.50 | Normal Cutting Capacities              |
| 25AF46M12V5-II0 (10) | 0.60 | Normal Cutting Capacities              |
| 25AF46M12V5-II0 (11) | 0.53 | Normal Cutting Capacities              |
| 25AF46M10V5-II0 (12) | 0.55 | Normal Cutting Capacities              |
| 25AF46M10V5-II0 (13) | 0.50 | Normal Cutting Capacities              |
| 25AF46K10V5-II0 (14) | 0.74 | Good Cutting Capacities                |
| 25AF60N10V5-II0 (15) | 0.57 | Normal Cutting Capacities              |
| 25AF46L10V5-KФ35 (16) | 0.31 | Low Cutting Capacities                 |
Table 4 presents the fuzzy simulation result of the second stage. The last has a simple and well-designed interface that make to choosing optimal abrasive wheel for the optimization of grinding process. Integral assessments of the cutting capacities of wheels (table 4) revealed new leaders in ensuring quality surface of the HSCPs HS10-4-3-10. In particular, the abrasive tools \( i=14; 8; 3 \) which includes in the first subclass with the integral evaluation of "good" at the first stage of modeling in the fuzzy logic environment showed themselves on the best side: \( i=14 \) – twice in the parameters \( R_{max}, \text{EFE}_{max} \); \( i=8 \) - once by HV; \( i=3 \) - twice by Sm, EFEa, i.e. by one - two parameters from possible variables \( j=1; 6 \). The correct choice of abrasive tool characteristics is important, when robust design of grinding operations performed by the best (basic) tool. This approach allows optimizing all objective functions with the greatest efficiency.

Modeling of fuzzy logic by size \( d_i \) additionally allows analyzing the role of individual components in the characteristics of wheels:
- It is advisable to grind the HSCPs HS10-4-3-10 with abrasive wheels hardness \( K \) (medium soft MS1). In particular, it is advisable to use the wheels 5SG46K12VXP (\( i=6 \) \( d_{0}\star = 0.654 \)) and 25AF46K10V5-PO3 (\( i=14 \) – \( d_{1}\star = 0.735 \)), which in comparison with wheels 5SG46I2VXP (I-soft M2) and 25AF46M10V5-PO3 (M-average hardness of C1), allows increasing the desirability function in 1.14 and 1.46 times.
- It is established that with the increasing of grain size from 60 (F60) to 46 (F46) is accompanied by a smaller increase in the desirability function compared to the role of hardness: in 1.1 times for high-porous wheels Norton (\( i=8; 6 \)); for high-porous wheels from grains 25A (\( i=15; 12 \) - only 1.02 times.
- It was found that the wheels of 25AF46M12V5-PO (\( i=10, d_{0}\star = 0.599 \)) and 25AF46M12V5-PO3 (\( i=11, d_{11}\star = 0.534 \)) with structure 12 allowed increasing the quality of HSCPs HS10-4-3-10 compared to the high-porous wheels of 10th structure: 25AF46M10V5-PO (\( i=12, d_{12}\star = 0.554 \)) and 25AF46M10V5-PO3 (\( i=13, d_{13}\star = 0.502 \)).
- Wheels with the pore-forming agent PO (\( i=10; 12 \) are more effective than the high-porous wheels with PO3 (\( i=11; 13 \)).

4. Conclusion

The contravention of verification of distribution normality of observations, in connection with foregoing information of surface quality HSCPs, the nonparametric statistic is selected that is characterized median and quartile latitude.

In flat grinding of high-speed cutting plates HS10-4-3-10, the optimal abrasive wheel for each parameter of surface quality was predicted: \( R_a \) – \( i=2; R_{max} \) – \( i=1; S_m \) – \( i=3; \text{EFE}_{max} \) – \( i=14, 2, 4; \text{EFE}_a \) – \( i=3 \) and HV – \( i=8 \).

In these well-tried wheels for grinding steel HS10-4-3-10 recommend the abrasive wheel with characteristics: hardness K, grain size F60, number of porous 12.

Optimal abrasive wheel by all parameter of grinded surface quality HSCPs predicted 25AF46K10V5-PO3, 5NQ46I6VS3 and 5SG60K12VXP with the greatest values of the desirability function.

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