Searching for abrasive wheels characteristics to improve grinding quality of parts from alloy 1933T2

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Abstract——**Selection of optimization results of abrasive wheels characteristics of the surface quality with fuzzy logic involvement are carried out in flat grinding conditions of high-strength aluminum alloy 1933T2 parts. The quality of grinded surfaces was evaluated using three groups of parameters: roughness, indicators of flatness deviations, microhardness; each of them is represented by measures of position and dispersion: the median and quartile latitudes. Statistical methods do not have complex analysis capability of a large number of process output parameters. According to the results of fuzzy logic modeling in MATLAB environment, it was found that the best cutting abilities of abrasive wheels as a whole complex of the studied parameters during grinding of parts of high-strength aluminum alloy 1933T2 were predicted for high porous wheels of silicon carbide green 08C046I12V01P02 and 39C46I12VP with the «good» rating, and the worst -for sinter-corundum 5SG46K12VXP.**

Keywords——*flat grinding; aluminum alloy; abrasive wheel; nonparametric statistics; fuzzy logic*

I. INTRODUCTION

Aluminum alloys are promising materials that are currently used in many fields of industry and first of all in aviation industry, automobile manufacturing, etc. Final processing has a great impact on the surface layer quality of the parts and, accordingly, on their performance characteristics. Grinding of aluminum alloys parts is characterized by the following features: high cutting speeds, low forces and grinding temperatures and abrasive tool loading [1;2]. It is advisable to use tools with special characteristics for aluminum alloys grinding.

High-porous wheels (HPW) grinding has shown [3] that they can reduce the roughness of the treated surface within the categorical value and can increase the microhardness by 1.4 times. HPW provide a machine time reduction and reduce the cost of operations.

High quality indicators for modern machines and units in aerospace, automotive, electronics and other fields of mechanical engineering require an increase in their accuracy (precision). The problem being solved is multi-purpose and is provided at various stages of the product life cycle by diagnosis, optimization of adaptive control of manufacturing, operation in production conditions and at the stage of debugging and repair. For each of them there are special requirements for quality identification, to improve the efficiency of which fuzzy logic (FL) is involved [4]. It is known that fuzzy logic used to create mathematical models based on linguistic considerations, in which the principal role belongs to language and experience of the expert. In this sense, FL is equivalent to the theory of fuzzy sets, i.e. classes with inaccurate, blurred boundaries.

Fuzzy set theory [5-7] is a generalization and rethinking of the most important areas of classical statistics and Cybernetics.

The aim of this study is to optimize the feature selection of abrasive tools taking into account surface qualities of parts made of high strength and aluminum alloy 1933T2 during pendulum-flat grinding with FL using. The quality of the workpiece surface is characterized by roughness parameters – R_a, R_{max}, S_m (GOST 25142–82), the indicators of flatness deviation – EFE_{max}, EFE_a, EFE_q (GOST 24642–81) named the highest, the average and the square mean respectively, and a microhardness HV (GOST 9450–76). Methods of their measurement and calculation are presented in [8].

II. METHODS OF EXPERIMENTAL STUDY

The procedure consists of three consecutive stages: the conditions of the full-scale experiment, the techniques of experimental data interpretation on the basis of statistical methods and FL realization.

A. Method of full-scale experiment

The following conditions of experiments realization were adopted in the work: surface-grinding machine – model 3G71M; the object of study – samples of high strength aluminum alloy 1933T2 (σ_B=480–490 MPa; $\sigma_{0,2}$=175 MPa) with dimensions L×B×H=40×40×45 mm, grinded area of which is L×B; the shape and size of the is HPW 01 250×20×76 mm [9]; technological parameters – speed range v_w=35 m/s, longitudinal feed s_l=7 m/min, cross feed s_c=1 mm/double pass, cutting depth t=0.015 mm, operating allowance z=0.15 mm; flooded coolant – 5% emulsion Equal–6 (under 0258-024-00148845-98 specification) with the 7-10 l/min flow. Spindle with the

wheel is lowered to a depth t in the time point when the longitudinal table with the workpiece is shifted to the left most position relative to the operator. Taking into account that the scheme s_s of specifying the feed is selected in mm/double-stoke, and abrasive tool has a clockwise rotation; the from-left-to-right table stroke is a working one and runs while the wheel is cutting-in. Its reverse is considered as sparking-out, finally forming the topography of the grinding surface in the conditions of down cutting. The samples were fixed with clamps on the clamping plate of the universal modular fixture that excluded the error of location when the form deviation takes place.

With the aim of an information content reduction, the variable grinding conditions were described by a code (e, i), which is particularly convenient when the response is presented in the form of y_{ei}. The index $e = \overline{1;7}$ is distributed according to the quality parameters of the surface. Roughness is characterized by the parameters: $R_{ai} = y_{1i}$, $R_{maxi} = y_{2i}$, $S_{mi} = y_{3i}$, which are located on the surface in the vector s_s direction and exceeding their analogues in the orthogonal direction (along the vector s_l). Flatness deviations are estimated by three indicators: main indicator $EFE_{maxi} = y_{4i}$ and two auxiliary indicators - arithmetic mean $EFE_{ai} = y_{5i}$ and square mean $EFE_{qi} = y_{6i}$. Microhardness HV_i is marked as y_{7i}. Code $i = \overline{1;5}$ characterizes the HPW grains material of black silicon carbide – 37C46I12VP (i=1); green silicon carbide – 39C46I12VP (i=2), 63C40L7V (i=4), 08C046I12V01P02 (i=5) and synthercorundum – 5SG46K12VXP (i=3). Among them only the wheel of Russian production i=4 has normal porosity.

B. Experimental statistics

The peculiarity of the grinding process is that abrasive grains in the tool have an arbitrary shape, a chaotic arrangement in the bundle, different projection height from the bundle in the radial and axis direction, a different number of active grains and cutting edges per unit of the wheel contact area when cutting-in. The foregoing allows considering the observations as continuous random quantities (RQ) and evaluating their behavior on the basis of probability-theoretic approaches. To accelerate the calculations, we selected the program Statistica 6.1.478.0. The experimental data are presented in the form of independent sets [10-12]:

$$\{y_{eiv}\}, e = \overline{1;7}, i = \overline{1;5}, v = \overline{1;30}, \qquad (1)$$

where v is the number of parallel experiments, which it is advisable to carry out with the same v (in this case v = 30).

In statistics, the following frequencies are used to estimate RQ [13-16]:

– measures of position (reference values)

$$\text{average } \bar{y}_{ei} = y_{ei}, \qquad (2)$$
$$\text{medians } \tilde{y}_{ei}; \qquad (3)$$

– measures of dispersion (precision)

$$\text{standard deviations } SD_{ei}, \qquad (4)$$
$$\text{ranges } R_{ei} = |y_{max} - y_{min}|_{ei}, \qquad (5)$$
$$\text{quartile latitude } QL_{ei} = \left|y_{0,75} - y_{0,25}\right|_{ei} \qquad (6)$$

The parametric method is based on (2), (4), (5), and rank statistics - on (3), (6). Acceptance of the null hypothesis H_0 regarding the homogeneity of dispersions

and normality of distributions (1) is considered in the paper [8].

C. The modelling technique of fuzzy logic

FL is equivalent to the theory of fuzzy sets A_{ei}, i.e. classes with defuse boundaries, which are represented by sets of ordered pairs, composed of elements y_{eiv} of universal sets $\{y_{eiv}\}$ and the corresponding grades of membership $\mu_A (y_{eiv})$:

$$A_{ei} = \left\{\left(y_{eiv}, \mu_A(y_{eiv})\right)\middle| y_{eiv} \in \{y_{eiv}\}\right\},$$

where $\mu_A(y_{eiv})$ are characteristic functions, which indicates the degree of membership y_{eiv} of fuzzy sets A_{ei}.

FL modelling for the experimental values was carried out in MATLAB, using a special bump pack Fuzzy Logic Toolbox. The last one has a simple and well-designed interface that makes it easy to design and diagnose fuzzy models [5,6]. Desirability function d_{ei} proposed by Harrington [13] is used to evaluate the surface quality of workpieces. The idea of conversion the natural values of particular responses into the dimensionless scale of desirability or preference is the basis of the function forming. Scale of desirability refers to the psychophysical categories. FL is implemented as three sequentially executed procedures: differential selection of HPW $i = \overline{0;5}$ for each parameter of surface quality $e = \overline{1;7}$; the separate assessments of cutting ability of HPW for all the attributes of roughness $(e = \overline{1;3})$ and form accuracy $(e = \overline{4;6})$; integral evaluation of HPW cutting ability for all attributes of output parameters. In terms of non-parametric statistics, the attributes take into account (3) and (6) simultaneously.

III. STUDY RESULTS AND THEIR DISCUSSION

Table 1 presents the test results of observations (1) for homogeneity of dispersions (acceptance of H_0) according to three criteria: 1– Levene's, 2 – Hartley's, Cochran's and Bartlett's (which are presented in the program with one set); 3 – Brown–Forsythe's. In table 1 the sign "+" means that the H_0 for (1) was taken at least for two criteria. It was revealed that for all parameters of the surface topography H_0 is accepted at a 5% significance level, i.e. the difference between the variances of deviations for wheels $i = \overline{1;5}$ is random.

TABLE I. TEST (1) OF DISPERSIONS HOMOGENEITY AT A CONFIDENCE LEVEL OF P=0.05

Parameter	Expected confidence level p for criteria			Acceptance of H_0
	Levene's	*Hartley's, Cochran's and Bartlett's*	*Brown–Forsythe's*	
R_a	0.001	0.001	0.002	+
R_{max}	0.001	0.001	0.001	+
S_m	0.002	0.001	0.003	+
EFE_{max}	0.001	0.003	0.001	+
EFE_a	0.001	0.001	0.001	+
EFE_q	0.001	0.001	0.001	+
HV	0.003	0.001	0.004	+

Verification of observations' distribution normality (H_0) (1) using the Shapiro–Wilk's test was carried out for all surface parameters separately. Test results for each abrasive wheels are shown in table 2. According to theoretical statistics, H_0 occurs when satisfying inequalities: $p_i > 0.5$, $i = \overline{1;5}$. Thus, the total number of

analyzed situations is N=7×5=35. Test results (table 2) showed that H_0 have been accepted in 5 of 35 cases, which is highlighted in the table.

Based on two test results, the nonparametric statistics method characterized by the measures (3) and (6) was chosen as «the home field» for interpretation (1). After their statistical interpretation, the measures $\tilde{y}_{ei}$ and QL_{ei}, are considered to be input data (table 3) during FL modelling

TABLE II. VERIFICATION OF DISTRIBUTIONS NORMALCY (1) FOR THE SHAPIRO–WILK'S TEST

Parameter	Wheel (i=$\overline{0;8}$)				
	37C (i=1)	39C (i=2)	5SG (i=3)	63C (i=4)	08C (i=5)
	H_0 for normal distribution				
R_a	0.18	0.03	**0.82**	0.13	0.12
R_{max}	0.16	0.01	0.38	**0.72**	**0.79**
S_m	0.42	0.02	0.13	0.17	**0.68**
EFE_{max}	0.01	0.01	**0.53**	0.11	0.13
EFE_a	0.03	0.01	0.13	0.03	0.25
EFE_q	0.02	0.01	0.02	0.05	0.12
HV	0.12	0.12	0.25	0.01	0.18

TABLE III. INPUT DATA OF PARTS SURFACE QUALITY FOR FL MODELING

Parameter (e = $\overline{1;7}$)	Measures	Wheel (i = $\overline{0;8}$)				
		37C(i=1)	39C(i=2)	5SG(i=3)	63C(i=4)	08C(i=5)
R_{ai} (1)	$\tilde{y}_{1i}$	0.327	0.3	0.327	0.364	0.189
	QL_{1i}	0.116	0.176	0.057	0.073	0.023
R_{maxi} (2)	$\tilde{y}_{2i}$	1.951	1.828	1.925	2.278	1.101
	QL_{2i}	0.319	0.996	0.396	0.545	0.265
S_{mi} (3)	$\tilde{y}_{3i}$	94.7	103.9	81	99.2	98.2
	QL_{3i}	42.2	40.9	21.2	20.3	28.4
EFE_{maxi} (4)	$\tilde{y}_{4i}$	10	6.5	20	8.5	10
	QL_{4i}	6	1.75	5	4	3.25
EFE_{ai} (5)	$\tilde{y}_{5i}$	5.9	3.8	11.6	4.6	6.1
	QL_{5i}	3.4	1.0	2.3	2.7	1.9
EFE_{qi} (6)	$\tilde{y}_{6i}$	6.3	4.2	12.6	5.3	7.5
	QL_{6i}	3.2	1.3	2.6	2.7	1.9
HV_i (7)	$\tilde{y}_{7i}$	1806	1838	1612	1763	1614
	QL_{7i}	149.8	138.5	160.1	163.6	139.3

As can be seen from table 3, the smallest measure of position for the value R_a occurs when i=5, and for EFE_{max} - when i=2. It was found that the greatest process stability for QL has been observed when: i=5 for the parameters R_a, R_{max} and EFE_{max}; and when i=2 - for HV.

It has been established that statistical methods do not give a comprehensive assessment of the parts surface quality, when micro- and macrogeometry is evaluated by three quality parameters; each of them is represented additionally by precision. This also applies to microhardness. In general case, statistical methods can predict the leading position of the HPW on the reference value (2), (3) or forming precision (4)-(6) of one specific parameter of the parts topography. Therefore, FL was involved in our study. In MATLAB modelling the experimental data after their statistical interpretation is usually considered to be input variables: $\tilde{y}_{ei}, QL_{ei}$, $e = \overline{1;7}$, $i = \overline{1;5}$ (table 3).

The procedure of FL fulfilment was conducted in three sequentially executed 3 stages:

1. Differential evaluation of HPW cutting ability based on the surface qualities (i = $\overline{1;5}$) for each parameter (e = $\overline{1;7}$).

2. Differential evaluation of HPW cutting ability on the surface topography for groups of roughness parameters (e = $\overline{1;3}$) and flatness deviations (e = $\overline{4;6}$). In this case, the microhardness indicator (e=7) was excluded because in the surface quality analysis it describes a single feature.

3. Integral choice of the optimal HPW characteristic i = $\overline{0;8}$ for all quality indicators of the workpiece surface, which made it possible to develop more complete guidelines for flat grinding of high strength aluminum alloy 1933T2 workpieces.

The results of fuzzy modeling at stages 1 and 2 should be used when solving local problems; for example, for HPW search - considering only the surface roughness or workpiece form accuracy and etc.

The FL procedures are described in the work [14]. Table 4 presents after-first-stage results; they estimated the wheels by the attributes for each parameter separately. First stage results of modelling may be of local interest. In particular, if according to the service requirements for the manufacture of parts only one specific indicator of surface quality should be maintained, it is necessary to ensure only roughness requirement, etc. Table 4 shows that HPW i = 5 – d_{51}= 0.821 has the best cutting ability for R_a parameter and the worst one HPW i = 2 when d_{21}= 0.191.

TABLE IV. RESULTS OF THE FUZZY LOGIC DIFFERENTIAL EVALUATION OF HPW I = $\overline{1;5}$ CUTTING ABILITIES

Wheels i=$\overline{1;5}$	Desirability functions d_{ei} for parameters e = $\overline{1;7}$						
	R_{ai}, y_{1i}	R_{maxi} ,y_{2i}	S_{mi}, y_{3i}	EFE_{maxi} ,y_{4i}	EFE_{ai} ,y_{5i}	EFE_{qi} ,y_{6i}	HV_i, y_{7i}
1	0.215	0.532	0.138	0.535	0.535	0.534	0.538
2	0.191	0.152	0.130	0.886	0.886	0.886	0.776
3	0.500	0.533	0.881	0.141	0.130	0.124	0.160
4	0.476	0.326	0.529	0.874	0.537	0.692	0.310
5	0.821	0.881	0.204	0.842	0.850	0.857	0.505

Based on the results shown in table 4, we start the second stage of the modelling. The task is the separate evaluation of grinding quality for two sets of attributes: e = $\overline{1;3}$ and e = $\overline{4;6}$. The model includes four variables: three inputs and one output (figure 1).
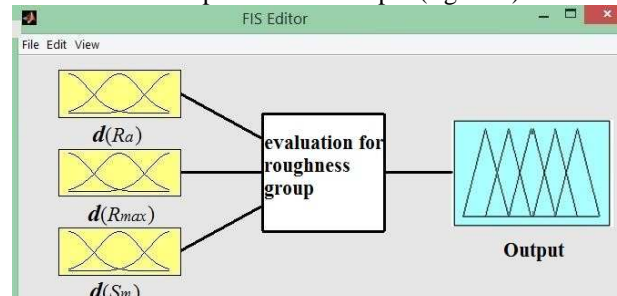

Fig. 1. Complex evaluation system of parts quality parameters for roughness group

The value for each input variable lies in the interval of [0;1] (table 5). And the degree of desirability including 5 estimates of VP. P. Sat. G. VG (table 6) was involved for the output variable. Microhardness was

excluded from the analysis of input parameters due to its being represented by one attribute.

TABLE V. NUMERICAL RANGES OF INPUT VARIABLE

Type of estimation	Input parameters		
Linguistic	Bad	Normal	Good
Numerical	[0.1;0.5]	[0.1;0.5;0.5;0.9]	[0.5;0.9]

TABLE VI. NUMERICAL RANGES OF OUTPUT VARIABLE

Type of estimation	Output parameters				
Linguistic	VB	B	Sat	G	VG
Numerical d	[0.0; 0.2)	[0.2; 0.37)	[0.37; 0.63)	[0.63; 0.80)	[0.8; 1.00]
Note: VB – very bad. B – bad. Sat – satisfactory. G – good. VG – very good.					

Table 7 shows after-the-second-stage results of modelling. It was found that the fuzzy model using allows easy access and searching for optimal HPW for the individual and combined parameters.

From table 7 it is seen that wheel 5SG (i=3) has the best cutting abilities for roughness parameters with d=0.714; and wheel 39C (i=2) has the worst ones with d=0.23. In terms of form accuracy, the highest estimate was obtained during 39C (i=2) abrasive wheel grinding with d=0.897, and the lowest for wheel 5SG (i=3) - with d=0.114. For microhardness the optimal cutting ability was obtained for 39C (i=2) tool grinding (d=0.776), and the worst – for 5SG (i=3) tool grinding (d=0.160). The discrepancy of grades of the cutting ability of wheels for different quality parameters makes it difficult to select their optimal characteristics.

TABLE VII. SECOND STAGE RESULTS OF FUZZY MODELLING

Wheels $i = \overline{1;5}$	Roughness		Form accuracy		Microhardness	
	$d_{i\cdot}.e = \overline{1;3}$	Concl usion	$d_{i\cdot}.e = \overline{4;6}$	Concl usion	$d_{i\cdot}.e = 7$	Concl usion
1	0.160	VB	0.513	Sat	0.538	Sat
2	0.121	VB	0.897	VG	0.776	G
3	0.714	G	0.115	VB	0.160	VB
4	0.433	Sat	0.718	G	0.310	B
5	0.673	G	0.868	VG	0.505	Sat
Note. Abbreviations in the conclusions are the same as in table 6						

The third (final) stage of modeling should be carried out only if it is necessary to optimize the cutting abilities of the HPW for all parameters of surface quality $e = \overline{1;7}$. At this stage, the desirability function is denoted as $d_{i\cdot\cdot}$, where the additional point "•" in the index characterizes the complete (integral) averaging of the "output". i.e. for all e=(1;7) and partially i for a number of HPW. To do this, we created a model of four variables: three inputs and one output (figure 2). The values for each variable of the input according to the desirability function correspond to the output variables (table 8), and their linguistic values are also represented by five classes (see table 6).
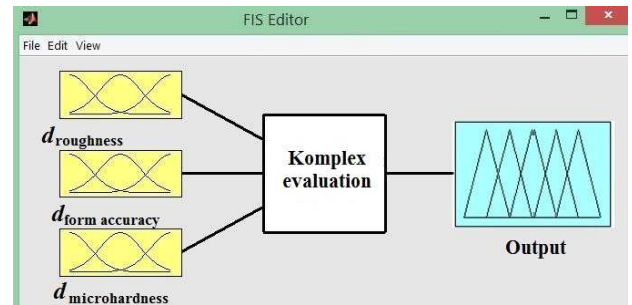

Fig.2. Complex evaluation system of parts' surface quality for all investigated parameters

It is established that during the complex evaluation of cutting abilities, the top position got the wheel 08C (i=5) with d=0.707, while the last position went to the circle 5SG (i=3) with d=of 0.219. It is revealed that the best results (X-evaluation) for the surface quality of grinded parts are predicted for wheels of silicon carbide green (08C and 39C).

TABLE VIII. FINAL STAGE RESULTS OF FUZZY MODELING

Wheels (i = $\overline{1;5}$)	$d_{i\cdot\cdot}$	Conclusions
37C 46 I 12 VP (1)	0.323	poor
39C 46 I 12 VP (2)	0.640	good
5SG 46 K 12 VXP (3)	0.219	bad
63C 40 L 7 V (4)	0.493	satisfactory
08C 046 I 12 V01 P02 (5)	0.707	good

Wheel 63C40L7V (i=4) of Russian production was satisfactorily rated and took the last place in cutting abilities. Sinter-corundum HPW (i=5) was tested as an experiment and showed the worst results.

IV. CONCLUSIONS

1. The involvement of fuzzy logic and statistical processing of observations proved to be an effective tool in the searching for optimal HPW by cutting abilities.

2. Each stage of fuzzy modeling allows one to solve variety of production tasks depending on the initial design and engineering requirements. Thus, the first stage gives an opportunity to select the characteristics of HPW as it is necessary to provide one separate quality parameter. The second stage allows evaluating HPW cutting properties for the parameter group. The third stage of modelling is to optimize the topography for the whole range of investigated parameters.

3. According to fuzzy logic modelling results in MATLAB, it was found that the best cutting ability of HPW for an integral complex of studied parameters while grinding high-strength aluminum alloy 1933T2 was predicted for wheels 08C046I12V01P02 and 39C46I12VP with a rating of «good».

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