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THE INFLUENCE OF SELECTED BRUSHING PROCESS PARAMETERS ON THE TOOL'S OPERATING TIME

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Abstract: The article concerns the possibility of carrying out an optimization process of the extending the life of a brush tool which is use during the process of removing burrs and rounding edges. The work focused on the influence of selected parameters on the wear time of tools. A number of tests were carried out to optimize the selection of parameters in terms of tool life, while maintaining the proper quality of the manufactured products, which translates into their reliability. As part of the work carried out, an optimal set of parameters was prepared to extend the tool's operational time. These parameters are the rotational speed of 1400 rpm and the external diameter of the tool of 200 mm. Thanks to the use of new parameters of the brushing process, the tool's operational time was extended by about 67%.The work carried out, after verification as part of large-scale production, led to a reduction in the consumption of tools, which had a positive impact on the improvement of the company's financial result (reduction of cost per part) and also contributed to the reduction of the carbon footprint. The work indicates further areas for development.

Key words: edge deburring, optimization, processing, measurement, operation, automation

1. INTRODUCTION

Manufacturing companies, especially those operating in the aviation industry, aim to ensure the proper quality of their products, which then translated into the reliability of the manufactured devices. These requirements have a direct impact on the performance, safety and operational life of the aircraft. Due to the increased performance of currently produced engines, compared to the designs from the last century, with simultaneous actions aimed at reducing the weight of all aircraft components, the requirements related to guaranteeing appropriate material and drawing properties, were increased [1-5].

The second, equally important goal is to strive to maximize profits by reducing all types of costs related to the production of parts. Taking into account the economic situation and economic conditions ("Ready for 55"), companies operating in the aviation industry set one of their main goals to reduce unit costs to increase competitiveness compared to other manufacturers operating in a similar production area. This goal is achieved by reducing the demand for electricity, reducing tools used in the production process, and reducing the number of man-hours devoted to the production of components. One of the possibilities to improve financial results by reducing production costs, as well as ensuring appropriate technological possibilities and repeatability, is the automation of individual production stages [6-14].

One of the possibilities to improve the economic results of the plant by reducing unit costs directly related to production, as well as ensuring appropriate technological capabilities and repeatability, is the automation of individual stages of production processes. The introduction of robotization and automation of individual production operations, further enables objective optimization of individual production operations by eliminating the subjective feelings of individual operators from the optimization procedures. The introduction of automation and robotization also improves working conditions by eliminating the risk of injuries to employees as well as limiting the impact of harmful factors such as noise and dust on employees [15-19]. In a broader perspective, it also enables the impartial conduct of research plans aimed at establishing a set of technological parameters ensuring, on the one hand, minimization of costs (minimization of tool wear), as well as sustaining the level of quality of manufactured products necessary for the aviation industry. Therefore, before starting the work described in this publication, a fully automated workstation was introduced, enabling the brushing process to be carried out in fully repeatable conditions.

In line with the above trend, research work was undertaken to optimize the brushing process by modifying selected parameters of the production process in order to reduce tool wear (extend tool life). The above-mentioned works are of key importance due to the company's goals, because while maintaining the current quality standard, they will allow for reducing operating costs and, as a result, reduce the carbon footprint. In the work carried out so far [20] related to the brushing process, it was observed that changing the parameters of the technological process, such as rotational speed or engagement depth, translates directly into the level of mutual interaction moments between the tool and the processed detail. Due to the complexity of the deburring process and the need to find an optimum guaranteeing the most effective use of

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the tool, it was decided to carry out a number of experiments aimed at determining the local minimum in relation to the "consumption" of the tool during the process. For this purpose, it was decided to carry out a number of experiments based on a two-level static determined plan. This means that the selected process parameters will be set on two extreme positions corresponding to the minimum and maximum values of the selected parameter. The planned research aims to determine the impact of individual brushing parameters on the final thickness of the bristles from which the tool is made. The final result of the experiment will be an equation describing the degree of tool wear depending on the selected values of individual parameters, which will make it possible, using analytical methods, to determine the local minimum corresponding to the longest operating time of the brush used for deburring. Then, the set of technological parameters prepared in this way will be tested in large-scale production to confirm the correctness of the work carried out.

2. DESCRIPTION OF THE PROBLEM

The proper implementation of the brushing process of the device's components is directly related to the quality of the finished product and safety during assembly. The basic purpose of the brushing process is to remove all types of burrs created at earlier stages of the production process [21-24]. This will enable the proper assembly of individual engine components and will also contribute to reducing the risks faced by the employee during the assembly process. From the point of view of the reliability and durability of the components of a modern jet engine, the key factor is the requirement to ensure the desired value of the edge radius. This radius is directly related to the local stress level, which translates into the life of the parts and the entire device (engine, aircraft).

With reference to the work related to the introduction of industrial robots to machining operations, many research works have been created [25-32]. These studies indicates to many advantages of introducing robotization in the form of increased repeatability and contributing to the reduction of product manufacturing costs. Industrial robots are successfully used for deburring, milling, deburring of thin-walled elements, grinding and polishing, and in measurement control of required places [33-39].

Thanks to the automation of the brushing process, the repeatability of the process was increased, it was possible to control the mutual impact of the processed detail and the tool, and it also led to a significant improvement in working conditions by reducing exposure to noise, dust and other harmful factors [20, 40, 41].

3. PROPOSED SOLUTION

In order to obtain unequivocal and objective optimization results, it was decided to carry out a number of tests. The purpose of the tests is to obtain a mathematical description of the rate of brush wear (bristle abrasion) depending on the selected process parameters. Such action will make it possible, using mathematical analysis methods, to find local minimums allowing for a reduction in the number of tools used and, consequently, will reduce the unit cost of manufactured components. Before carrying out the tests, it was decided to analyze possible process parameters that impact on the level of interaction between the tool (brush) and the detail. The influence of the rotational speed and the depth of penetration of the workpiece into the tool was examined in [20].

Performed research clearly shows that:

– A double increase in the brush rotation speed translates into a linear increase in torque. The obtained results confirm that the above relationship is correct for various rotational speeds;
– The increase in the depth of the detail in relation to the disc translates into a non-linear increase in torque. The observed effect is much smaller for higher rotational speeds.

Therefore, it was decided that the rotational speed and the depth of engagement of the detail to the tool would be used in further work.

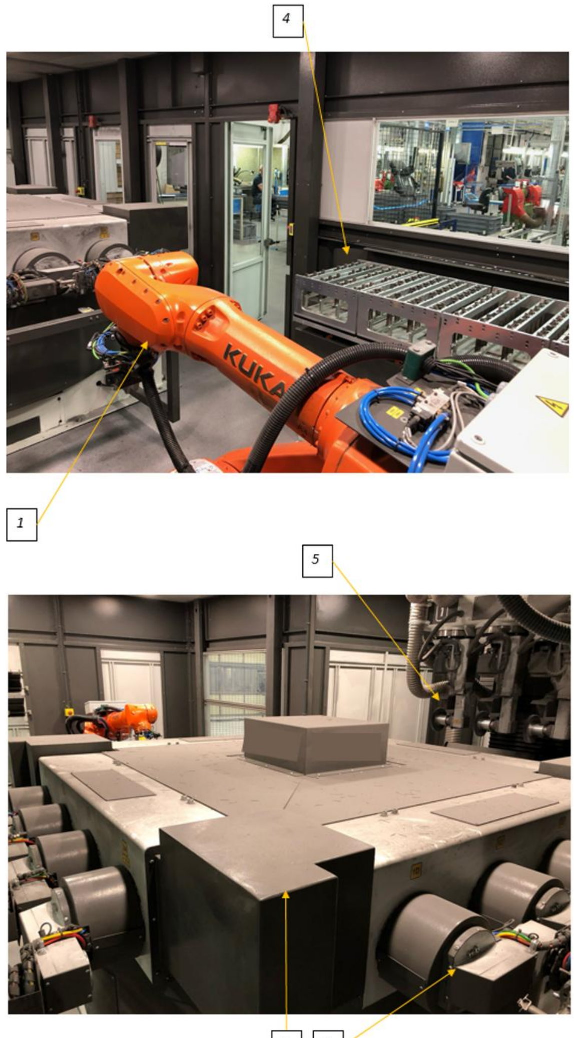

Fig. 1. Work station (1 - industrial manipulator, 2 - rotary table, 3 - workpiece gripper, 4 - workpiece magazine, 5 - tool holder)

The workstation used for the edge deburring process is shown schematically (Fig. 1). The station includes an industrial manipulator used to fasten processed details on a rotary table, after previously taking parts from the warehouse. In order to improve the operation of the station, it was equipped with a gripper warehouse. The last components of the workstation are the columns serving as handles and drives for the brushes used in the process. The entire area of the workstation is fenced with special barriers designed to ensure an appropriate level of safety for employees. Due to the assumed capacity of the workstation, it was decided not to consider the possibility of modifying the operating time allocated to the deburring procedure. From the point of view of cost reduction, extending the operation time would not have a beneficial effect on reducing the overall process costs. On the other hand, the time allocated for the analyzed operation has been optimized in terms of production cycle and does not require any further modifications from the company point of view.

One of the parameters of the technological process may also be the resistive moment of the tool generated during operation (due to the friction occurring between the rotating tool brought into contact with the workpiece). For the workstation presented (Fig. 1), the resistive torque is determined based on the current consumption of individual servo drives. It was considered to link the above-mentioned brush resistance torque with the bristle abrasion rate. In large-scale production conditions, a number of different parts are brushed at the workstation, which differ in size and thus affect the analyzed parameter. Therefore, it was decided to eliminate this parameter in further considerations. Also, the variation associated with the different number of burrs to be removed on individual parts affects the variability of the resistive torque. As a consequence, this makes it impossible to optimize tool consumption depending on the parameter in question. In order to illustrate the presented situation, the results of the registered resistance torque for individual production pieces are presented.

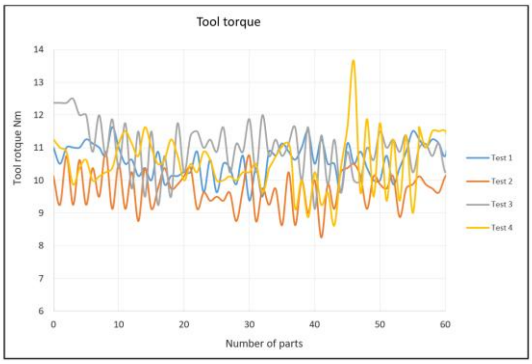

Fig. 2. Tool torque in relations with numer of brushed parts

In order to confirm the observations, it was decided to carry out four tests. Based on the graphical presentation of the results (Fig. 2), it was concluded that the resistive torque changes chaotically, regardless of tool wear.

Based on experience related to large-scale production, it was decided to use a brush-type tool in all optimization works (Fig. 3).

Fig. 3. A brush-type tool used in the production process

The basic technical parameters of the tool (Fig. 3) include an external diameter of 200 mm, a bristle length of 35 mm (measured along the radius) and a bristle thickness of approximately 1.1 mm. The material from which the bristles are made is silicon carbide (SiC), known under the trade name ABRALON612. The brush disc is made of structural steel.

In order to obtain an equation characterizing the tool wear process, it was decided to conduct an experiment based on a two-level static determined plan (Fig. 4).

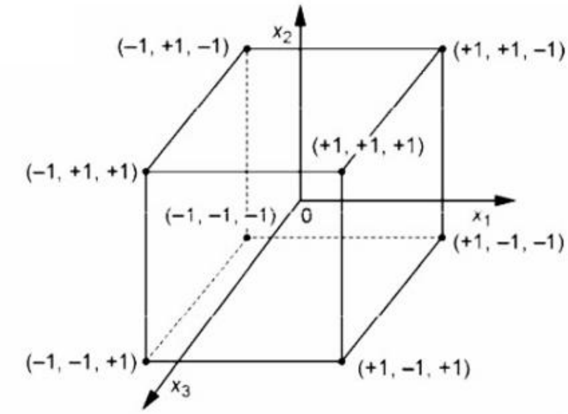

Fig. 4. Implementation scheme of experiment (3 input factors on 2 levels) [42]

A test plan was used without taking into account the effects of interactions between the analyzed parameters. To systematize the tests, a planning matrix was prepared in Table 1. Due to the complexity of the movements of the tool and the processed detail, it was impossible to present a single value defining the depth of penetration of the detail into the tool. Initially, this value was selected empirically based on the obtained process results (the value of the edge radius and the quantity of burr removal, average depth of approximately 4 mm, maximum of approximately 10 mm).

Therefore, it was decided to control the brush diameter parameter, which translated into shifting each point from the trajectory of mutual movements by a specific value. Therefore, the value of 198 mm from Table 1 should be interpreted as an increase in the engagement by 1 mm.

Tab. 1. Test matrix, columns X1, X2, X3 define the top level ("+") and bottom level ("-") of selected process parameters

Test number	X1	X2	X3	Rotationa i speed rpm	Engagement as brush diameter mm	Number of brushed parts
1	+	+	+	2000	200	60
2	+	+	-	2000	200	30
3	+	-	+	2000	198	60
4	+	-	-	2000	198	30
5	-	+	+	1400	200	60
6	-	+	-	1400	200	30
7	-	-	+	1400	198	60
8	-	-	-	1400	198	30

Planned test in the test matrix were performed randomly. The capacity of the test stand made it possible to conduct a test con-

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sisting of 12 repetitions at the same time to eliminate the influence of randomness.

4. TEST RESULTS

Analysis of the tool wear in large-scale production conditions, it was observed that the bristles wear out at a maximum distance of approximately 8 mm, measured from the outer edge of the brush (Fig. 5). It was observed that the bristles were worn – a reduction in thickness in the circumferential direction of the brush. No wear of the bristles was observed in the axial direction of the tool.

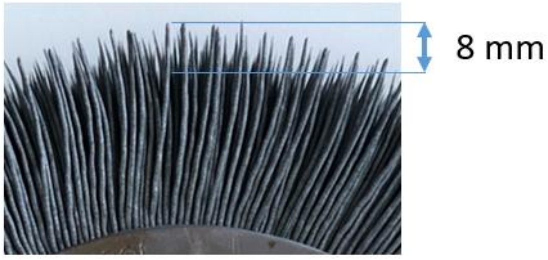

Fig. 5. The depth to which the brush tool was wear

It was decided to adopt the assumption of measuring the bristle thickness at a distance of approximately 4 mm from the maximum diameter of the brush (Fig. 6). Measurements were taken using a caliper.

Fig. 6. Place of measurement of bristle thickness after the test

The results of the measured bristle thickness according to the presented schema are presented in Table 2.

Tab. 2. Test results – measured bristle thickness

Test number	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}	y_{11}	y_{12}	$\bar{y}$
1	0.64	0.55	0.55	0.63	0.73	0.64	0.59	0.51	0.41	0.41	0.55	0.56	0.56
2	0.9	0.6	0.83	0.48	0.66	0.74	0.73	0.64	0.43	0.95	0.86	0.86	0.72
3	0.6	0.52	0.62	0.53	0.53	0.54	0.53	0.58	0.55	0.55	0.6	0.54	0.56
4	0.57	0.48	0.46	0.75	0.6	0.55	0.61	0.69	0.66	0.55	0.62	0.7	0.60
5	0.4	0.54	0.42	0.64	0.64	0.69	0.76	0.8	0.7	0.82	0.74	0.85	0.67
6	0.8	0.92	0.75	0.69	0.83	0.8	0.62	0.5	0.62	0.45	0.7	0.65	0.69
7	0.47	0.67	0.3	0.45	0.46	0.4	0.36	0.4	0.38	0.35	0.56	0.5	0.44
8	0.3	0.4	0.55	0.59	0.3	0.63	0.53	0.56	0.64	0.77	0.89	0.49	0.55

where: y_n – bristle thickness in the n-th measurement,
$\bar{y}$ – average value

In order to obtain mathematical equation following calculations have to be made:

Calculation of the unit of variability:

– For rotational speed:

$$\Delta x_1 = \frac{r_{max} - r_{min}}{2} = \frac{2000-1400}{2} = 300\ rpm \tag{1}$$

– For brush diameter:

$$\Delta x_2 = \frac{d_{max} - d_{min}}{2} = \frac{200-198}{2} = 1\ mm \tag{2}$$

– For number of brushed parts:

$$\Delta x_3 = \frac{q_{max} - q_{min}}{2} = \frac{60-30}{2} = 15\ pcs \tag{3}$$

Calculations of the central values for inputs:

– For rotational speed:

$$x_{10} = \frac{r_{max} + r_{min}}{2} = \frac{2000+1400}{2} = 1700\ rpm \tag{4}$$

– For brush diameter:

$$x_{20} = \frac{d_{max} + d_{min}}{2} = \frac{200+198}{2} = 199\ mm \tag{5}$$

– For number of brushed parts:

$$x_{30} = \frac{q_{max} + q_{min}}{2} = \frac{60+30}{2} = 45\ pcs \tag{6}$$

Coding of inputs:

– For rotational speed:

$$x_1 = \frac{\hat{x}_1 - \hat{x}_{10}}{\Delta \hat{x}_1} = \frac{r-1700}{300} \tag{7}$$

– For brush diameter:

$$x_2 = \frac{\hat{x}_2 - \hat{x}_{20}}{\Delta \hat{x}_2} = \frac{d-199}{1} \tag{8}$$

– For number of brushed parts:

$$x_3 = \frac{\hat{x}_3 - \hat{x}_{30}}{\Delta \hat{x}_3} = \frac{q-45}{15} \tag{9}$$

Calculation of the coefficients of the regression equation:

The variance of the measurement error was calculated based on the following formula:

$$S^2(y)_i = \frac{\sum_{i=1}^{j} (y_{ui} - \bar{y}_i)^2}{j-1} \tag{10}$$

Values for performed tests are presented in Table 3.

Tab. 3. Error variance for individual trials

Test number	S2
1	0.0079
2	0.0253
3	0.0010
4	0.0070
5	0.0200
6	0.0171
7	0.0094
8	0.0276

The coefficients of the regression equation are as follows:

$$b_0 = \frac{1}{N}\sum_{i=1}^{j} x_{0i}{y_i}^2 = 0.600 \quad (11)$$

$$b_1 = \frac{1}{N}\sum_{i=1}^{j} x_{1i}{y_i}^2 = 0.011 \quad (12)$$

$$b_2 = \frac{1}{N}\sum_{i=1}^{j} x_{2i}{y_i}^2 = 0.061 \quad (13)$$

$$b_3 = \frac{1}{N}\sum_{i=1}^{j} x_{3i}{y_i}^2 = -0.043 \quad (14)$$

Assessment of the repeatability of the experiment conditions:
– Calculation of the G coefficient value:

$$G = \frac{S^2(y)_{i\,max}}{\sum_{i=1}^{n} S^2(y)_i} = 0.151 \quad (15)$$

– Calculation of the number of degrees of freedom:

$$f_1 = N = 8 \quad (16)$$

$$f_2 = r - 1 = 11 \quad (17)$$

– Determination of the critical value of the G coefficient of the Cochran statistic:
Critical values of the Cochran G statistic (α=0.05). Values read from position [42].

$$G_{kr} = G_{(\alpha;f_1;f_2)} = 0.2364 \quad (18)$$

Because the following condition is met:

$$G < G_{kr} \quad (19)$$

The experiments were conducted with satisfactory repeatability.

Checking the significance of regression coefficients:
– Calculation of variations in measurement errors:

$$S^2(y) = \frac{1}{N}\sum_{i=1}^{N} S^2(y)_i = 0.014 \quad (20)$$

– Determining the number of degrees of freedom:

$$f = N(r-1) = 88 \quad (21)$$

Determination of the critical value of the t coefficient. Value read from position [42].

$$t_{kr} = t_{(\alpha;f)} = 1.99 \quad (22)$$

$$b_{kr} = t_{(\alpha;f)}\sqrt{\frac{S^2(y)}{Nr}} = 0.024 \quad (23)$$

Hence:

$|b_0| > b_{kr}$ so the coefficient is considered as significant (24)

$|b_1| < b_{kr}$ so the coefficient is considered as not significant (25)

$|b_2| > b_{kr}$ so the coefficient is considered as significant (26)

$|b_3| > b_{kr}$ so the coefficient is considered as significant (27)

After eliminating the insignificant term, the regression equation takes the following form:

$$y = 0.600 + 0.061x_2 - 0.043x_3 \quad (28)$$

Assessment of the adequacy of the regression equation:
– Calculation of adequacy variance:

$$S_{ad}^2(y) = \frac{r\sum_{i=1}^{N}(\hat{y}_i - \bar{y}_i)^2}{N-k-1} = 0.033 \quad (29)$$

– Determination of calculation value for F coefficient:

$$F = \frac{S_{ad}^2(y)}{S^2(y)} = 2.278 \quad (30)$$

– Calulation of numer of degrees of freedmon for numerator:

$$f_1 = N - k - 1 = 5 \quad (31)$$

– Calulation of numer of degrees of freedmon for denominator:

$$f_m = f_2 = N(r-1) = 88 \quad (32)$$

Critical values of F test Fischera-Snedecora (α=0.05). Values read from position [42].
– Calculation of critical value of F test coefficient:

$$F_{kr} = F_{(\alpha,f_1,f_m)} = 2.33 \quad (33)$$

Since the relationship $F < F_{kr}$ is met, the obtained regression equation is considered adequate.

Decoding the regression equation by substituting equations (8) and (9) into formula (28):

$$y = 0.061458\,d - 0.00288\,q - 11.5 \quad (34)$$

where: y – bristle thickness, d – brush outer diameter, q – quantity of brushed parts.

In order to maintain the appropriate quality of the manufactured products, it was decided to control the results of the brushing process both visually (visual inspection of the absence of burrs after brushing). The results, such as the removal of all burrs, prove that the process was carried out correctly. The condition of the parts before and after the brushing process is shown in Fig. 7.

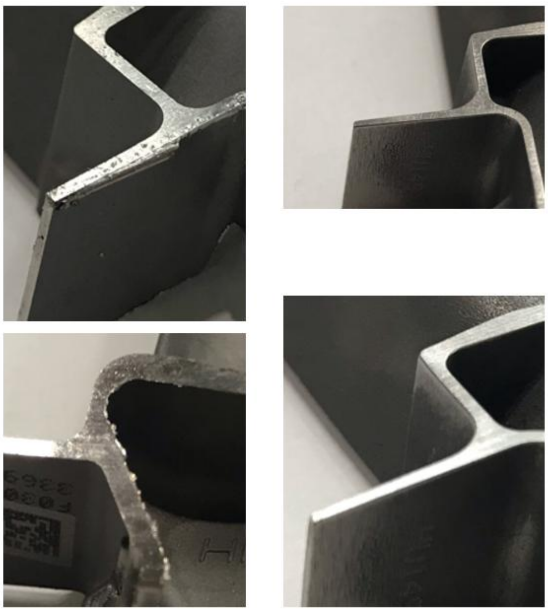

Fig. 7. Typical parts condition before (left side) and after (right side) of brushing process

The second control parameter analyzed to determine the correctness of the brushing process is the edge radius. A profilograph is used to measure the mentioned radius. For all tests with different process parameters, selected edges were measured (the measurement points were selected based on experience). The location of measurement points in the area of the blade lock is shown schematically in Fig. 8.

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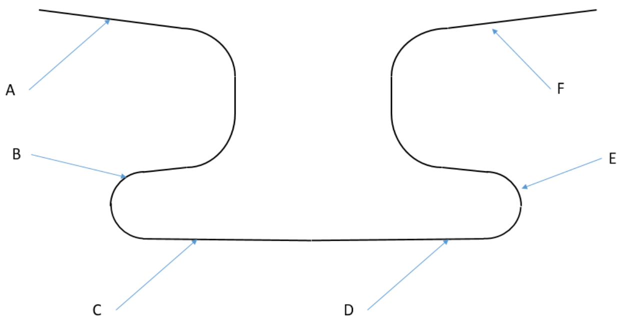

Fig. 8. Location of control points – blade lock

The values of the edge break radius, measured for all tests, are in Table 4.

Tab. 4. Results of the tests - the radius of edge break in chosen locations of the detail

Test number	Measured value of Edge break, mm					
-	A	B	C	D	E	F
1	0.16	0.11	0.17	0.16	0.31	0.29
2	0.15	0.10	0.13	0.15	0.34	0.36
3	0.18	0.19	0.17	0.14	0.25	0.27
4	0.27	0.16	0.19	0.19	0.33	0.3
5	0.17	0.12	0.18	0.14	0.24	0.27
6	0.13	0.11	0.13	0.13	0.29	0.25
7	0.13	0.12	0.15	0.13	0.30	0.30
8	0.14	0.10	0.20	0.13	0.32	0.35

The test results are presented in Fig. 9 in the form of a histogram.

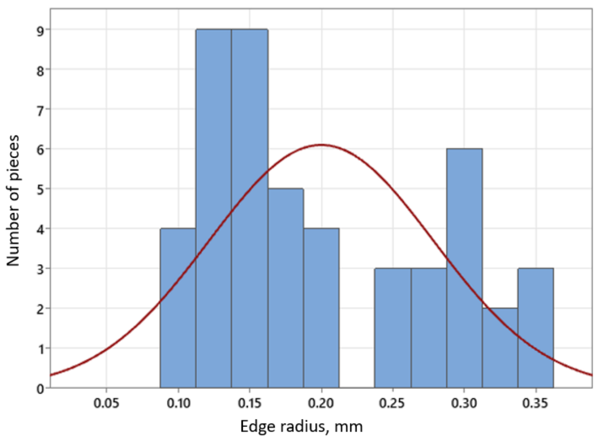

Fig. 9. Results of test- histogram

The break radius values obtained in the tests, ranging from 0.10 to 0.40 mm, are considered as satisfactory from the point of view of the operational requirements of brushed details. In order to confirm the obtained mathematical model, it was decided to carry out large-series tests. The tests used process parameters prepared based on the obtained mathematical model of the tool wear rate.

5. DISCUSSION OF THE RESULTS

The carried out optimization procedure made it possible to mathematically describe the nature of brush wear depending on the selected parameters of the brushing process. As a result of the mathematical operations performed, information was obtained about which of the selected process parameters significantly affect the wear time of the tools life (outer diameter of the brush, number of processed details), and which of them can be neglected (rotational speed). Importantly, from the point of view of the quality of the manufactured parts, in the entire analyzed range of selected process parameters, i.e. for brush diameters in the range of 198 to 200 mm, rotational speeds of 1,400 to 2,000 rpm, the brushing process fully guaranteed the correct removal of burrs and proper edge break radius.

In order to visualize the data collected during all test trials, it was decided to prepare a chart (Fig. 10) illustrating the rate of tool wear depending on the rotational speed and feed (brush diameter).

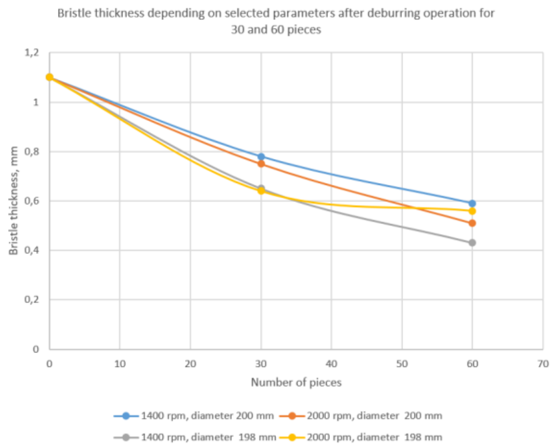

Fig. 10. Bristle thickness depending on selected parameters after deburring operation for 30 and 60 pieces

The graph clearly shows that the bristles were worn out the least, both after 30 and 60 pieces, in the case of the following combination of parameters: rotational speed of 1400 rpm and brush diameter of 200 mm. From the other hand, the worst values were achieved for the following combination of analyzed parameters: rotational speed 1400 rpm, brush diameter 198 mm.

In turn, the graphical representation in Fig. 11 of the obtained equation is as follows:

$$t = 0.061458\,x\,d - 0.00288\,x\,q - 11.5 \qquad (35)$$

Based on the prepared charts and analysis of data collected during experiments, it was decided to recommend the following combination of process parameters for further testing:

– tool rotation speed 1400 rpm;
– external diameter of the tool 200 mm.

The estimated life of the brush has been extended, from the initial value of approximately 60 pieces to a value of 120 pieces (an increase of 100%).

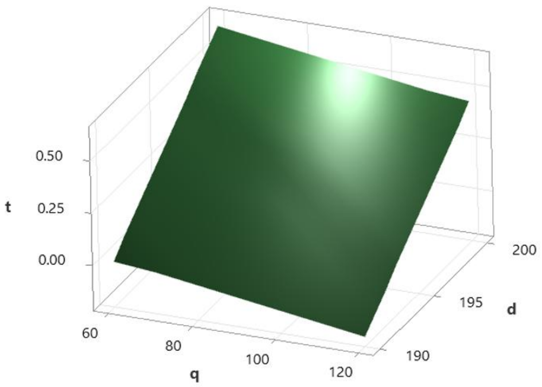

Fig. 11. Graphical presentation of equation (35) (t – bristle thickness mm, d – brush diameter mm, q – number of processed parts)

Based on the test results in large-scale production, it was confirmed that the prepared set of parameters allowed for a significant extension of the tool's use time. It turned out that after tests lasting several days, the actual life of the brush is not 120, as the analysis might suggest, but 100 pieces. The difference between the theoretical and actual life expectancy of the brush (expressed in the number of pieces successfully processed) can be explained by the different amount of burr to be removed between individual pieces (natural variation in the production process), as well as the difference in the component on which the tests were carried out (tests used for developing a mathematical description of the brush wear rate was carried out using one type of part, while tests confirming the effectiveness of the introduced changes were carried out in production conditions, where individual components differed in size). The increase in the life expectancy of the brush from the initial value of 60 pieces to 100 pieces per tool should be considered a satisfactory value.

There are a number of studies in which the authors dealt with the selection of optimal parameters of the technological process for the simultaneous extension of the tool operating time and the quality of the obtained details. The authors of the study [43] worked on extending the tool operating time depending on the input parameters. Modification of a number of parameters had a different impact on the length of tool use. Some of the parameters were characterized by a linear translation, and some by a non-linear translation on the length of tool use. The result itself in the form of the number of minutes varied from about 90 to over 670 minutes, depending on the selected set of parameters. In turn, in the study [44], the author selects the parameters of the technological process in order to both extend the tool life and reduce the consumption of electric energy. Similarly to the authors of the study [43], he obtains both linear and non-linear relationships between the parameters of the technological process and the tool life. The final set of proposed parameters translates into an extension of the tool life by about 20%. As can be seen in the cited studies, different researchers dealt with similar topics and obtained similar results, i.e. their nature and results do not differ significantly from the observed regularities for the case under consideration.

6. CONCLUSIONS

Based on the experiments carried out to define the mathematical description of the tool wear rate, the following conclusions can be drawn:

– the rotational speed of the brush is a parameter irrelevant from the point of view of the abrasion rate of the brush bristles;
– the values of the tool diameter and the number of processed pieces have a significant impact on the rate of bristle abrasion;
– for the analyzed process and the associated pair of materials (both the tool and the workpiece), the brush wear process can be described by the following equation (35);
– all configurations of modified parameters enabled the deburring process to be carried out correctly, i.e. by removing all the burr present on the parts and guaranteeing the edge deburring radius in the range from 0.10 to 0.36 mm, which should be considered a correct value from the point of view of strength;
– modification of technological process parameters made it possible to extend the tool life by approximately 67%, which allowed to reduce the unit cost of manufactured details by PLN 0.75/piece in large-scale production conditions;
– the work carried out to optimize the parameters of the deburring process, thanks to reducing the number of tools used, also led to a reduction of the carbon footprint left by the production plant.

The work carried out on the optimization of the brushing process sheds new light on the approach to cost optimization, especially in large-scale production. It turns out that a small change in the parameters of the technological process leads to significant savings and has a positive impact on the natural environment. Optimization of production processes not only through robotization and automation, but also in the form of selecting technological parameters leading to the extension of the operational time of tools (while maintaining an appropriate level of quality) should be a natural stage in the maturation of production processes.

As part of further work aimed at optimizing the brushing process, attention can be paid to verifying the selected brush material. So far, this area has not been verified empirically. Also, experiments related to bristle thickness may lead to a reduction in unit costs.

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