Rounding sharp edges of machine parts with elastic polymer abrasive wheels

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Abstract. The effectiveness of elastic polymer-abrasive wheels when rounding edges has been proved. The research showed the influence of cutting speed, deformation of the tool and feed along the edge on the quality of the machined edge and the productivity of the process. Empirical equations are proposed for calculating the parameters of quality and productivity depending on the processing regime parameters.

1. Introduction

In aircraft industry and other branches of engineering rounding sharp edges on machined parts is mandatory. At present, at many enterprises, these operations are performed manually, which contributes to an increase in the cost of production of engineering products and a decrease in its quality. Therefore, the mechanization and automation of edge rounding are extremely necessary measures. One of the ways to perform rounding operations on sharp edges is to process elastic abrasive tools, the classification and description of which are given in the relevant reference literature, for example [1].

The issues of evaluating the performance of the process and the quality of products after machining have been dealt with in many works, for example [2–9], however, the parameters characterizing the performance of the process and the quality of rounded edges during processing with elastic abrasive wheels have not yet been determined or researched.

Table 1. Parameters of the studied elastic abrasive wheels.

| Brands of the wheel | \(D_k, \text{ mm}\) | \(B_k, \text{ mm}\) | \(d_k, \text{ mm}\) | Abrasive | Grain \(Z, \mu\text{m}\) | Feed \(S, \text{ mm/min}\) | Deformation \(\Delta Y, \text{ mm}\) |
|---------------------|-------------------|-------------------|-------------------|---------|----------------|-----------------|------------------|
| CF-FB-0,5AFIN       | 193               | 50                | 76,5              | Al\(_2\)O\(_3\) | 45-50          | 33, 52, 82, 130 | 3; 3,5; 4; 4,5   |
| FS-WL-2SCRS         | 147               | 26                | 25,4              | SiC     | ~160           | 104, 130, 160, 200 | 1,5; 2; 2,5; 3   |
| CB-ZS P180          | 75                | 45                | -                 | SiC     | 80             | 130, 200, 255, 255 | 1; 2; 3; 4       |
| FF-ZS ACRS          | 75                | 45                | -                 | SiC     | ~160           | 130, 200, 255, 255 | 1; 2; 3; 4       |

\(D_k\) – wheel diameter, mm; \(B_k\) – wheel width, mm; \(d_k\) – bore diameter, mm.

Elastically abrasive wheels of 3M brands such as CF-FB-0,5A FIN, FS-WL-2SCRS, CB-ZS P180, FF-ZS ACRS has been used to study the process of forming radii of rounding. The main parameters of these tools are given in Table 1 as well as in the reference list [10-11].
Experiments on the processing of samples' edges of aluminum alloy B95pchT2 were carried out on a universal milling machine model Deckel Maho DMC 635 V with rotational frequencies of the wheel \( n = 500, 1000, 1250, 1600 \) rpm. The feed along the edges and deformation of the wheel ranged within the limits given in Table 1.

When machining the edges with an elastic wheel, the ABC surface is formed on the piece shown in Figure 1, which is characterized by an irregular geometric shape and an inequality of dimensions \( X \) and \( Y \).

If the material of the wheel had ideally elastic properties, then at an angle \( \alpha = 45^\circ \) the dimensions \( X \) and \( Y \) would be equal. In fact, the material of the wheel has viscous elastic properties with the capacity for relaxation.

To ensure the equal size of \( X \) and \( Y \), appropriate value of the angle \( \alpha \) must be selected.

Measurements of dimensions \( X \), \( Y \) and \( p \) were performed on a large instrumental microscope with a digital reading device BMI 1C with an accuracy of 0.001 mm.

In order to study the effect of processing modes on process performance and the quality of the obtained rounding radii, it is necessary to determine the limiting values of the wheel deformation (\( \Delta Y \)) and the position of the wheel relative to the machined edge.

The largest values of the deformation of the wheel \( \Delta Y \) (Figure 2, b) must be taken from the durability conditions of the wheel. For the CF-FB-0,5AFIN wheel, the \( \Delta Y \) value was 4.5 mm, for the FS-WL-2SCRS wheel - 3 mm, for the CB-ZS P180 and FF-ZS ACRS wheels - 4 mm. It is established that the excess of the specified value leads to intensive wear of the wheel [12].

It was proposed to evaluate the quality of the rounded edges by the following indicators: location accuracy (positioning), radius shape accuracy (roundness), and surface finish roughness. Performance indicators are: the actual rounding radius and the relative removed edge layer.

2. Location accuracy (positioning) of the processed radius \( \delta \). Is a relative deviation from the symmetry of the rounding radius positioning

\[
\delta = \frac{X - Y}{Z_i},
\]

where \( X \), \( Y \) are the coordinates of the transition of the end of the rounding into a straight line (Figure 1); \( Z_i \) – the average value along the \( X \) and \( Y \) axes, which is determined by the expression:

\[
Z_i = \frac{X + Y}{2}.
\]
The relative deviation from the symmetry of the arrangement of the rounding radius $\delta$ is significantly influenced by the position of the wheel relative to the edge being machined - the angle $\alpha$.

The relative deviation from the symmetry of the arrangement of the rounding radius $\delta$ (1) depends on the ratio of the sizes $X$ and $Y$. The optimal arrangement of the radius corresponds to $\delta = 0$, i.e. to the equality $X = Y$. This is achieved by choosing the appropriate angle (Figure 2, b).

Figure 3 shows the dependences of $\delta$ on the angle $\alpha$, from which it follows (in the studied modes) that for the CF-FB 0.5A FIN wheel the optimum is $\alpha = 20^\circ$, for the FS-WL 2S CRS wheel – $\alpha = 40^\circ$, for the CB-ZS P180 and FF-ZS ACRS wheels - $16^\circ$.

With increasing deformation $\Delta Y$ (Figure 4), the CF-FB 0.5A FIN wheel and BB-ZB Type C-P120 brushes increase the $\delta$ value, and on the opposite the FS-WL 2S CRS, CB-ZS P180 and FF-ZS ACRS wheels - decrease. This is due to the difference in stiffness of the tools. For a small-rigid tool CF-FB 0.5A (rigidity $C_t = 0.0162$ N / mm$^2$-mm) an increase in size $X$ occurs more intensively than an increase in size $Y$ due to their high compliance. For the tougher CB-ZS P180, FF-ZS ACRS and FS-WL 2S CRS wheels (rigidity $C_t = 0.0993$ N / mm$^2$-mm) with a low flexibility of its material, $Y$ growth exceeds $X$ growth. When choosing treatment modes, it is necessary to ensure zero equality of the parameter $\delta$.

It is established that the change in cutting speed and feed does not affect the indicator $\delta$. This is confirmed by statistical processing of experimental data.

On the basis of the conducted research, a mathematical relationship $\delta$ was obtained in the form of a polynomial of the 2nd degree.
\[ \delta = a_1 \cdot \alpha^2 + a_2 \cdot \Delta Y^2 + a_3 \cdot \alpha + a_4 \cdot \Delta Y + a_5 \cdot \Delta Y \cdot \alpha + a_6, \]  

(2)

where \( \alpha \) is the angle characterizing the position of the wheel relative to the edge being machined in degrees, \( \Delta Y \) is the deformation of the tool, mm.

The values of the coefficients \( a_1 - a_6 \) are given in Table 2.

| Coefficient | Wheel CF-FB 0.5A FIN | Wheel FS-WL 2S CRS | Wheel CB-ZS P180 | Wheel FF-ZS ACRS |
|-------------|----------------------|--------------------|------------------|------------------|
| \( a_1 \)   | -2.2095 \times 10^{-4}| -2.4724 \times 10^{-4}| -0.0706305      | -3.6853 \times 10^{-3} |
| \( a_2 \)   | 0.119885              | 0.398099           | 1.36642          | 0.0502261        |
| \( a_3 \)   | -0.0249246            | 0.159299           | 3.41477          | 0.0751851        |
| \( a_4 \)   | -1.21977              | -2.14867           | -6.04949         | -1.33592         |
| \( a_5 \)   | 0.0165369             | 8.8884 \times 10^{-3}| -0.048132       | 0.0667152        |
| \( a_6 \)   | 2.17522               | -0.617307          | -31.3847         | -0.0472628       |

3. Relative roundness error – \( k \)

Represents the deviation of the shape along the radius:

\[ k = \frac{\Delta h}{r}, \]  

(3)

where \( \Delta h \) is the deviation of the actual segment from the theoretical one: \( \Delta h = h_T - h \).

Here, \( h_T = 0.293 \cdot r_T \) is the theoretical segment height; \( h \) is the actual height of the segment (see Figure 2, a):

\[ h = 0.707 \cdot \bar{X} + p_r - p, \]

where \( p_r \) is the theoretical size of the removed edge:

\[ p_r = 0.414 \cdot r, \]

\( p \) is the actual size of the removed edge.

On the basis of experimental data, the dependence of the relative error of roundness \( k \) on the cutting speed \( V \), shown in Figure 5, it is established that the values of \( k \) vary in the range from 0 to 0.25. At the same time, for a radius of up to 1 mm, the accuracy of the form is within 0.25 mm, which satisfies the requirements of GOST 30893.1-2002 (ISO 2768-1-89) for all accuracy classes.

If we ensure the equality to zero of the parameter \( \delta \), then the relative error of the radius form \( k \) decreases.

It is established that the feed \( S \) and the deformation of the wheel \( \Delta Y \) do not affect this parameter. This is confirmed by statistical processing of experimental data.

![Figure 5](image-url)

Figure 5. Dependencies of relative error of radius shape - \( k \) versus cutting speed \( V \) for tools:
1 – Wheel CF-FB 0.5A FIN when \( \Delta Y = 4 \) mm, \( \alpha = 27.8°, S = 82 \) mm/min;
2 – Wheel FS-WL 2S CRS when \( \Delta Y = 2 \) mm, \( \alpha = 26.2°, S = 130 \) mm/min;
3 – Wheel CB-ZS P180 when \( \Delta Y = 2 \) mm, \( \alpha = 16.26°, S = 130 \) mm/min;
4 – Wheel FF-ZS ACRS when \( \Delta Y = 2 \) mm, \( \alpha = 16.26°, S = 130 \) mm/min.
Control of the value of $k$, if necessary, can be carried out by reducing the cutting speed $V$ (see Figure 5).

Since $k$ does not depend on the deformation $\Delta Y$ and on the feed $S$, the dependence on the cutting speed $V$ can be represented by the expression:

$$k = b \cdot V + c.$$  \hspace{1cm} (4)

The values of the coefficients $b$ and free members $c$ are given in Table 3.

**Table 3.** The values of the coefficients in the equation (4).

| Instrument               | Coefficient b | Free member c |
|--------------------------|---------------|---------------|
| Wheel CF-FB 0,5A FIN     | $3.134 \times 10^{-4}$ | $-0.094$     |
| Wheel FS-WL 2S CRS      | $7.863 \times 10^{-5}$ | $0.1318$     |
| Wheel CB-ZS P180        | $2.546 \times 10^{-4}$ | $0.11$       |
| Wheel FF-ZS ACRS        | $2.546 \times 10^{-4}$ | $0.09$       |

4. **Relative layer cut edge– $\rho$**

This parameter characterizes the performance of the process and represents the actual size of the removed edge when machining 1 mm tool width:

$$\rho = \frac{P}{B_k},$$  \hspace{1cm} (5)

where $B_k$ is the width of the wheel in mm.

It represents the actual size of the cut edge when machining 1 mm tool width.

Research $\rho$ according to (5), depending on the deformation of the tool, has established that with an increase in the $\Delta Y$ value, the actual removed layer increases for all the studied wheels. This is explained by the fact that with increasing strain, the vertical component of the force increases, and, consequently, the depth of the introduction of single grains in the processed material also increases.

With an increase in the rotation speed $V$, it is established that the actual removed layer is magnified. This is due to an increase in the dynamic component of the impact force of an abrasive grain on the treated surface.

With an increase in feed along the edge $S$, the value of $\rho$ decreases. This is due to the fact that with an increase in feed along the edge, the processing time decreases (with the same deformation and rotational speed).

**Table 4.** The values of the coefficients in the equation (6).

| Coefficient | CF-FB 0,5A FIN | FS-WL 2S CRS | CB-ZS P180 | FF-ZS ACRS |
|-------------|----------------|--------------|-------------|-------------|
| $a_1$       | $2.85325 \times 10^{-5}$ | $2.3 \times 10^{-3}$ | $8.82355 \times 10^{-4}$ | $0.001$     |
| $a_2$       | $-6.3375 \times 10^{-10}$ | $1.215 \times 10^{-8}$ | $2.45371 \times 10^{-8}$ | $7.05867 \times 10^{-8}$ |
| $a_3$       | $-6.2625 \times 10^{-7}$ | $-3.69625 \times 10^{-9}$ | $-2.11216 \times 10^{-9}$ | $3.3033 \times 10^{-10}$ |
| $a_4$       | $2.463 \times 10^{-5}$ | $-2.1125 \times 10^{-3}$ | $4.9355 \times 10^{-5}$ | $-6.66667 \times 10^{-7}$ |
| $a_5$       | $4.42 \times 10^{-6}$ | $1.14838 \times 10^{-5}$ | $1.31943 \times 10^{-6}$ | $5.055 \times 10^{-8}$ |
| $a_6$       | $-1.00275 \times 10^{-5}$ | $-1.12238 \times 10^{-5}$ | $-1.67901 \times 10^{-6}$ | $-1.35134 \times 10^{-5}$ |
| $a_7$       | $4.725 \times 10^{-7}$ | $9.8775 \times 10^{-7}$ | $2.73859 \times 10^{-7}$ | $2.6732 \times 10^{-8}$ |
| $a_8$       | $2.6625 \times 10^{-6}$ | $-2.47375 \times 10^{-6}$ | $-1.64831 \times 10^{-7}$ | $-7.97608 \times 10^{-9}$ |
| $a_9$       | $-5.0925 \times 10^{-9}$ | $5.54875 \times 10^{-9}$ | $1.98937 \times 10^{-9}$ | $-1.3376 \times 10^{-10}$ |
| $a_{10}$    | $-2.0745 \times 10^{-10}$ | $-2.71875 \times 10^{-9}$ | $9.0522 \times 10^{-10}$ | $-8.39 \times 10^{-12}$ |
| $a_{11}$    | $0.001$ | $0.006$ | $1.10294 \times 10^{-3}$ | $-0.003$ |
On the basis of the conducted research, a mathematical dependence of $\rho$ on all parameters was obtained in the form of a polynomial of the 2nd degree:

$$\rho = a_1 \cdot \Delta Y^2 + a_2 \cdot V^2 + a_3 \cdot S^2 + a_4 \cdot \Delta Y + a_5 \cdot V + a_6 \cdot S + a_7 \cdot \Delta Y \cdot V + a_8 \cdot \Delta Y \cdot S + a_9 \cdot V \cdot S + a_{10} \cdot \Delta Y \cdot V \cdot S + a_{11},$$  \hspace{1cm} (6)

where $\Delta Y$ is the deformation of the tool, mm; $V$ is the cutting speed, m/min; $S$ is the feed along the edge, mm/min.

The values of the coefficients $a_1$–$a_{10}$ and the free member $a_{11}$ are given in Table 4.

The obtained results on the accuracy and productivity of the process will be the basis for optimizing the processing parameters when rounding the edges of machine parts with elastic abrasive wheels.

5. Roughness of a surface of the rounded edges

The surface roughness of the rounded edges must meet the requirements of the drawing on the work pieces.

To study the roughness on the rounded edges of the samples, an optical Bruker Contour GT-KI profilometer (Germany) was used.

Based on the studies and measurements, the dependences of roughness on the rounding radius of the processing modes for the studied tools were obtained.

It has been established (see Figure 6) that with increasing deformation of the tool, the roughness increases. This is explained by the fact that with increasing $\Delta Y$ the radial force of $P_y$ increases, and therefore the depth of the introduction of abrasive grains also increases.

![Figure 6. Dependence of roughness $Ra$ on deformation $\Delta Y$: 1 – for the wheel CF-FB 0.5A FIN; 2 – for the wheel FS-WL 2S CRS; 3 – for the wheel CB-ZS P180; 4 – for the wheel FF-ZS ACRS. The processing modes are the same as in Figure 4.](image)

A change in the cutting speed $V$ and feed rate $S$ does not affect the $Ra$ value. This is confirmed by statistical processing of experimental data. The dependence of the $Ra$ deformation on $\Delta Y$ can be represented by the expression:

$$Ra = b \cdot \Delta Y + c.$$ \hspace{1cm} (7)

The values of the coefficients $b$ and free members of $c$ are given in Table 5.

| Instrument          | Coefficient $b$ | Free member $c$ |
|---------------------|-----------------|-----------------|
| Wheel CF-FB 0.5A FIN| 0.167           | 0.25            |
| Wheel FS-WL 2S CRS  | 0.133           | 1.8             |
| Wheel CB-ZS P180    | 0.25            | 0.75            |
| Wheel FF-ZS ACRS    | 0.367           | 1.233           |

To compare the efficiency of the operation when rounding the edges of the investigated elastic tools, Table 6 shows the results of determining the parameters $k$, $Ra$ and $\rho$ when machining on the same modes for all tools: cutting speed $V = 600$ m / min; wheel deformation $\Delta Y = 3$ mm and longitudinal feed $S = 130$ mm / min.

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As can be seen from the Table 6, the highest productivity and the greatest roughness are noted when processing with FS-WL 2SCRS and FF-ZS ACRS wheels which is due to their greater grain size.

| №  | Instrument       | Z, µm | k   | Ra  | ρ    |
|----|------------------|-------|-----|-----|------|
| 1  | Wheel CF-FB-0,5AFIN | 45-50 | 0.09404 | 0.751 | 0.0006259 |
| 2  | Wheel FS-WL-2SCRS  | ~160  | 0.17998 | 2.199 | 0.0301528 |
| 4  | Wheel CB-ZS P180   | 80    | 0.26276 | 1.500 | 0.0190376 |
| 5  | Wheel FF-ZS ACRS   | ~160  | 0.24276 | 2.334 | 0.0297210 |

The FS-WL-2SCRS wheel turned out to be the most productive, while the achievable roughness $Ra_{2.334}$ meets the requirements of the drawing ($Ra_{3.2}$).

**Conclusion**

The expediency of using elastic polymer-abrasive wheels for rounding edges on parts both in terms of the quality of the processed edge and the productivity of the process has been proved. The obtained empirical equations for calculating the parameters of quality and productivity depending on the regime parameters of processing can be successfully applied in production conditions.

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