Experimental research of cutting forces at finishing processing of machine components by elastic polymer-abrasive circles

Yu V Dimov, D B Podashev
Irkutsk National Research Technical University, 83, Lermontov St., Irkutsk, 664074, Russia
E-mail: Dimov-Ura@yandex.ru; dbp90@mail.ru

Abstract. This article presents the results of experimental studies of forces arising from the interaction of elastic polymer-abrasive wheel with the treated surface. The dependences of normal and tangential components of cutting force on the speed, tool deformation and feed are established. Cutting forces directly influence the removal rate, roughness of the processed surface, temperature in the cutting zone and residual stresses in the surface layer.

Many works, for example [1-8], are devoted to the evaluation of process performance and quality of products after machining. Analysis of these works, as well as publications [9-13] allows to draw a conclusion that the forces arising in the process of machining by elastic polymeric-abrasive circles, as well as at any other type of abrasive processing, have a direct influence on the productivity of the machining process, the formation of the surface layer, the temperature in the cutting zone and tool wear. In addition, knowledge of the cutting forces is needed to determine the capacity of the equipment in the development of part manufacturing technology.

The normal component of the machining force Py directly determines the depth of penetration of the cutting elements of the elastic polymer-abrasive wheel, and therefore the intensity of material removal and roughness of the machined surface.

Elastic abrasive discs of 3M (Minnesota Mining and Manufacturing Company) were used for the experimental studies, the binder of which is a polymeric material Scotch-Brite™. FS-WL 8A MED, FS-WL 6S FIN, FS-WL 2S CRS, DB-WL 8S MED and DB-WL 7S FIN are pressed circles. Circle of mark CF-FB 0.5A FIN - the very elastic lobe brush made of material Clean&Finish. In the designation of elastic polymer-abrasive circles of the company 3M figures (8, 7, 6, 2, 0.5) denote the structure, A - abrasive material Al2O3, S - abrasive material SiC, grain size: FIN (thin grain), MED (medium grain), CRS (coarse grain).

Parameters considered in the present work of elastic polymer-abrasive circles are investigated in [14] and given in the table 1.
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Table 1. Parameters of elastic polymer-abrasive wheels

| Parameter                | FS-WL-8A MED | FS-WL-6S FIN | FS-WL-2S CRS | DB-WL-8S MED | DB-WL-7S FIN | CF-FB-0.5A FIN |
|--------------------------|--------------|--------------|--------------|--------------|--------------|----------------|
| D_k, mm                  | 140,5        | 129,5        | 147,2        | 147,8        | 145,8        | 193            |
| B_k, mm                  | 26           | 25,5         | 26           | 25,6         | 25,5         | 50             |
| r_k, mm                  | 17,5         | 17,5         | 17,5         | 17,5         | 17,5         | 45             |
| d_k, mm                  | 25,4         | 25,4         | 25,4         | 25,4         | 25,4         | 76,5           |
| M_k, kg                  | 0,278        | 0,162        | 0,162        | 0,284        | 0,232        | 0,418          |
| γ_k, kg/m³               | 712,8        | 501,6        | 377,4        | 666,3        | 562          | 339            |
| Abrasive                 | Al₂O₃        | SiC          | SiC          | SiC          | SiC          | Al₂O₃          |
| Graininess Z, µm          | 50-60        | 45-50        | ~100         | 50-60        | 45-50        | 45-50          |

D_k – wheel diameter, mm; B_k – width of the wheel, mm; r_k – sleeve radius, mm;
  d_k – hole diameter, mm; M_k – wheel weight, kg; γ_k – wheel material density, kg/m³.

The complex of experimental researches on samples from high-strength aluminum alloy B95pchT2
was carried out on the universal milling machine of Deckel Maho DMC 635V brand with the use of a
three-component dynamometer of Kistler (Switzerland) model 9253B23.

In connection with a significant range of experimental data, a dispersion analysis of the dependence
of forces on the regime parameters of processin was carried out on the universal milling machine of Deckel Maho DMC 635V brand with the use of a three-component dynamometer of Kistler (Switzerland) model 9253B23.

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Table 2 gives an example of the results of the dispersion analysis of dependencies for two circles at
a confidence level 0.95:

- CF-FB-0.5A FIN (lightest rigidity) \( P_y = f(ΔY) \) at \( V = 606.3 \text{ m/min} \); \( S = 130 \text{ mm/min} \); \( P_y = f(V) \) at
  \( ΔY = 4.5 \text{ mm} \); \( S = 130 \text{ mm/min} \) and \( P_y = f(S) \) at \( ΔY = 4.5 \text{ mm} \); \( V = 606.3 \text{ m/min} \);
- FS-WL 8A MED (lightest rigidity) \( P_y = f(ΔY) \) at \( V = 441.4 \text{ m/min} \); \( S = 130 \text{ mm/min} \); \( P_y = f(V) \) at
  \( ΔY = 1.5 \text{ mm} \); \( S = 130 \text{ mm/min} \) and \( P_y = f(S) \) at \( ΔY = 1.5 \text{ mm} \); \( V = 441.4 \text{ m/min} \).

Table 2. Results of the dispersion analysis of dependencies

| Brand of the wheel | Function | \( S_{x}^2, \text{H}^2 \) | \( S_{y}^2, \text{H}^2 \) | \( F = S_{x}^2/S_{y}^2 \) | Factor's influence | Conf.level \( S_{0} \cdot t, \text{H} \) |
|--------------------|----------|-------------------------|-------------------------|--------------------------|-------------------|------------------|
| CF-FB-0.5A FIN     | \( P_y = f(ΔY) \) | 0,0808                  | 0,00388                 | 20,825                   | significant       | ±0,122           |
|                    | \( P_y = f(V) \) | 0,0037                  | 0,00057                 | 6,442                    | significant       | ±0,047           |
|                    | \( P_y = f(S) \) | 0,0226                  | 0,00097                 | 23,3                     | significant       | ±0,002           |
| FS-WL 8A MED       | \( P_y = f(ΔY) \) | 29,579                  | 0,11229                 | 263,4                    | significant       | ±0,658           |
|                    | \( P_y = f(V) \) | 19,56                   | 0,24016                 | 81,144                   | significant       | ±0,960           |
|                    | \( P_y = f(S) \) | 1,9755                  | 0,0641                  | 30,817                   | significant       | ±0,125           |

Conclusion on the significance or insignificance of the influence of the factor in question \( ΔY \), \( V \) and
\( S \) on the force \( P_y \) is obtained using the Fisher Criterion. If \( F = (S_{x}^2/S_{y}^2) > F_{0.95} \), the factor has a significant
impact on the force under study. \( F_{0.95} \) – Fisher's criterion at a confidence level 0.95. That's the criterion
for degrees of freedom \( f_1 = k – 1 = 3 \) and \( f_2 = k(n – 1) = 20 \) according to reference data [15] is \( F_{0.95} = 3.1 \).

Confidence limits are defined as \( Δ = ± S_{0} \cdot t \), where \( t \) – Student quantum. With the number of degrees
of freedom \( t = 1,96 \).

Figure 1 shows the dependencies of the normal (a) and tangential (b) cutting force (by 1 mm of the

processing width) on the deformation of the wheel. As a result of measurement at the set modes of processing the arithmetic average on all 6 levels (180 values) is accepted.

It is established that the normal and tangential component of the force increases with increasing deformation. This is explained by the fact that with increasing deformation the elastic and centrifugal components of the force increase $P_y$. For the same reason, the tangential cutting force increases $P_z$.

Figure 2 shows the dependences of the normal (a) and tangential (b) components of the cutting force on the cutting speed, from which it can be seen that as the cutting speed increases, the values of the cutting force components for different wheels change unequivocally. This is explained by too different structure and rigidity of the studied wheels.

Studies have shown that elastic abrasive wheels are not perfectly elastic. They have viscous-elastic properties, which means that during the period of one revolution, when the next contact of the tool with the surface to be machined, there is no time to restore the desired deformation. Therefore, for less viscous wheels, the forces increase and for more viscous wheels, the forces decrease.

![Graph showing dependences of normal and tangential components of cutting force on deformation](image)

1 – FS-WL 8A MED at $V = 441.4$ m/min; 2 – FS-WL 6S FIN at $V = 406.8$ m/min; 3 – FS-WL 2S CRS at $V = 462.4$ m/min; 4 – DB-WL 8S MED at $V = 464.3$ m/min; 5 – CF-FB 0,5A FIN at $V = 606.3$ m/min.

**Figure 1.** Dependence of normal $P_y$ (a) and tangential $P_z$ (b) component of the cutting force per 1 mm machining width on deformation $\Delta Y$ of the wheels at $S = 130$ mm/min
Fig. 2. Dependence of normal $P_y$ (a) and tangential $P_z$ (b) the cutting force component of the cutting force per 1 mm machining width from the cutting speed $V$ for wheels at $S = 130$ mm/min.

Fig. 3 shows the dependencies of the normal (a) and tangential (b) cutting force on the longitudinal feed, from which it can be seen that as the longitudinal feed increases, the values of the cutting force increases for stiffer circles and decreases for less rigid ones. This is due to the different visco-elastic properties of elastic wheels and the extremely low thickness of the material to be removed.
The dependencies given in Figures 1, 2 and 3 are approximated by the expressions obtained to simplify the application of the research results for practical purposes.
These equations are valid for the elastic polymer-abrasive circles studied in the present paper when processing high-strength aluminum alloy B95PhT2. The equations were obtained in the following form:

\[ P_1 = a_1 \cdot \Delta Y + a_2 \cdot V_2 + a_3 \cdot S_2 + a_4 \cdot \Delta Y + a_5 \cdot V + a_6 \cdot S + a_7 \cdot \Delta Y \cdot V + a_8 \cdot \Delta Y \cdot S + a_9 \cdot V \cdot S + a_{10} \cdot \Delta Y \cdot V \cdot S + a_{11}; \] (1)

\[ P_2 = b_1 \cdot \Delta Y + b_2 \cdot V_2 + b_3 \cdot S_2 + b_4 \cdot \Delta Y + b_5 \cdot V + b_6 \cdot S + b_7 \cdot \Delta Y \cdot V + b_8 \cdot \Delta Y \cdot S + b_9 \cdot V \cdot S + b_{10} \cdot \Delta Y \cdot V \cdot S + b_{11}. \] (2)

The values of the coefficients \(a_{1-10}, b_{1-10}\) and free terms \(a_{11}, b_{11}\) of these equations are given in Table 3.

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Coefficient} & \text{FS-WL 8A MED} & \text{FS-WL 6S FIN} & \text{FS-WL 2S CRS} & \text{DB-WL 8S MED} & \text{CF-FB 0,5A FIN} \\
\hline
a_1 & 1,0002 & 1,1485 & -0,295 & 1,11331 & 0,05 \\
\hline
a_2 & -1,2\cdot10^{-7} & -5,4\cdot10^{-8} & -1,6\cdot10^{-6} & -7,8\cdot10^{-8} & 3,04\cdot10^{-7} \\
\hline
a_3 & 7,47\cdot10^{-8} & -6,9\cdot10^{-7} & -3,6\cdot10^{-6} & 4,98\cdot10^{-8} & -5,1\cdot10^{-7} \\
\hline
a_4 & 5,07\cdot10^{-4} & 0,0957 & 1,685 & 3,38\cdot10^{-4} & 0,15 \\
\hline
a_5 & -4,7\cdot10^{-5} & -4,9\cdot10^{-5} & -2,7\cdot10^{-3} & -5,2\cdot10^{-4} & -5,5\cdot10^{-5} \\
\hline
a_6 & -3,5\cdot10^{-4} & 1,66\cdot10^{-5} & -5,5\cdot10^{-3} & -3,5\cdot10^{-4} & -9,4\cdot10^{-4} \\
\hline
a_7 & 6,07\cdot10^{-9} & -8,9\cdot10^{-7} & 1,34\cdot10^{-3} & 4,05\cdot10^{-9} & 4,8\cdot10^{-8} \\
\hline
a_8 & 1,68\cdot10^{-8} & 5,1\cdot10^{-6} & 3,6\cdot10^{-3} & 1,12\cdot10^{-8} & 1,4\cdot10^{-4} \\
\hline
a_9 & 4,05\cdot10^{-11} & 6,25\cdot10^{-8} & 1,74\cdot10^{-5} & 2,7\cdot10^{-11} & 8,18\cdot10^{-7} \\
\hline
a_{10} & -3,4\cdot10^{-11} & -3,4\cdot10^{-8} & -6,5\cdot10^{-6} & -2,3\cdot10^{-11} & -4,1\cdot10^{-7} \\
\hline
a_{11} & 0,0625 & 0,385 & -0,65 & 0,291 & -0,2 \\
\hline
b_1 & 0,4 & 0,574 & -0,1475 & 0,463 & 0,025 \\
\hline
b_2 & -2,3\cdot10^{-7} & -2,1\cdot10^{-7} & -8,04\cdot10^{-7} & -3,9\cdot10^{-8} & 7,3\cdot10^{-7} \\
\hline
b_3 & 1,49\cdot10^{-9} & -3,4\cdot10^{-7} & -1,8\cdot10^{-6} & 2,49\cdot10^{-8} & -8,3\cdot10^{-7} \\
\hline
b_4 & 2,03\cdot10^{-4} & 0,0478 & 0,9 & 8,44\cdot10^{-6} & 0,03 \\
\hline
b_5 & -9,3\cdot10^{-7} & -2,7\cdot10^{-4} & -1,35\cdot10^{-3} & -2,6\cdot10^{-4} & -8,2\cdot10^{-6} \\
\hline
b_6 & -7,1\cdot10^{-2} & 5,43\cdot10^{-6} & -2,75\cdot10^{-3} & -1,77\cdot10^{-4} & -8,6\cdot10^{-5} \\
\hline
b_7 & 1,2\cdot10^{-10} & -4,4\cdot10^{-7} & 6,7\cdot10^{-4} & 2,02\cdot10^{-9} & 1,2\cdot10^{-4} \\
\hline
b_8 & 3,36\cdot10^{-10} & 2,56\cdot10^{-5} & 1,8\cdot10^{-1} & 5,6\cdot10^{-9} & 3,49\cdot10^{-5} \\
\hline
b_9 & 8,09\cdot10^{-13} & 3,13\cdot10^{-8} & 8,71\cdot10^{-6} & 1,35\cdot10^{-11} & 2,04\cdot10^{-9} \\
\hline
b_{10} & -6,8\cdot10^{-13} & -1,7\cdot10^{-8} & -3,2\cdot10^{-6} & -1,1\cdot10^{-11} & -1,04\cdot10^{-7} \\
\hline
b_{11} & 0,05125 & 0,1525 & -0,28 & 0,291 & -0,05 \\
\hline
\end{array}
\]

Thus, the results of the carried out researches and the received equations of dependence of normal \(P_1\) and tangential \(P_2\) components of cutting force on regime parameters of processing, can be used for effective forecasting of productivity of process and quality of the processed surface, and also required capacity of the equipment for performance of operation.

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