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Investigation of force parameters acting on a single cutting insert made of ceramics in face milling of hardened steel

Sergey N. Grigoriev[a], Marina A. Volosova, Vladimir D. Gurin and Anton Ye. Seleznyov

Moscow State University of Technology "STANKIN", 1 Vadkovsky per., 127994 Moscow GSP-4, Russian Federation

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Abstract – In the present paper, mathematical models for force parameters affecting single cutting insert made of oxide ceramics during finish milling of hardened steels are derived taking into account wear of inserts. Experiments showed that nitride Physical Vapor Deposition (VPD) coatings on oxide ceramics substrate CC6(Al_2O_3-TiC) produced by Moscow State University of Technology "STANKIN" provide at least 10% decrease of cutting forces. It was realized that cutting inserts wear influences the force parameters, especially axial force P_x, that makes it possible to use those parameters as diagnosis indicators.

Key words: Milling / diagnosis / cutting ceramics / force parameters / coating / hardened steel

1 Introduction

Milling of hardened steels using cutting tool equipped with non-resharpened mechanically fixed indexable inserts made of ceramics is the most common process when machining parts for industrial equipment like dies, molds, etc. The ratio of related parts being machined using CNC machine tools grows up with enhancing of design and control systems parameters of multiaxial and multifunctional machine tools as well as cutting tools parameters.

Increase of technical and economic indices of processing parts made of hardened steels using cutting tools with ceramic cutting part can be provided by online monitoring of cutting tool conditions.

Efficiency of cutting tool diagnosis systems is mainly defined by indirect information about dominating defect of cutting tool that cannot be measured directly in the real time mode [1].

The computer-aided manufacturing generally includes the diagnosis automation [2]. For this purpose, the appropriate mathematical models describing function relations between process parameters and factors and taking into account the influence of dominating defect (i.e. tool failure criterion) are required [3].

As it is shown in literature [4], the tool failure criterion when milling or turning hardened steels using cutting tool equipped with ceramics is flank wear h_f [5]. The commonly recommended limit value of h_f is about 0.4 mm.

Representation of tool conditions criterion should be maximally adequate on the cutting forces parameters [6].

However, the function relations between cutting forces components and parameters of face milling of hardened steels considering wear of ceramic inserts are underexplored [7].

It should be noticed that there are five cutting force components acting to every cutting edge of milling cutter during machining. Of course, the analysis of overall force parameters produced during face milling when several inserts are involved to cutting process simultaneously, can be carried out by using the force parameters models describing force parameters induced on single insert of face mill cutter at each moment of time [8].

2 Measurement of force parameters in finish face milling of hardened steels

Analysis of cutting force components during the milling process (Fig. 1) shows that the concurrent measurement of all force parameters using a single measuring device is impossible. Among existing measuring methods, the most technically simple one is a measurement of overall force parameters using high-precision equipment. In present work, the force components P_v, P_h and P_x were measured, where P_h is a force acting along the vector of feed V_s^-; P_v is normal to P_h; P_x is an axial force parallel to the axis of cutting tool. In Figure 1, the P_x force appears to be the origin of force parameters coordinates.

[a] Corresponding author: science@stankin.ru

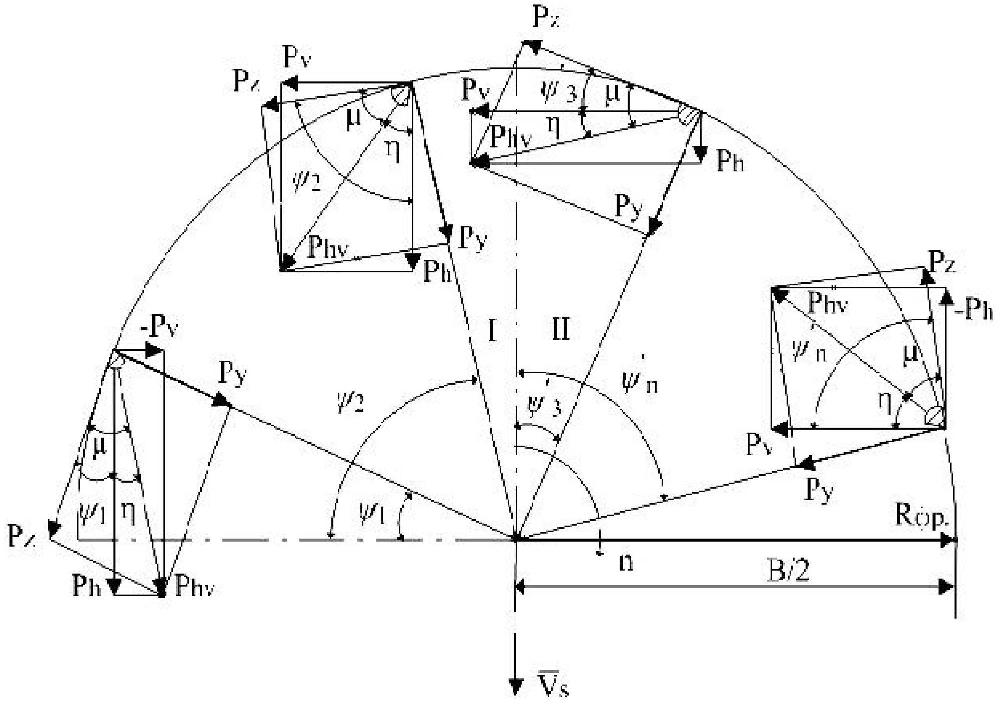


Fig. 1. Force parameters for different orientations of cutting insert during face milling used for calculation of force components P_z and P_y with measured values of P_v and P_h.

The above mentioned force parameters have been measured using the high-precision multicomponent dynamometer Multicomponent Force Plate by Kistler Type 9253B21 (Switzerland). It was firmly fixed on the table of vertical milling machine BM127M having the infinitely variable feedrate control. Data collection and analysis were performed by Kistler DynoWare software. The sensitivity threshold is less than 0.01 N, as it is specified in technical data of device.

The face milling cutter used in experiment has a diameter D_a of 100 mm and equipped with one four-sided insert made of CC650 (Sandvik) ceramics, both uncoated and coated.

The geometric parameters of the insert are: $\alpha = 6°$, $\varphi = 84°$, $\lambda = +5°$, $\varphi_1 = 6°$, $r = 0.8$ mm; negative rake $\gamma = -26°$ is produced by chamfer with width $f = 0.3$ mm and inclination angle of 20°.

The cutting conditions have been varying in the following range: cutting speed $V = 125{-}500$ m.min^{-1}; depth of cut $a_p = 0.1{-}0.5$ mm; chip load $f_z = 0.06{-}0.15$ mm.

Work material: hardened steel ShKh15 (European equivalent is 100Cr6) with a hardness of 61–63 HRC.

In Figure 2, a sample of oscilloscope trace for force parameters P_v, P_h, P_x during conventional milling using the insert made of CC650 ceramics with width of cut $B = 62$ mm is shown.

Using the oscilloscope traces of P_v and P_h, the force components P_z (tangential) and P_y (radial) were calculated using the following procedure.

As it follows from graphical construction shown in Figure 1, for all rotational positions of insert with maximum possible rotation angle of 180°, i.e. when the width of cut B is equal to the cutter's diameter D_a, the forces P_z and P_y can be derived using the equations:

$$P_z = P_{hv} \cos \mu \tag{1}$$

$$P_y = P_{hv} \sin \mu \tag{2}$$

Angle μ in (1) and (2) is one between the resulting force $R_{hv} = \sqrt{P_h^2 + P_v^2}$ and the tangential force P_z so that $\mu = \psi \pm \eta$, where ψ is the rotation angle of insert. We believe that this angle matches the rotational angle of point of the resulting force application on the active length of main cutting edge for it is very small within the selected set of factors and parameters [8]. The depth of cut doesn't exceed 0.5 mm.

Figure 1 also allows the conclusion that with $0 \le \psi \le 90°$ the angle $\eta = \mp \mathrm{arctg} \frac{P_v}{P_h}$. The minus or plus sign depends on the direction of the force P_v, which is located in area I in Figure 1. If $90 < \psi \leqslant 180°$, then $\eta = \pm \mathrm{arctg} \frac{P_h}{P_v}$. In this case the sign of angle η is defined by the direction of the force Ph shown in Figure 1 in area II.

Figure 3 represents the graphic charts of the force parameters P_v, P_h, P_x derived from five oscilloscope traces at each moment of time during the cutting process (Fig. 3a), as well as forces P_z and P_y calculated using the above procedure (Fig. 3b). Cutting conditions are : $V = 193$ m.min^{-1}, $f_z = 0.06$ mm; $a_p = 0.3$ mm. Width of cut $B = 100$ mm, that means both conventional and

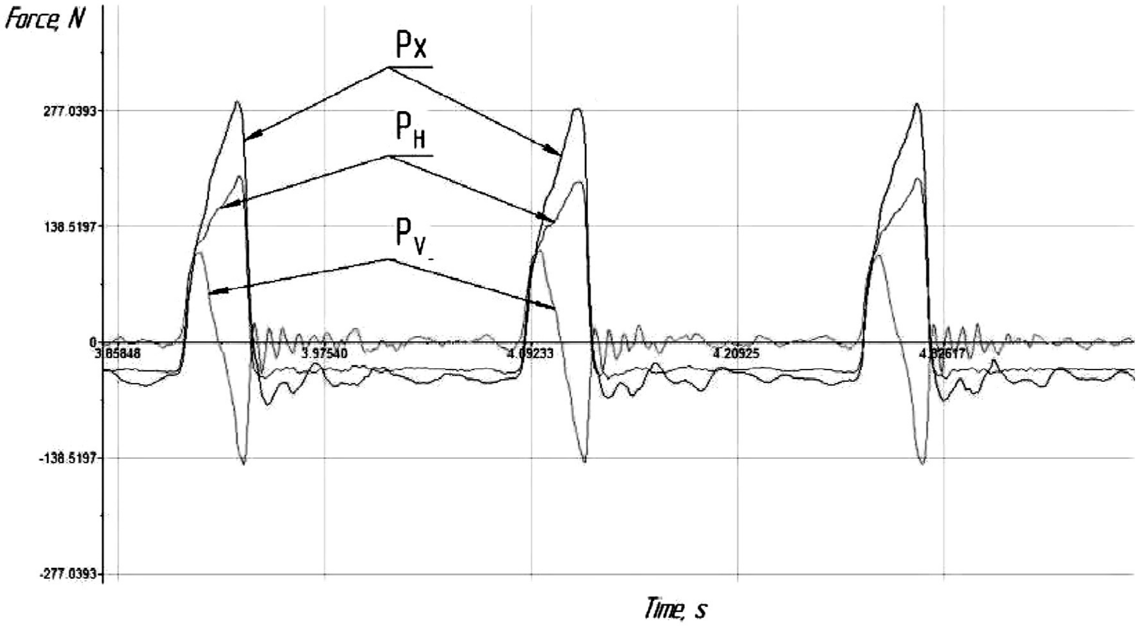


Fig. 2. Oscilloscope trace of the force parameters P_v, P_h, P_x for insert made of CC650 ceramics having a sharp cutting edge.

climb cutting were performed during one pass using insert made of CC650 ceramics.

As it can be seen from the charts of P_z and P_y (Fig. 3b) we show that the sign of these force parameters was not changed during the entire working period of insert, but monotonically increased and decreased in the areas of conventional and climb milling (in Fig. 1, areas I and II, respectively). It is also notable that forces P_z and P_y are almost equal to P_v and P_h in which they are transformed both when using sharp and worn cutting tool at the moment of rotation of the insert at the angle $\psi = 90°$, according to Figure 1. From what has been said above it follows that the derived parameters matches all the fundamentals of common metal cutting theory referring the cutting forces acting in face milling.

3 Functional relationship between force parameters arising on a single cutting insert and cutting conditions taking into consideration the cutting edge wear

The mathematical models representing the force parameters acting on the insert both in its initial and current state are based on the following polynomial:

$$P_i = P_i\left(h_f = 0\right) + \Delta P_i\left(h_f\right) \tag{3}$$

where $P_i\left(h_f = 0\right)$ is an instantaneous value of the force parameter in initial state of the insert; $\Delta P_i\left(h_f\right)$ is an increment of this parameter in current state of the insert with the failure criterion $h_f > 0$.

The quantitative functional relationship between tangential, radial and axial forces and instantaneous angle of rotation ψ_i of a single insert under different milling factors can be represented analytically by polynomial multiplicative mathematical models as follows:

$$\begin{aligned} P_{zi} &= C_{Pz} t^{X_{Pz}} \left(S_z \sin\psi_i\right)^{y_{Pz}} V^{Z_{Pz}} \\ &\quad + C'_{P_z} t^{X_{Pz}} \left(S_z \sin\psi_i\right)^{y_{Pz}} h_3^{m\,P_z} V^{Z_{Pz}} \end{aligned} \tag{4}$$

$$\begin{aligned} P_{yi} &= C_{Py} t^{X_{Py}} \left(S_z \sin\psi_i\right)^{y_{Py}} V^{Z_{Py}} \\ &\quad + C'_{P_y} t^{X_{Py}} \left(S_z \sin\psi_i\right)^{y_{Py}} h_3^{m\,P_y} V^{Z_{Py}} \end{aligned} \tag{5}$$

$$\begin{aligned} P_{xi} &= C_{Px} t^{X_{Px}} \left(S_z \sin\psi_i\right)^{y_{Px}} V^{Z_{Px}} \\ &\quad + C'_{P_x} t^{X_{Px}} \left(S_z \sin\psi_i\right)^{y_{Px}} V^{Z_{Px}} \end{aligned} \tag{6}$$

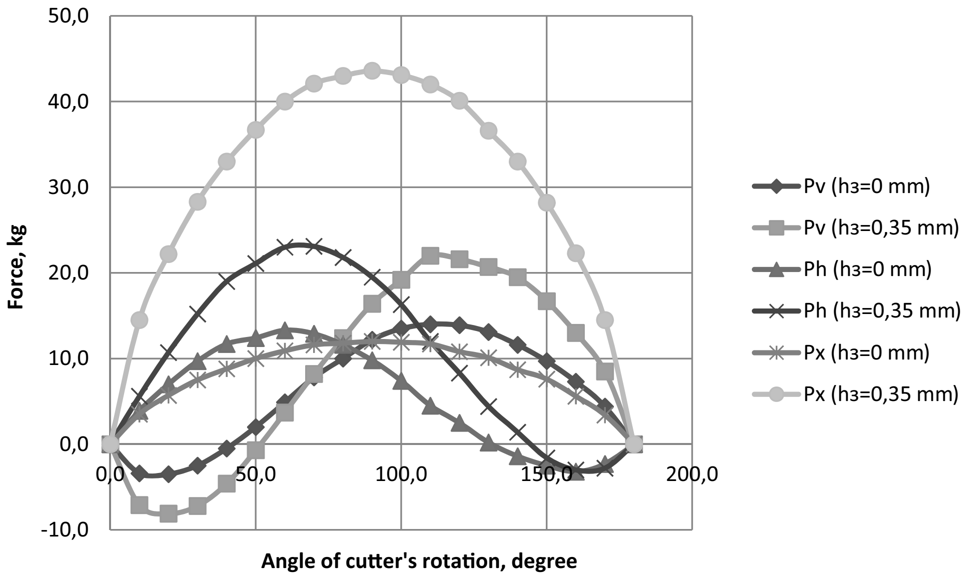
In these equations, C_{Pz}, C'_{P_z}, C_{Py}, C'_{P_y}, C_{Px}, C'_{P_x} are the constant quotients where x, y, z, m are to describe, correspondingly, extent of the impact of depth of cut, nominal chip thickness $a_i = S_z \sin\psi_i$ when rotating the insert to the angle ψ_i with the depth of cut less or equal to the cutting edge radius, cutting speed, flank wear rate.

The impact of the above described common factors in finish milling of hardened steel ShKh15 (100Cr6, 61–63 HRC) to the force parameters was studied by a single-factor experiment. The experiments include the conventional and climb milling during one pass of the insert. Figures 4–6 show the results of experiment in double logarithmic coordinates.

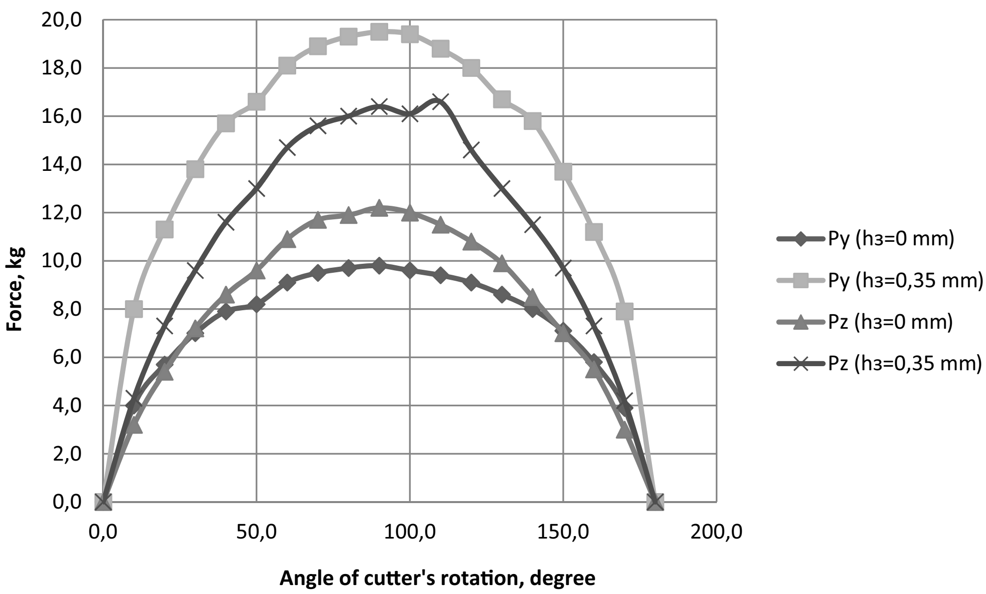
These charts show that dependencies between the instantaneous values of cutting force components and considered factors are represented as straight lines in logarithmic coordinates, which proves the description of these dependencies by the exponential function in Equations (4)–(6).

The constant quotients (exponents) were derived with software using the least-squares method.

As a result of study, the following mathematical models of the tangential, radial and axial cutting force



(a)



(b)

Fig. 3. (a) Charts of force parameters P_v, P_h and P_x obtained from Kistler dynamometer, and (b) charts of the calculated force parameters P_z and P_y.

components with finish face milling of hardened steels were produced:

$$P_{zi} = 260a_p^{0.8}(f_z \sin\psi_i)^{0.75} + 101a_p^{0.8}(f_z \sin\psi_i)^{0.75}h_f^{0.11}, \text{ [kgf]} \quad (7)$$

$$P_{yi} = 130a_p^{0.98}(f_z \sin\psi_i)^{0.5} + 162a_p^{0.98}(f_z \sin\psi_i)^{0.5}h_f^{0.22} \text{ [kgf]} \quad (8)$$

$$P_{xi} = 210a_p^{0.75}(f_z \sin\psi_i)^{0.7} + 693a_p^{0.75}(f_z \sin\psi_i)^{0.7}h_f^{0.38} \text{ [kgf]} \quad (9)$$

After the elementary manipulations, the mathematical models (7)–(9) were transformed to a more convenient form:

$$P_{zi} = 260a_p^{0.8}(f_z \sin\psi_i)^{0.75}(1 + 0.39h_f^{0.11}), \text{ [kgf]} \quad (10)$$

$$P_{yi} = 130a_p^{0.98}(f_z \sin\psi_i)^{0.5}(1 + 1,24h_f^{0.22}), \text{ [kgf]} \quad (11)$$

$$P_{xi} = 210a_p^{0.75}(f_z \sin\psi_i)^{0.7}\left(1 + 3,3h_f^{0.38}\right), \text{ [kgf]} \quad (12)$$

The mathematical models (10)–(12) are true within the range of cutting speed $V = 100{-}220$ m.min^{-1}, because in this case the cutting speed doesn't influence neither on the force parameters P_{zi}, P_{yi} and P_{xi}, nor on their

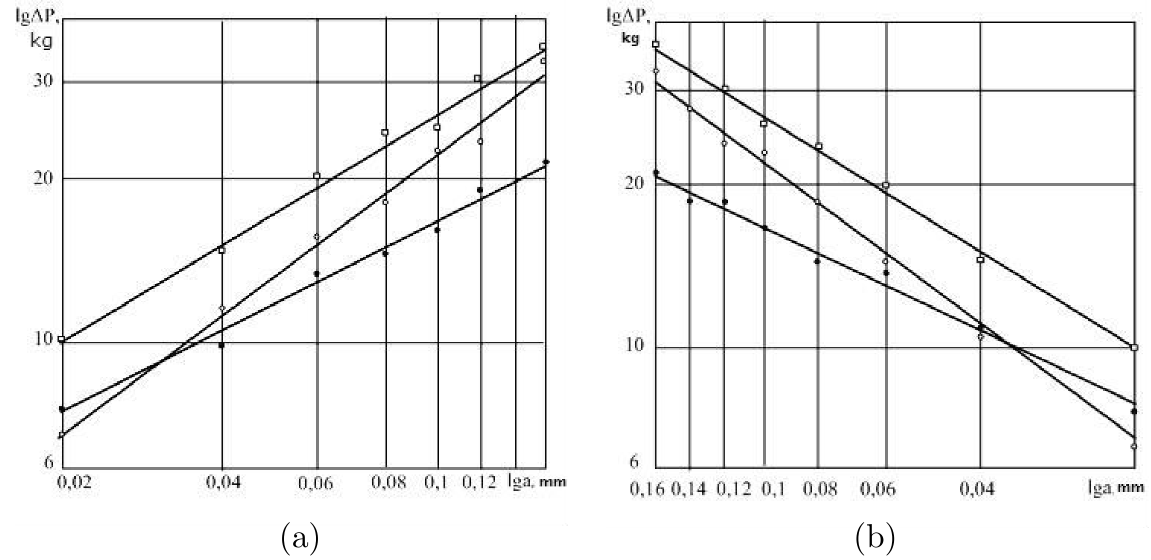


Fig. 4. Impact of the depth of cut, a, on the force parameters P_{zi}, P_{yi} and P_{xi} in conventional (a) and climb (b) phases of face milling: –○– – ΔP_z, –●– – ΔP_y, –□– – ΔP_x.

increment caused by the flank wear h_f in conventional and climb milling of hardened steels.

Within the range of cutting speed $V = 220-500$ m.min^{-1} it is proposed to calculate the force parameters P_{zi}, P_{yi} and P_{xi} using the following equations:

$$P_{zi} = 3796 a_p^{0.8} (f_z \sin\psi_i)^{0.75} V^{-0.5} (1 + 0.39 h_f^{0.11}), \text{ [kgf]} \quad (13)$$

$$P_{yi} = 1878 a_p^{0.98} (f_z \sin\psi_i)^{0.5} V^{-0.5} (1 + 1,24 h_f^{0.22}), \text{ [kgf]} \quad (14)$$

$$P_{xi} = 2864 a_p^{0.75} (f_z \sin\psi_i)^{0.7} V^{-0.5} \left(1 + 3,3 h_f^{0.38}\right), \text{ [kgf]} \quad (15)$$

The reason for this is that in the specified range the values of force parameters significantly decrease with increasing cutting speed.

The chip thickness a_i and depth of cut a_p influence on the forces adequately both in the area of conventional milling where a increases from 0 to $a_{\max}$, and in one of climb milling where a decreases from $a_{\max}$ to 0. It allows using the Equations (10)–(15) to calculate the force parameters at every moment of time during rotation of the insert at the angle ψ varying from 0° to 180°.

The mathematical models of the instantaneous values of P_{V_i} and P_{h_i} can be carried out with respect to the cutting forces layout:

$$P_{h_i} = P_{z_i} \cos\psi_i + P_{y_i} \sin\psi_i \quad (16)$$

$$P_{V_i} = P_{z_i} \sin\psi_i - P_{y_i} \cos\psi_i \quad (17)$$

Equations (16) and (17) are true within the range $0° \leqslant \psi_i \leqslant 180°$ when in the area II (Fig. 1) the conversion formulas for functions $\sin\psi_i$ and $\cos\psi_i$ where $\psi_i = 90° + \psi_i'$ are used.

Comparison of values of forces P_{V_i} and P_{h_i} derived using the models (10)–(15) with the corresponding values obtained from result of experiment shows that the difference between them is 7%. For instance, calculated values are: $P_V = -2.4$ kg and $P_h = 9.6$ kg with $\psi_i = 30°$, $P_V = 8.9$ kg and $P_h = 37.5$ kg with $\psi_i = 50°$. The appropriate experimental data are: $P_V = -2.25$ kg and $P_h = 9.5$ kg with $\psi_i = 30°$; $P_V = 8.8$ kg and $P_h = 37.6$ kg with $\psi_i = 50°$.

Thus, it can be stated that the derived mathematical models of the instantaneous values of the force parameters P_{z_i}, P_{y_i}, P_{x_i} adequately describe the functional relationship between factors and components of cutting force in milling hardened steels using tool with ceramic inserts.

In addition, the experimental researches of influence of wear resistant coatings on the considered cutting parameters were conducted. In experiment, the inserts made of CC650 ceramics with nitride coatings ZrN, Ti-TiN-TiAlN, NbTiAl-NbTiAlN were used [9]. The coating was performed in MSUT "STANKIN" using the Physical Vapor Deposition (PVD) method with a preliminary cleaning in a two-stage vacuum-arc discharge. The study revealed that the coatings provide decrease of P_z, P_y, P_x by about 10%. This can be brought into the previously derived models (10)–(15) as the as a correction factor $k_{\text{coat}} = 0.9$.

The conducted studies show that P_{z_i}, P_{y_i} and P_{x_i} decrease with the same exponential factor $m = -0.5$ starting with the cutting speed of 220 m.min^{-1}. Hypothetically, it can be explained by the temperature increase in the cutting area that provides lowering the hardness of local volumes of the deformed material.

To confirm the hypothesis, the milling process of one ceramic insert was recorded using a high-speed digital video camera Photron FASTCAM SA5 at the speed of 5000 frames per second. The cutting conditions are as follows: $V = 400$ m.min^{-1}, $a_p = 0.5$ mm, $f_z = 0.08$ mm (Fig. 7).

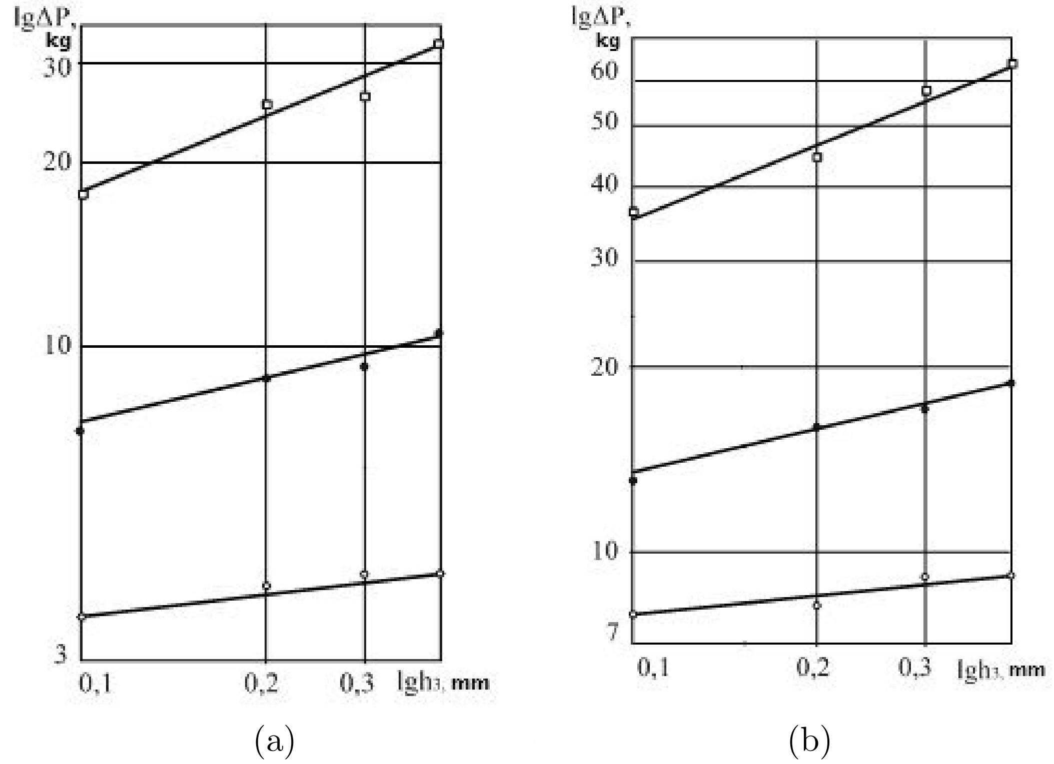


Fig. 5. Impact of flank wear rate, h_f, on the increment ΔP of cutting force components P_{zi}, P_{yi} and P_{xi} with chip thickness $a = 0.04$ mm (a) and $a = 0.12$ mm (b) in face milling: –○– – ΔP_z, –●– – ΔP_y, –□– – ΔP_x.

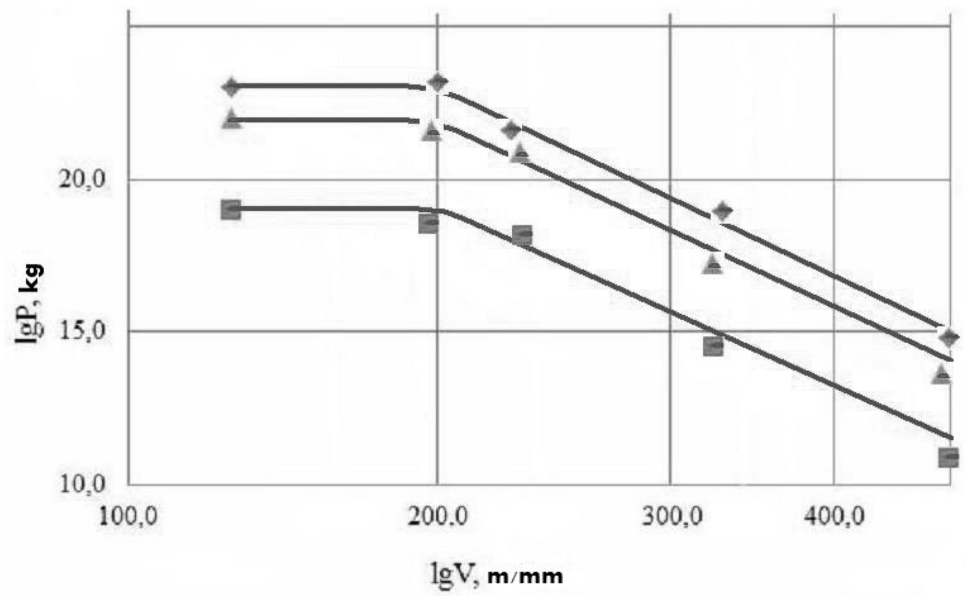


Fig. 6. Impact of flank wear rate, h_f, on the force parameters P_{zi}, P_{yi} and P_{xi} with insert being rotated to 90° ($a = 0.08$ mm), $f_z = 0.08$ mm, $a_p = 0.5$ mm, $h_f = 0$ mm. chip thickness $a = 0.04$ mm (a) and $a = 0.12$ mm (b) in face milling: –○– – ΔP_z, –●– – ΔP_y, –□– – ΔP_x.

Fig. 7. Frame of the high-speed video recording of finish milling of hardened steel using the milling cutter with ceramic inserts.

During the cutting, the machined layer of the material is heated to the temperature close to its melting point, thus transforming from the solid phase to the liquid one, and keeping the original hardness in the surface layer. This fact is proved by the subsequent hardness control using the Rockwell durometer Wilson Hardness R574T, Instron (USA). After the machining (removing the stock), the hardness is equal to 61–63 HRC (average of 5 points).

The Figure 7 represents a single frame of the high-speed video of milling the hardened steel ShKh15 (100Cr6, 61–63 HRC) where the flying particles are circled. Those particles are in the liquid phase, for the high-speed video shows that they change their shape during their flight.

This confirms that at high cutting speed the local volumes of hardened steel transform to the liquid phase that allows the uniform decrease of all the force parameters.

4 Conclusion

The derived mathematical models of the force parameters acting to a single cutting insert made of ceramics in finish milling of hardened steel, allow analyzing those parameters under different conditions taking into account the wear rate of the inserts with sufficient precision.

The flank wear h_f most strongly influences the axial force P_x which increases up to 3 times and more with the limiting value of the failure criterion. Thus, the axial force can be used as a diagnosis indicator. Increase of the cutting speed to over 220 m.min^{-1} provides decrease of the cutting force components with the same exponential factor $m = -0.5$ that can be explained by heat of local volumes of hardened material being deformed before transforming to the liquid phase.

The derived models allow modeling the total force parameters acting to the face milling cutter when several inserts are involved to chip removal. This helps to choose the appropriate force parameter for the cutting tool diagnosis, and requires the research in this field to be continued.

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