International Journal of INNOVATIVE AND INFORMATION MANUFACTURING TECHNOLOGIES
Donetsk National Technical University & International Union of Machine-Builders
International Journal of Innovative and Information Manufacturing Technologies, SHEI "Donetsk National Technical University"; 58, Artyoma Street, 83001 Donetsk, Tel.: +38 062 305 01 04, Fax: +38 062 301 08 05, E-mail: tm@mech.dgtu.donetsk.ua, http://iimt.donntu.edu.ua

MODELING OF CUTTING FORCES IN DIAMOND DRILLING

ROSHCHUPKIN Stanislav, BRATAN Sergey, NOVOSYOLOV Yuri

[1] Subdivision; Mechanical engineering; 14, Gogolya Street, 299000 Sevastopol, RUSSIAN FEDERATION
[2] The Department "Polytechnic Institute"; SHEI "Sevastopol state university"; 33, Universitetskaya Street, 299000 Sevastopol, RUSSIAN FEDERATION
Corresponding author: ROSHCHUPKIN Stanislav, e-mail: st.roshchupkin@yandex.ru

Submitted 01.06.2015; accepted 01.06.2015

Abstract.This paper represents results of development of probabilistic mathematical models which allow to calculate cutting forces arising in diamond drilling. Proposed models take into account stochastic nature of the drilling process, conditions and geometry of the tool, physico - mechanical properties of the processed material and cutting parameters. In order to verify the adequacy of the developed models a series of experiments was carried out. Obtained expressions can be used for solving optimization and control tasks in diamond drilling process.
Keywords: diamond drilling, cutting force, mathematical model, stochastic, abrasive grain

1. Introduction

At the present time nonmetallic materials, such as ceramics and glasses, are gaining a great popularity worldwide as constructional materials. It caused by their specific properties which are usually unachievable for other materials. It is high mechanical strength, chemical durability, resistance to high temperatures, dielectric properties and corrosion resistance.

The widespread usage of nonmetallic materials is restrained by the difficulties of their machining caused by high hardness and tendency for brittle fracture. One of the most labor-intensive processes is hole machining.

There are some methods of hole machining in nonmetallic materials: ultrasonic machining (USM), chemical and photochemical methods and diamond drilling. The most effective method is diamond drilling. Diamond drilling is an intense kind of abrasive machining in which material removal process occurs as a combination of microcutting and brittle fracture. Removing chips in this process is very difficult. Generally diamond drilling is similar to face grinding.

In order to understand the abrasive cutting processes nature many investigations have been conducted and many mathematical models have been developed [1,2,3,4,5]. However, existing models were designed for calculation of process variables only for constant, steady-state drilling conditions.

In the previous studies conducted by the authors [6, 7] were obtained probabilistic expressions which allowed to set cutting parameters for any moment of machining, but for the practical application of them it is necessary to identify some of their parameters. One of the most important parameters are cutting forces.

This paper represents probabilistic mathematical models for the prediction of normal and tangential forces in diamond drilling that account for changes of the tool condition for the period of its life and stochastic nature of the drilling process.

2. Cutting forces modeling

In diamond drilling total cutting force is made of forces arising from interaction of single diamond grains with the workpiece. Significant influence on force characteristics of the process takes shape of the cutting edges and their orientation [2]. The grain shape can be approximated by paraboloid of revolution. During processing the cutting edges become blunted with formation of a wear flat on the diamond grains.

S.N. Korchak [3] developed model for calculation of normal P_y and tangential P_z forces acting per unit length of conventional cutting edge in microcutting with abrasive grains which have wear flat:

$$P_y = \left(\frac{\sqrt{3{,}25}a_3 \sin\beta}{\sin\beta_1} + 0{,}5b(z) \right)\tau_3 \qquad (1)$$

$$P_z = \left(\frac{\sqrt{3{,}25}a_3 \cos\beta}{\sin\beta_1} + 0{,}5\mu b(z) \right)\tau_3 \qquad (2)$$

where a_3 is the depth of cut by single grain; β is the angle between the resulting cutting force and cutting velocity; β_1 is the shearing angle; τ_3 is the average shear stress in a shear plane; μ is the friction coefficient; $b(z)$ is the width of wear flat.

Figure 1 shows the scheme of a single grain cutting.

The depth of cut by single grain a_3 in equations (1) and (2) differs from a geometric value t. It is a random variable because the abrasive grain interacts with random profile of microasperities.

When diamond grain contacts with one of the largest roughness point the width of wear flat $b(z)$ in direction of cutting velocity and width of cut $b(h_3)$ equals $\frac{\pi b(h_3)}{4}$, and average depth of cut [8]:

$$\overline{a_3} = \frac{1}{b_3}\int_0^{b_3} a_3(x)dx \quad a_3(x) = \begin{cases} y_3, npu \ \ y_3 \geq 0 \\ 0, npu \ \ y_3 < 0 \end{cases}$$

where y_3 is the coordinate of the surface roughness profile point to wear flat.

Width of cutting edge of worn grain can be calculated as:

$$b(h_3) = C_b\left(\frac{t_f - u}{t_f - u - h_3}\right)^m h_\tau^m \qquad (3)$$

where $C_b = 2\sqrt{2\rho_3}$ and m are the coefficients of grain shape; ρ_3 is the rounded radius of the top of the grain; h_τ is the coordinate of the grain profile point from its worn top; t_f is the maximum microcutting depth; h_3 is the wear value in a perpendicular direction to the cutting speed, defined as:

$$h_3 = h_{3\max}\left(1 - \frac{u}{t_f - \Delta h}\right)^z \qquad (4)$$

where z it the coefficient which can be determined analytically, Δh is the material removal value.

Distinguishing at the time τ in the zone of contact volume with the depth Δu, width of the diamond layer L_k and perimeter of drill circle πD we can calculate number of cutting grains which are in the distinguished volume as:

$$\Delta\lambda_b = L_k n_3 f_{\xi u}(u)\Delta u \pi D \qquad (5)$$

where n_3 is the number of grains per unit volume of the working tool layer; $f_{\xi u}(u)$ is the distribution density; D is the tool diameter.

$$f_{\xi u}(u) = C_h u^{\chi - 1} \qquad (6)$$

where C_h is the coefficient calculated from the condition that the unit area equal to bounded distribution curve

$$C_h = \frac{\chi}{H_u^\chi} \qquad (7)$$

where H_u is the size of the tool working surface layer, within which n_3 is calculated.

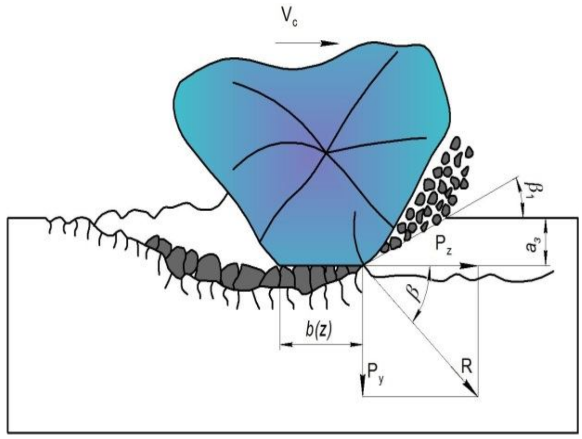

Fig.1. The scheme of a single grain cutting.

We introduce the term of conditional length of the cutting edges of abrasive grains in selected microvolume $b_\Sigma(h_3)$. If all points of wear flats contacted with machining material, conditional length of the cutting edges would be defined as a product of wear flat width on number of cutting grains. Accounting probability of the contact expression for $b_\Sigma(h_3)$ can be written in the form:

$$b_\Sigma(h_3) = b(h_3)P_k\Delta\lambda_b = b(h_3)[1 - P(M)]\Delta\lambda_b \qquad (8)$$

where $P(M)$ is the probability of material removal.

The value of the total forces acting on the abrasive grains, the tops of which are located in a distinguished microvolume, calculate as a product of forces defined by equations (1) and (2) on the conditional length of the cutting edges:

$$\Delta P_{\Sigma 3y} = P_{3y} b_{\Sigma}(h_3) = P_{3y} b(h_3)[1-P(M)]L_k n_3 f_{\xi u}(u)\Delta u \pi D \quad (9)$$

$$\Delta P_{\Sigma 3z} = P_{3z} b_{\Sigma}(h_3) = P_{3z} b(h_3)[1-P(M)]L_k n_3 f_{\xi u}(u)\Delta u \pi D \quad (10)$$

In the transition from discrete to continuous models after substitution of values P_y, P_z, $P(M)$, $f_{\xi u}(u)$ and after integration in u equations (9) and (10) take the form:

$$\sum_i P_{yi} = \frac{\tau\pi D\chi L_k n_3 C_b h^m{}_{3\max}(t_f-\Delta h)^{\chi+0,5}}{H_u^{\chi}} \times \left[\frac{0,96\Gamma(\chi)\Gamma(zm+3,5)(t_f-\Delta h)\sin\beta\overline{a_3}}{\Gamma(\chi+zm+3,5)\sin\beta_1} + \frac{\pi C_b h^m{}_{3\max}\Gamma(\chi)\Gamma(zm+2,5)}{6\Gamma(\chi+zm+3,5)}\right] \quad (11)$$

$$\sum_i P_{zi} = \frac{\tau\pi D\chi L_k n_3 C_b h^m{}_{3\max}(t_f-\Delta h)^{\chi+0,5}}{H_u^{\chi}} \times \left[\frac{0,96\Gamma(\chi)\Gamma(zm+3,5)(t_f-\Delta h)\sin\beta\overline{a_3}}{\Gamma(\chi+zm+3,5)\sin\beta_1} + \frac{\mu\pi C_b h^m{}_{3\max}\Gamma(\chi)\Gamma(zm+2,5)}{6\Gamma(\chi+zm+3,5)}\right] \quad (12)$$

The number of grains per unit volume of the working tool layer can be calculated as [8]:

$$n_{S_p} = \frac{n_{30}C_f(1+C_h\tau)((t_f-C_h\tau(t_f-h_3(0)+H))^{\chi}-(t_f-C_h\tau(t_f+H)-h_3(0))^{\chi}}{(1-C_h\tau)\chi} =$$
$$= \frac{n_{30}C_f(1+C_h\tau)((t_f+C_h\tau(\Delta h+h_3(0)))^{\chi}-(t_f-\Delta h C_h\tau-h_3(0))^{\chi}}{(1-C_h\tau)\chi}$$

3. Experimental verification of analytical models

In order to verify the adequacy of the developed models a series of experiments was carried out. Experiments have been conducted forverification equation for normal component of cutting force as it has the greatest influence on the drilling process and quality of machining.

Machining was performed on NC milling machine tool by diamond core drills with diamond grain size 125/100 and 160/125. All drills had grooves on the end for _mproveing coolant circulation.

Figure 2 shows experimental setup, figure 3 – diamond drills used in experiments.

As workpieces was used plates of sheet glass M1 and alumina ceramic Al2O3 with dimensions of 80 × 80 × 5 mm.

For researches was used full factorial experiment method of type 2^4.As varied factors were chosen diamond grain size G, feed rate S, workpiece microhardness H_V and the cutting velocity V.

Table 1 represents the upper (+) and lower (-) levels of varied technological factors . At each point in the plan experiment was repeated 3 times in random order to avoid bias .

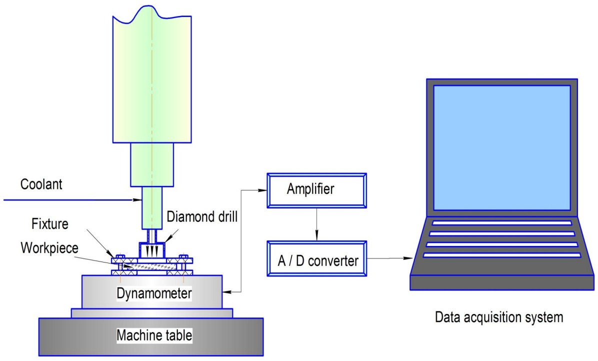

Fig.2. Experimental setup.

Fig.3. Diamond drills.

Table 1. Intervals of factors variation

Factors	G, μm	V , m/sec	S, mm/min	H_V, Gpa
Upper level (+)	112 (125/100)	2	15	5 (glass)
Lower level	142 (160/125)	3	25	15 (ceramic)

Table 2 shows a matrix of experiment plan and its results represented as arithmetic average of the results of three duplicate experiments.

Figure 4 shows changing of the normal cutting force for a period of machining

Table 1. Experiment plan and results

№	V	S	G	H_V	P_Y, H
1	+	+	+	+	446
2	+	+	+	-	209
3	+	+	-	+	467
4	+	+	-	-	205
5	+	-	+	+	361
6	+	-	+	-	158
7	+	-	-	+	375
8	+	-	-	-	174
9	-	-	+	+	364
10	-	-	+	-	160
11	-	-	-	+	381
12	-	-	-	-	175
13	-	+	+	+	450
14	-	+	+	-	209
15	-	+	-	+	469
16	-	+	-	-	207

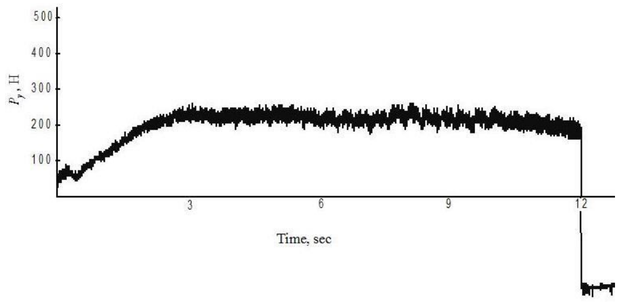

Fig. 4. Changing of the normal cutting force for a period of machining

For the mathematical description of results was used power depentanizer in form:

$$\bar{y} = C_y x_1^{\beta_1} x_2^{\beta_2} x_3^{\beta_3} x_4^{\beta_4} \qquad (13)$$

where $\bar{y}$ is the average value of the controlled parameter; x_1, x_2, x_3, x_4 are the values of variable parameters;
$C_y, \beta_1, \beta_2, \beta_3, \beta_4$ are the empirical coefficients.
After processing of the experimental data was obtained regression relationship:

$$P_Y = 37{,}87 S^{0{,}42} 3^{-0{,}17} H_V^{\,0{,}72} \qquad (14)$$

Adequacy of the model was evaluated by Fischer criterion.
On the basis of this relationship were build graphs (fig. 5-8) which graphically display an influence of technological factors (V, S, G, H_V)*on* normal cutting force.

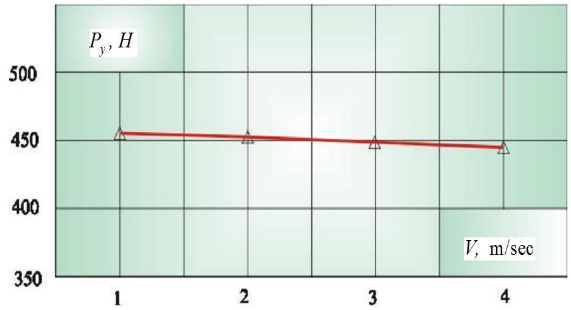

Fig. 5. The dependence of the normal cutting force on the cutting velocity.

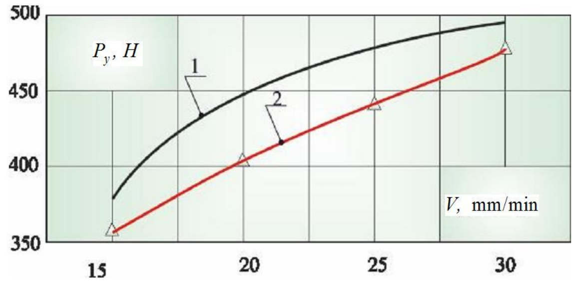

Fig. 6. The dependence of the normal cutting force on the feed rate:
1-Theoretical value; 2-Experimental value.

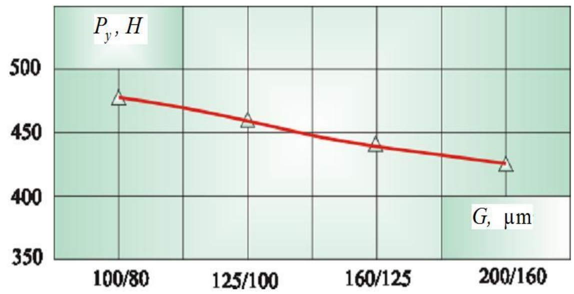

Fig. 7. The dependence of the normal cutting force on the diamond grain size.

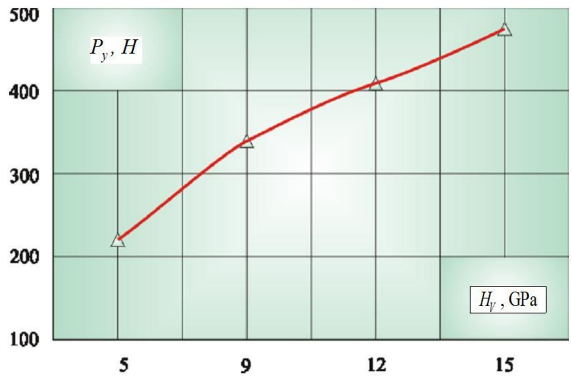

Fig. 8. The dependence of the normal cutting force on the microhardness.

The results of calculations of the normal cutting forces on the theoretical relationships (11) were compared with experimental results (Fig. 6). The divergence of results does not exceed 10%, that indicates on a sufficient degree of adequacy of the developed models.

4. Conclusion

A models for prediction normal and tangential forces in diamond drilling were developed. Proposed models take into accounts to chastic nature of the drilling process, conditions and geometry of the tool $(L_k, D, \rho_з, n_з, f_\xi(u), b(h_з))$, physico - mechanical properties of processed material $(\tau_з)$ and cutting parameters.

Predicted values are in a good agreement with experimental results.

Obtained expressions do not take into account geometrical deviations of the diamond drill and its dynamic oscillation. This will be task for further research.

Acknowledgements

This work was financially supported by Ministry of Education and Science of Russian Federation.

References

1. Balykov, A.V. Povyshenie jeffektivnosti obrabotki otverstij v detaljah iz hrupkih nemetallicheskih materialov na osnove almaznogo sverlenija.- Dis. na soiskanie uchenoj stepeni doktora tehnicheskih nauk po special'nosti 05.02.08 – Tehnologija mashi-nostroenija / – Moskovskij gosudarstvennyj tehnologicheskij universitet «STANKIN», Moskva, 2004.

2. Novosyolov Y.K. Dinamika formoobrazovanija poverhnostej pri abrazivnoj obrabotke – Sevastopol': Iz-vo SevNTU, 2012.-304 pp.

3. Korchak S.N. Proizvoditel'nost' processa shlifovanija stal'nyh detalej – M.: Mashinostroenie, 1974. – 280 pp.

4. Deniz Aslan, Erhan Budak. Semi-analytical force model for grinding operations/ Procedia CIRP 14 (2014) p. 7 – 12

5. Zhao N. L., Guan W. F. Modeling and Predicting Grinding Force of the Grinding Process / Advanced Materials Research, Vol 1055, pp. 165-170, Nov. 2014

6. Bratan S.M., Roshhupkin S.I. Vzaimosvjaz' peremeshhenij v tehnologicheskoj sisteme pri almaznom sverlenii nemetallicheskih materialov/ Visnik Sums'kogo derzhavnogo tehnichnogo universitetu. Naukovij zhurnal. Serija «Tehnichni nauki». Vidavnitstvo SumDTU. Vip. №1-2008-S. 49-53.

7. Bratan S.M., Roshhupkin S.I. Modelirovanie formoobrazovanija otverstij pri almaznom sverlenii nemetallicheskih materialov/ Vi-soki tehnologiї v mashinobuduvanni. Zb. nauk.pr. HNTU: Harkiv, Vip.2(17) -2008-S. 54-59

8. Bratan, S. M. Tehnologicheskie osnovy obespechenija kachestva i povyshenija stabil'nosti vysokoproizvoditel'nogo chistovogo i tonkogo shlifovanija. - Dissertacija na soiskanie uchenoj stepeni doktora tehnicheskih nauk po special'nosti 05.02.08 – Tehnologija mashinostroenija / S.M. Bratan– Odesskij nacional'nyj politehnicheskij universitet, Odessa, 2006.

9. Yanming Quana at al. The experimental research on small hole machining in glass using diamond abrasive core-tools. Advanced Materials Research Vols. 76-78 (2009) pp. 491-496.

10. Hui Huang at al. Force Characteristics in Drilling of Engineering Ceramic with a Brazed Diamond Tool. Key Engineering Materials Vols. 359-360 (2008) pp. 153-155