Investigation of the dependence of axial force and torque on the geometric parameters of carbide micro-drills with variable slopes of spiral grooves

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Abstract: *Micro-drilling (MD or μD) is type of machining (processing) technology used for the drilling of miniaturized parts of small diameter in micro-scale, ie. diameter in a range of a few microns to several hundred microns. In paper is given the dependence of axial efforts and torque on different modes of depth of drilling in micro-drilling with micro-drills from solid alloy VK60M with standard rake angle $\omega=30^0$ and f=0.01 [mm/turn*

KEY WORDS: *INDUSTRY 4.0, MICRO-DRILLS, AXIAL FORCE, TORQUE, REGRESSION MODEL.*

1. Introduction

The new knowledge society (KS) or knowledge based society (KBS) and "Industry 4.0" condition the accelerated development and use of new technology, materials and production systems in combination with digital technologies: Internet of Services (IoS), Internet of People (IoP), Internet of Things (IoT), Industrial Internet of Things (IIoT), Internet of Everything (IoE), Cloud Computing (CC) and etc. [1-4, 10-11, 13, 17, 19-21, 30-31, 34, 36, 38].

In knowledge society (KS) and "Industry 4.0" and today's fast-paced world with a large number of important applications of one of the most emerging and growing fields of production technologies are micro and nano-machining [22].

Micro- and nano-machining are the most promising technology for the production of miniaturized parts in micro- and nano-scale. Compound micro- and nano-machining is becoming more and more important and popular because of growing demand for industrial products with not only increased number of functions but also of reduced dimensions, higher dimensional accuracy and better surface finish. Micro- and nano-machining are required in a large number of fields like biotechnology, electronics, medicine, optics, aviation's, automobile and communication and etc. [22].

2. Micro-drilling

Micro-drilling (MD or μD) is type of machining (processing) technology used for the drilling of miniaturized parts of small diameter in micro-scale, ie. diameter in a range of a few microns to several hundred microns. Micro-drilling using micro drill bits possesses the same features as that of the macro scale drilling but slightly different ones. This uses a special drill geometry, tool holding devices, drilling cycle and speeds of drilling [15, 22-23, 25]. In paper [14] is presented analysis of dynamic characteristics of micro-drills, in papers [16, 18, 24] is presented analysis of stresses in micro-drills, cutting performance of micro-drills is presented in papers [23] optimization of geometric parameters of micro-drills in papers [27-29, 33, 35], wear mechanisms of micro-drills in papers [37] and etc.

On Fig. 1 is given micro-drilling with micro-drills on the CNC machine of the firm DATRON (Web site: https://www.datron.com/).

Micro-drilling is applied in industries such as electronics, aerospace, medicine and automobiles for machining parts with a diameter of several microns, due to a significant uptake in the use of miniaturised products and devices.

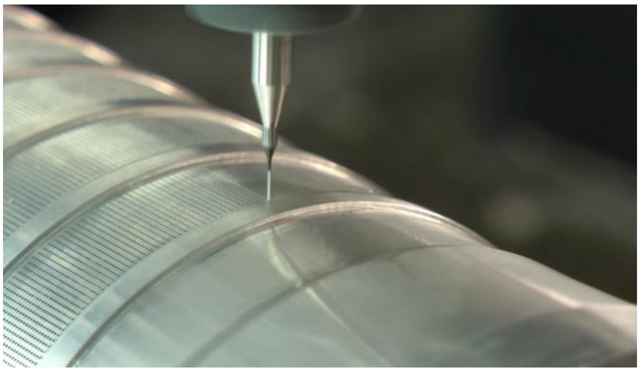

Fig. 1. *Micro-drilling with micro-drills on the CNC machine of the firm DATRON*

A number of different micro-drilling techniques have been developed that can generally be classified into [15]: conventional and non-conventional micro-drilling techniques. Conventional micro drilling makes use of drill bits of different configurations such as: twist, spade, D-shaped, single flute, compound drill and coated micro drill, while non-conventional micro drilling involves electrical, chemical, mechanical and thermal means which include laser, electro discharge machining (EDM), electrochemical machining (ECM), spark assisted chemical engraving (SACE), electron beam (EB), ultrasonic vibration (USV) or combinations of these approaches. These non-conventional micro-drilling techniques include: laser micro-drilling (LMD), electro discharge micro-drilling (EDMD), electrochemical micro-drilling (ECMD), electron beam micro-drilling (EBMD), spark assisted chemical engraving (SACE), ultrasonic vibration micro-drilling (USVMD) and etc. [15, 25]. On Fig. 2 is given overview and classification of laser drilling technologies [12].

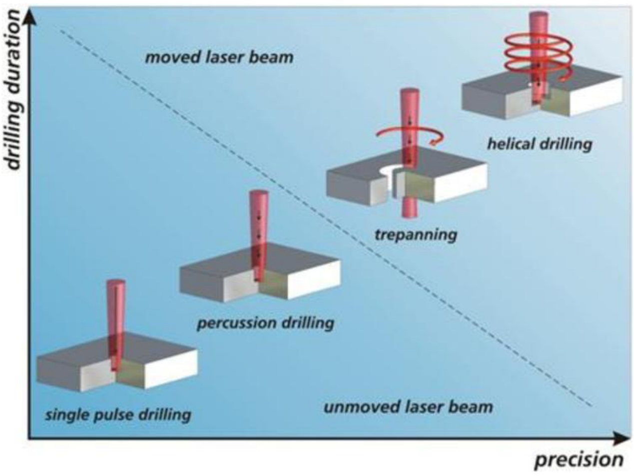

Fig. 2. *Classification of laser drilling technologies w.r.t. drilling duration and precision [12]*

3. Materials and methods

Experiments were conducted with micro-drills from solid alloy VK60M diameter φ=0,9 [mm] long spiral groove l=10 [mm]. Rake angle and spiral angle grooves respectively $\omega=30^0$, rear angle was 18^0. The feed of micro-drilling was: f=0.01 [mm/turn].

Material for micro-drilling it was fiberglass [27-29, 33].

All experimental investigation were realized in laboratory precision micro instrumental Department “Industrial Technologies Engineering Mechanics”, Georgian Technical University (GTU) from Tbilisi (Georgia) in close cooperation with specialists of the Institute of Manufacturing Technology and Quality Management (IFQ) Magdeburg University Otto-von-Guericke (Germany).

To measure the axial effort was the appliance is made on the basis of known methods and existing analogs, measuring element, which is the system of strain gauges mounted on the elastic casing (Fig. 3) [27-29, 33].

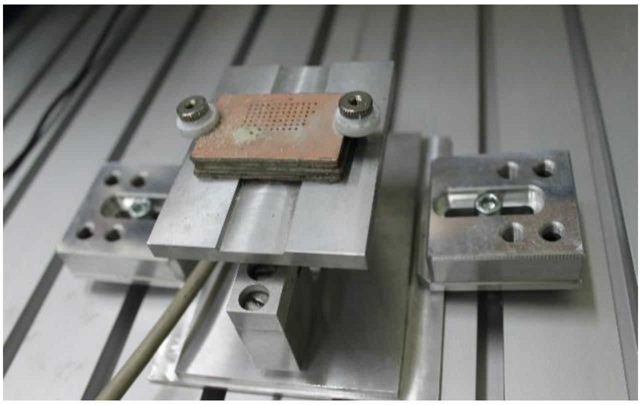

Fig. 3. *Instrument for measuring axial efforts*

Mathematical dependence between torque (T) from depth of drilling (D) during micro-drilling with micro-drills from solid alloy VK60M with standard rake angle $\omega=30^0$ and f=0.01 [mm/turn] can be determined by one of the following regression models in the form:

- linear regression model (LRM):

$$T = b_0 + b_1 \cdot D \qquad (1)$$

- quadrate regression model (QRM) or 2nd-degree polynomial regression model (PRM2):

$$T = b_0 + b_1 \cdot D + b_2 \cdot D^2 \qquad (2)$$

- cubic regression model (CRM) or 3rd-degree polynomial regression model (PRM3):

$$T = b_0 + b_1 \cdot D + b_2 \cdot D^2 + b_3 \cdot D^3 \qquad (3)$$

- power regression model (PRM):

$$T = a \cdot D^{b_1} \qquad (4)$$

- exponential regression model (ERM):

$$T = a \cdot e^{b_1 \cdot D} \qquad (5)$$

- complex power-exponential regression model (PERM):

$$T = a \cdot D^{b_1} \cdot e^{b_2 \cdot D} \qquad (6)$$

- logarithmic regression model (LogRM):

$$T = b_0 + b_1 \cdot \ln D \qquad (7)$$

The mathematical processing of the experimental data involves the determination of numerical values of the parameters b_0, b_1, b_2, b_3 and a for linear (LRM), quadratic (QRM), cubic (CRM), power (PRM), exponential (ERM), complex power-exponential (PERM) and logarithmic (LogRM) regression models and correlation analysis of the observed regression equations.

Parameter estimation for b_0, b_1, b_2, b_3 and a it was determined using the Levenberg-Marquardt (LM) method and a software system using this method. The choice of the regression model is realized on the basis of the values of the coefficient of correlation (R), coefficient of determination (R^2) and adjusment coefficient of determination ($AdjR^2$), according to the methodology described in scientific monographs [5-6] and papers [7-9, 26-29].

4. Results and discussion

4.1. Determination of dependence between axial efforts (P) from depth of drilling (D) during micro-drilling

Measured values for axial efforts (P) [gr.] on different modes of depth of drilling (D) [mm] during micro-drilling with micro-drills from solid alloy VK60M with standard rake angle $\omega=30^0$ and f=0.01 [mm/turn] are shown in Table 1 and Fig. 4.

Table 1. *Measured values for axial efforts (P) on different modes of depth of drilling (D) during micro-drilling with standard micro-drills ($\omega=30^0$) and f=0.01 [mm/turn]*

n [rpm]	Axial efforts (P) [gr.] on different modes of depth of drilling (D)						
	1	2	3	4	5	6	7
10000	260	290	200	310	310	220	320
15000	170	180	150	200	205	155	220
20000	120	140	105	160	160	108	170

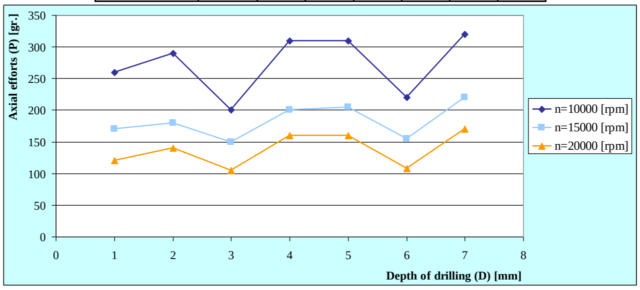

Fig. 4. *The chart of axial efforts (P) on different modes of depth of drilling (D) during micro-drilling with standard micro-drills ($\omega=30^0$) and f=0.01 [mm/turn]*

From Table 1 and Fig. 4, it can be concluded that the values for axial efforts (P) [gr.] on different modes of depth of drilling (D) [mm] during micro-drilling with micro-drills from solid alloy VK60M with standard rake angle $\omega=30^0$ and f=0.01 [mm/turn] range around the indicators of central tendency (Table 2 and Fig. 5).

Table 2. *Indicators of central tendency of axial efforts (P) on different modes of depth of drilling (D) during micro-drilling with standard micro-drills ($\omega=30^0$) and f=0.01 [mm/turn]*

Parameters	Sign	n=10000	n=15000	n=20000
Arithmetic mean	AM	272.8571	182.8571	137.5714
Geometric mean	GM	269.0382	181.2145	135.2789
Harmonic mean	HM	264.9859	179.5807	132.9747
Median	Med	290	180	140

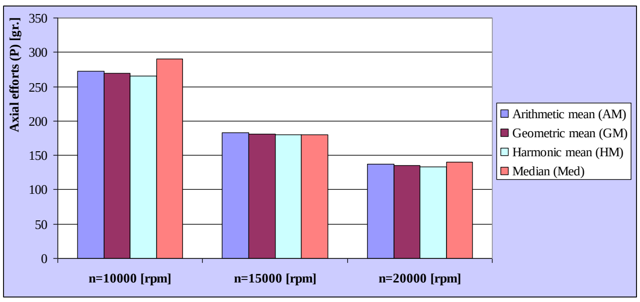

Fig. 5. *Graphical representation of indicators of central tendency of axial efforts (P) on different modes of depth of drilling (D) during micro-drilling with standard micro-drills ($\omega=30^0$) and f=0.01 [mm/turn]*

4.2. Determination of dependence between torque (T) from depth of drilling (D) during micro-drilling

Measured values for torque (T) [gr·sm] depending from depth of drilling (D) [mm] during micro-drilling with micro-drills from solid alloy VK60M with standard rake angle ω=30^0 and f=0.01 [mm/turn] are shown in Table 3 and Fig. 6.

Table 3. *Measured values for torque (T) depending from depth of drilling (D) during micro-drilling with standard micro-drills (ω=30^0) and f=0.01 [mm/turn]*

n [rpm]	Torque (T) [gr·sm] on different modes of depth of drilling (D)						
	1	2	3	4	5	6	7
10000	13	24	30	34	38	40	43
15000	12	20	24	25	25	26	30
20000	7	16	19	22	22	23	25

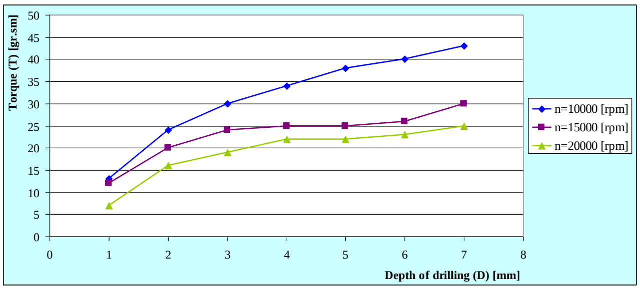

Fig. 6. *The chart of torque (T) depending from depth of drilling (D) during micro-drilling with standard micro-drills (ω=30^0) and f=0.01 [mm/turn]*

Values of indicators of central tendency for torque (T) [gr·sm] on different modes of depth of drilling (D) [mm] during micro-drilling with micro-drills from solid alloy VK60M with standard rake angle ω=30^0 and f=0.01 [mm/turn] is given in Table 4 and Fig. 7.

Table 4. *Indicators of central tendency of torque (T) on different modes of depth of drilling (D) during micro-drilling with standard micro-drills (ω=30^0) and f=0.01 [mm/turn]*

Parameters	Sign	n=10000	n=15000	n=20000
Arithmetic mean	AM	31.71429	23.14286	19.14286
Geometric mean	GM	29.78582	22.37541	17.91481
Harmonic mean	HM	27.35375	21.42016	16.18961
Median	Med	34	25	22

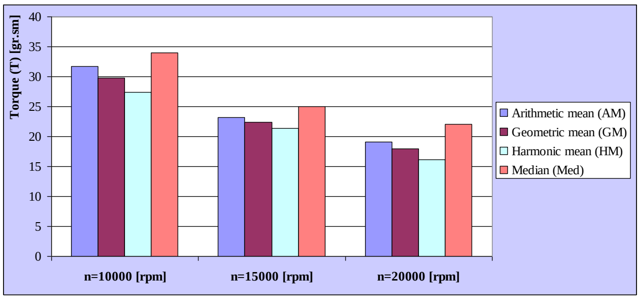

Fig. 7. *Graphical representation of indicators of central tendency of torque (T) on different modes of depth of drilling (D) during micro-drilling with standard micro-drills (ω=30^0) and f=0.01 [mm/turn]*

A comparative analysis of different regression equations of torque (T) [gr·sm] on different modes of depth of drilling (D) [mm] during micro-drilling with micro-drills from solid alloy VK60M with standard rake angle ω=30^0, f=0.01 [mm/turn] and n=10000 [rpm] is given in Table 5 and Fig. 8.

It can be seen from Table 5 and Fig. 8 that all 7 regression equations represent the experimental data well, since their correlation coefficient R is greater than 0.92. This is especially true of the 2nd, 3rd, 6th and 7th equations whose correlation coefficients are greater than 0.994.

Table 5. *Tabular view of analysis of different regression equations of torque (T) on different modes of depth of drilling (D) during micro-drilling with standard micro-drills (ω=30^0), f=0.01 [mm/turn] and n=10000 [rpm]*

No.	Title of regression model (RM)	Form of regression equation	R	R^2	AdjR^2
1.	Linear (LRM)	$T=13.14286+4.64286\cdot D$	0.96109	0.9237	0.90844
2.	Quadrate (QRM)	$T=4.57143+10.35714\cdot D-0.71429\cdot D^2$	0.99463	0.98929	0.98393
3.	Cubic (CRM)	$T=-1.42857+17.19048\cdot D-2.71429\cdot D^2+0.16667\cdot D^3$	0.99923	0.99847	0.99694
4.	Power (PRM)	$T=15.98218\cdot D^{0.5232}$	0.98728	0.97473	0.96967
5.	Exponential (ERM)	$T=17.84783\cdot e^{0.13545\cdot D}$	0.92478	0.85522	0.82627
6.	Power-exponential (PERM)	$T=15.2224\cdot D^{0.85697}\cdot e^{-0.09211\cdot D}$	0.99748	0.99496	0.99243
7.	Logarithmic (LogRM)	$T=13.16304+35.07391\cdot lnD$	0.99708	0.99417	0.99200

A similar analysis can be performed for comparative analysis of different regression equations of torque (T) [gr·sm] on different modes of depth of drilling (D) [mm] during micro-drilling with micro-drills from solid alloy VK60M with standard rake angle ω=30^0, f=0.01 [mm/turn] and n=15000 [rpm] and n=20000 [rpm].

5. Conclusion

The methodology of comparative analysis and the choice of the regression equation according to the correlation coefficient R and the coefficient of determination R^2 is of a general character and can be applied generally for the analysis of similar dependencies and processes and systems.

All 7 regression equations of function T=f(D) (sequentially: cubic, complex power-exponential, logarithmic, quadratic, power, linear and exponential) represent experimental data well, since their correlation coefficient R is greater than 0.92.

The experimental data of function T=f(D) are best represented by cubic (R=0.99923; R^2=0.99847 and AdjR^2=0.99694), and then complex power-exponential regression equation (R=0.99748; R^2=0.99496 and AdjR^2=0.99243) and etc.

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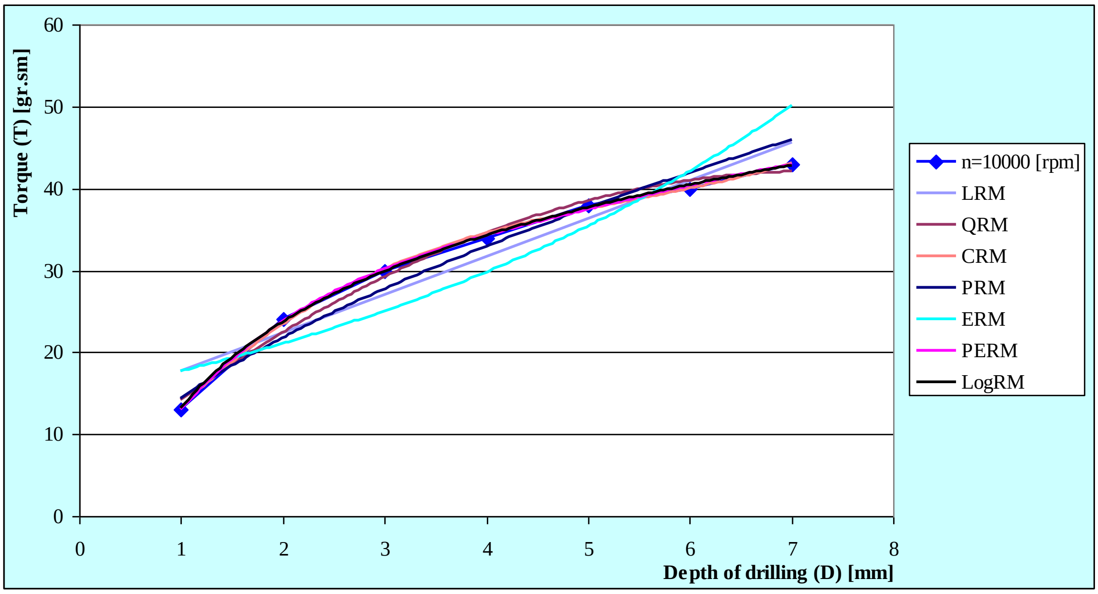

Fig 8. *Graphical representation of analysis of different regression equations of torque (T) on different modes of depth of drilling (D) during micro-drilling with standard micro-drills (ω=30^0), f=0.01 [mm/turn] and n=10000 [rpm]*

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