EXPERIMENTAL INVESTIGATION CUTTING FORCES AND MOMENTS IN ROUGHING GRINDING OF MINERAL MATERIALS

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Abstract: *The paper presents the experimental installation for measuring cutting forces and moments in the roughing grinding process of mineral materials (granite, basalt, marble) using the RPO200-AKS plan grinding machine tool with type 1A1 diamond discs, cutting with the front side with characteristics specific to roughing operations, mounted on a 76.2 mm mandrel.*

The chosen factorial experimental design is 3^1x2^2*. This was the basis for conducting the experiments, establishing three input variables: cutting speed, longitudinal feed, cutting depth and output variables: cutting force components* F_x, F_y, F_z *and cutting moments* M_x, M_y, M_z.

Using the Data Fit program version 9.1.32 the regression functions for the force components F_x, F_y, F_z *were obtained. The experimental research conclusions regarding the variation of cutting forces and moments as well as the degree of machinability in the case of mineral materials tested in the roughing grinding process.*

Keywords: *roughing grinding, mineral materials, diamond discs, cutting forces, cutting moments.*

1. General introduction

The main parameters that generally characterize the grinding process are: cutting forces; chip temperature; quality (roughness) of the machined surface and diamond disc wear. These parameters are found in the specialized literature as criteria for evaluating the machinability of materials or criteria for assessing the cutting capacity of cutting tools [Enache, 2000].

There is a trend towoards reorienting raw materials, replacing ferrous and non- ferrous materials with mineral-ceramic, composite, cast or sintered mineral materials. These have superior characteristics in operation and functioning [Pleniceanu, 2009].

Basalt castings have o long service life and high reliability. As limitations, they have lower tensile and bending strength and much higer fragility than metals [Ștefănescu, 2000].

Basalt can be used as a subsitute for ferrous and non-ferrous materials, as it has high Mohs hardness values and other special properties, namely: high resistance to wear and corrosion [Popp, 2017].

The uses of granite in the machine building industry (machine tool frames, gearbox housings made of granite) make granite a substitute for massive and heavy parts that require vibration stability and absolute rigidity [Brabie, 2006].

The large quantities of granite around the world make it, like basalt, a substitute raw material available to all producers.

The casting workability of crushed granite in combination with a binder is practically unlimited in construction of large machine tool parts such as frames, housings [Ciupan, 2020].

Zhang and his collaborators [Zhang, 2014] studied the grinding process of ceramics and the mechanism of grinding force. The study states that the rigidity and precision of machine tools, process parameters such as coolant, tool wear, and the size of abrasive particles of grinding weels have an influence on magnitude of grinding force and its variation.

Nakayama and his team [Nakayama, 1988] studied the magnitude of cutting forces when machining hard and brittle materials by the grinding process and concluded that the development of high cutting forces is not mandatary when machining them.

Grinding with diamond discs is considered to be cutting with randomly arranged cutting edges on the periphery of diamond disc.

The grinding process can be assimilated to a micro-chiping process, and the diamond disc is considered to be similar to a cylindrical front milling cutter with multiple micro-cuts randomly arranged on the circumference, presenting a variable geometry. Sadu refers to the kinematics of genereting complex surfaces and their generation by grinding with analogy the surface milling process [Sandu, 2008].

Hao and his collaborators [Hao, 2017] analyticaly established a new detailed methodology for modeling grinding forces that was experimentally validated and used to study a specific problem that previous methods canot address. Thus, they proposed a new methodology for predicting grinding forces with detailed information (e.g., on three components, including rubbing, plowing and cutting forces.

Liuyang and his team [Liuyang, 2023] conducted an extensive analysis of the removal behavior of the machined material as well as an analysis of cutting force patterns within the grinding process taking into account the abrasive wheel, processes and workpiece materials. The research highlighted the material removal mechanism for five types of materials, and the constitutive models were concluded with specific parameter values. Thus, it was established that the JH-2 constitutive model is frequently used for the brittle materials.

Figure 1 shows the principle of processing with diamond discs.

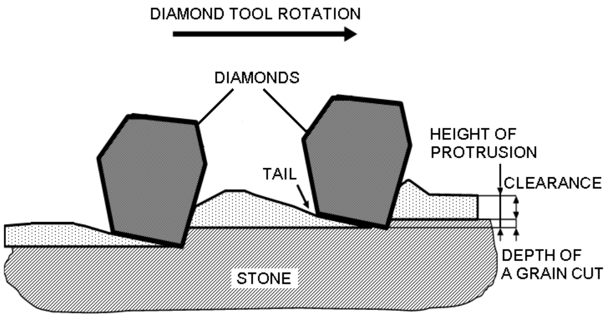

Figure 1: *The principle of diamond disc processing* [Valea, 2019].

Figure 1 highlights the diamond grains as cutting edges, the depth of cut, the mineral material subjected to the abrasion process, and the rotation of the diamond disc.

2. Experimental setup

The stand of studying cutting forces includes: kistler dynamometer; kistler amplifier and computer with specialized software.

Figure 2 shows the layout of the data collection equipment durind the experiments. The interconnection of the kistler dynamometer – aplifier – computer can be seen, as well as the clamping of the semi-finished product on the magnetic table of the grinding machine interconnection with the dynamometer for collecting data during the grinding process. A kistler dynamometer model 9257B was placed on the electromagnetic plate of the grinding machine, and workpieces were fixed with the M8 screws to its base plate [Valea, 2019].

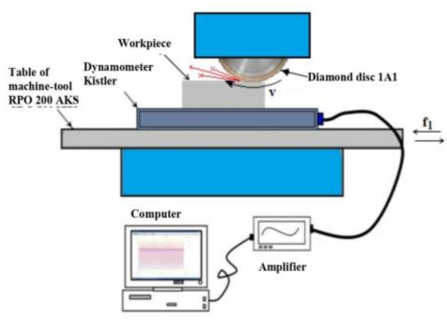

Figure 2: *Schematic layout measuring equipment* [Valea, 2019].

The computing equipment coupled to the kistler amplifier via an interface facilitates the three chanal acquisition of the cutting force and moments denoted by F_x, F_y, F_z, respectively M_x, M_y, M_z corresponding to the dynamometer reference system.

Figure 3 shows the layout of the data acquistiton system in the experiments performed on the RPO200-AKS surface grinding machine from the mechanical workshop at SC Vrancart SA Adjud, Vrancea.

Figure 3: *Have the equipment for acquiring results from the RPO200-AKS plan grinding machine from SC Vrancart Adjud* [Valea, 2019].

The super-abrasive discs used in rough grinding of mineral materials are type 1A1 discs with the following specifications:

1A1-175-10-3 D126 M75 H76.2;
1A1-200-10-3 D126 M75 H76.2;
1A1-300-15-4 D126 M75 H76.2.

For roughing grinding of mineral materials, manufacturers of abrasive tools recommended, in their catalogs, the use of diamond discs with grain size D126, metal bond M and concentration 75.

3. Experimental results

3.1. Determination of cutting forces and moments during roughing grinding of granite and basalt.

Force components F_x, F_y, F_z and moment components M_x, M_y, M_z were measured for each test with a specialized dynamometer Kistler 9257B.

Figure 4 shows the variations of the force component F_z *[N]* for the three tested mineral materials (basalt, granite and marble).

It can be observed that:

- within the 12 factorial experiments, the force component F_z shows fluctuations in value for hard mineral materials (granite and basalt);
- in factorial experiment 4, with the cutting regime: v = 47 m/s, f_l = 4.08 m/min and a_p = 0.03 mm), the maximum value of the force component F_z (268.1 N) was recorded when roughing grinding basalt, followed by the value of the force component F_z (386.3 N) when processing granite, while when grinding marble, the force component F_z reached the highest value (562.9 N).

A possible explanation in the case of marble is the mismatch between the super-abrasive disc and the hardness and nature of the mineral material being processed, which causes the abrasive tool to clog, which can lead to improper cutting [Valea, 2019];

- according to the criterion of cutting forces, it can be found that rough grinding of hard materials (basalt and granite) with diamond discs is more convenient, compared to grinding marble.

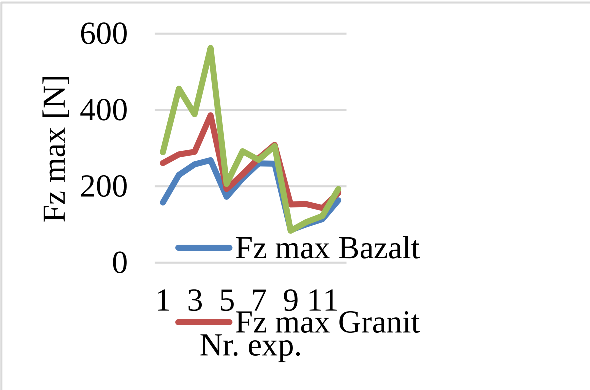

Figure 4: *Variations of the force components F_z max measured during rough grinding of the studied mineral materials*

Table 1 presents the program matrix for the factorial experiment of type $3^1 \times 2^2$ [Cicală, 2005] with the input variables v, f_l, a_p and the output parameters F_z and M_z for roughing grinding of granite.

Table 1. *The program matrix for for the factorial experiment of type $3^1 \times 2^2$ with the input variables v, f_l, a_p and the output parameters F_z and M_z for roughing grinding of granite.*

Exp. no.	Input variables			Output parameters	
	v [m/s]	f_l [mm]	a_p [mm]	F_z max [N]	M_z max [N m]
1	47.00	2.38	0.01	260.9	4.451
2	47.00	2.38	0.03	283.1	5.635
3	47.00	4.08	0.01	290.1	6.55
4	47.00	4.08	0.03	386.3	7.251
5	31.00	2.38	0.01	192.7	2.84
6	31.00	2.38	0.03	231.3	4.242
7	31.00	4.08	0.01	273.6	4.39
8	31.00	4.08	0.03	308.9	7.724
9	27.00	2.38	0.01	152.5	4.291
10	27.00	2.38	0.03	153.5	3.819
11	27.00	4.08	0.01	143	4.415
12	27.00	4.08	0.03	182.8	5.423

From the analysis of the data collected in Table 4 and from the ratio of the forces obtained, it can be seen that the highest value of the force component F_z (386.3 N) obtained during the rough grinding of granite is in experiment 4, with the cutting regime: v = 47 m/s; f_l = 4.08 m/min; a_p = 0.03 mm, and the lowest value of the force component F_z (143 N) is recorded in experiment 11, with the cutting regime: v = 27 m/s; f_l = 4.08 m/min; a_p = 0.01 mm. The moment component M_z (7,724Nm) has its maximum value in experiment 8 [Valea 2019].

The regression function for the force component F_z during rough grinding of granite is obtained with the Data Fit program version 9.1.32. The regression function for the force component F_z is:

$$F_z=11,291176614v^{0,904141222}\cdot f_l^{0,421790930}\cdot a_p^{0,160796442}$$

Figure 5 shows the variation of the real (measured) F_z component and the modeled F_z component for the regression function obtained during rough grinding of granite samples.

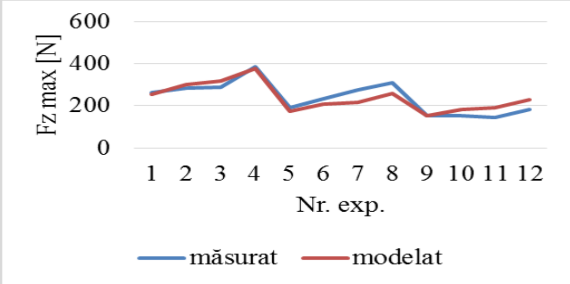

Figure 5: *The variation of the real (measured) F_z component and the modeled F_z component for the regression function obtained during roughing grinding of granite samples.*

Analyzing the representations in figure 5, the following conclusions can be formulated:

- the value of the force component F_z reached a maximum (386.3 N) in experiment 4, with the cutting regime: v = 47 m/s; f_l = 4.08 m/min and a_p = 0.03 mm;
- the real (measured) values of the force components F_z for the regression function obtained during roughing grinding of granite samples follow the variation of the modeled values with small exceptions.

Table 2 presents the program matrix for the factorial experiment of type 3^1 x 2^2 with the input variables v, f_l, a_p and the output parameters F_z and M_z for the roughing grinding of basalt.

Table 2. *The program matrix for the factorial experiment of type 3^1 x 2^2 with the input variables v, f_l, a_p and the output parameters F_z and M_z for the roughing grinding of basalt.*

Exp. No.	Input variables			Output parameters	
	v [m/s]	f_l [mm]	a_p [mm]	F_z max [N]	M_z max [N m]
1	47.00	2.38	0.01	157.3	7.155
2	47.00	2.38	0.03	229.7	7.187
3	47.00	4.08	0.01	257.4	6.005
4	47.00	4.08	0.03	268.1	6.12
5	31.00	2.38	0.01	172.1	3.326
6	31.00	2.38	0.03	220,3	4.93
7	31.00	4.08	0.01	259,6	5.878
8	31.00	4.08	0.03	259,4	6.48
9	27.00	2.38	0.01	85,36	1,749
10	27.00	2.38	0.03	100,1	2.166
11	27.00	4.08	0.01	113.9	2.125
12	27.00	4.08	0.03	163.6	4.635

From the analysis of the data collected in table 2 and from the ratio of the forces and from the ratio of the forces obtained, it can be seen that the highest value of the force component F_z (268.1 N), obtained during the roughing grinding of basalt, is in experiment 4. The lowest value of the force component F_z (85.36 N) is found in experiment 9. The moment component M_z (7.187 Nm) has a maximum value in experiment 2 [Valea, 2019].

The regression function for the force component F_z during the roughing grinding of basalt is obtained with the Data Fit program version 9.1.32. The regression function for the component F_z is:

$$F_z=13{,}658026347 v^{0{,}720590649} f_l^{0{,}564112774} a_p^{0{,}141510727}$$

Figure 6 illustrates the variation of the real (measured) F_z component and the modeled F_z component for the regression function obtained during the roughing grinding of basalt samples.

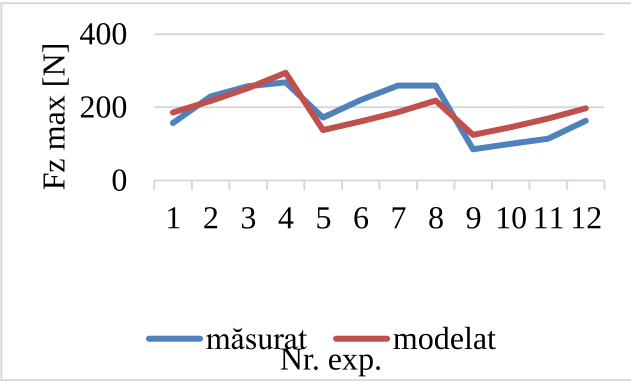

Figure 6: *The variation of the real (measured) F_z component and the modeled F_z component for the regression function obtained during the roughing grinding of basalt samples.*

Analyzing the representations in figure 6, the following conclusions can be formulated:
- the value of the force component F_z has a maximum of (268.1 N) in experiment 4;
- the real (measured) values of the force components F_z for the regression function obtained during the roughing grinding of basalt samples follow the variation of the modeled values with small exceptions.

3.2 Calculation of cutting forces *F* and moments *M* during roughing grinding.

Using relations (1) and (2), the components of forces *F [N]* and moments *M [Nm]* were calculated. The results are presented in tables 3 and 4.

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

$$M = \sqrt{M_x^2 + M_y^2 + M_z^2} \quad (2)$$

Table 3 presents the components of the result forces *Fgranite max [N]* and *Fbasalt max [N]*.

Table 3. *The components of the result forces Fgranite max [N] and Fbasalt max [N].*

No. exp.	Fgranite max [N]	Fbasalt max [N]
1	260.9	157.3
2	283.1	229.7
3	290.1	257.4
4	386,3	268.1
5	192.7	172.1
6	231.3	220.3
7	273.6	259.6
8	308.9	259.4
9	152,5	85.36
10	153.5	100.1
11	143	113.9
12	182.8	163.6

Figure 7 illustrates the variation of the Fmax force components measured during rough grinding of hard mineral materials (granite and basalt).

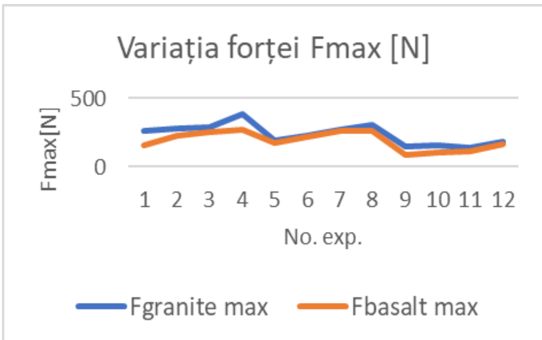

Figure 7: *The variation of the Fmax force components measured during rouging grinding of hard mineral materials (granite and basalt).*

Table 4 presents the resultant components of the moments *M granite max [Nm]* and *M basalt max [Nm].*

Table 4. *The resultant components of the moments M granite max [Nm] and M basalt max [Nm].*

No. exp.	Mgranite max [Nm]	Mbasalt max [Nm]
1	27.366	18.048
2	24.593	18.315
3	22.967	30,849
4	32.928	25
5	16.027	23.3
6	23.064	26.066
7	27.658	41.648
8	31.331	37.222
9	13.936	10.371
10	16,9	10.956
11	18.894	15.83
12	24.577	18.863

Figure 8 illustrates the variation of the components of the moments M max [Nm] measured during roughing grinding of hard mineral materials (granite and basalt).

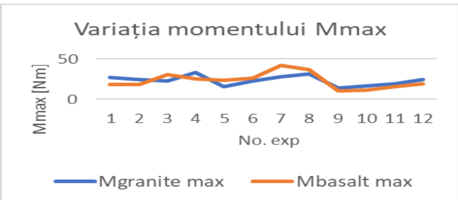

Figure 8: *The variation of the components of the moments M max [Nm] measured during roughing grinding of hard mineral materials (granite and basalt).*

4. CONCLUSIONS

From the analysis of the experimental results obtained, the following conclusions can be drawn regarding the cutting forces during roughing grinding of the tested mineral materials:

- the forces recorded by the kistler dynamometer during roughing grinding are small, on the order of a few hundred [N];
- mathematical models established for roughing grinding and the regression functions investigated reproduce the variation of the magnitudes of the cutting force components (F_x, F_y and F_z);
- higher values of cutting forces, of the three components F_x, F_y and F_z, were obtained for the force component F_z. This recorded a maximum of 562.9 N during roughing grinding of marble. The high value of the force component F_z can be explained by the improper cutting of the marble mineral material with low hardness, which caused premature clogging of the diamond disc and its delayed self-sharpening [Valea, 2019];
- according to the criterion of cutting forces during roughing grinding, basalt has the best machinability, followed by granite;
-it is found that hard materials have good behavior when roughing grinding with diamond discs;
- when roughing grinding hard mineral materials with diamond discs, higher cutting forces are developed the higher the hardness of the processed materials;
- during the tests carried out, it was found that the values of the resultant force *F[N]* and the resultant moment *M[Nm]* present low values.

Reference

1. [Brabie, 2006] Brabie, Gh. *Optimizarea proceselor și echipamentelor tehnologice de prelucrare mecanică*. Editura AGIR, București, 2006

3. [Cicală, 2005] Cicală, E.F. *Metoda experimentelor factoriale. Proiectarea experimentelor, modelare, optimizare*. Editura Politehnica, Timișoara, 2005.

3. [Ciupan, 2020] Ciupan, M. *Contribuții privind proiectarea unor componente structurale din materiale compozite pentru masini-unelte moderne*. Teza de doctorat, Universitatea Tehnica din Cluj-Napoca, 2020.

4. [Enache, 2000] Enache, Şt., Străjescu, E., Tănase, I., Opran, C., Balici, M. *Capacitatea de aşchiere a sculelor*. Editura Academiei Române, Bucureşti, 2000

5. [Hao, 2017] Hao Nan Li [ab]Tian Biao Yu [a], Zi Xuan Wang [a], Li Da Zhu [a], Wan Shan Wang [a]. *Detailed modeling of cutting forces in grinding process considering variable stages of grain-workpiece micro interactions.* International Journal of Mechanical Sciences Volume 126, June 2017, Pages 319-339. Available from, https://www.sciencedirect.com/science/article/abs/pii/S0020740316308268

6. [Liuyang, 2023] Liuyang Li [a], Yanbin Zhang [a], Xin Cui [a], Zafar Said [b], Shubham Sharma [c], Mingzheng Liu [a], Teng Gao [a], Zongming Zhou [d], Xiaoming Wang [a], Changhe Li [a]. *Mechanical behavior and modeling of grinding force: A comparative analysis.* Journal of Manufacturing Processes Volume 102, 29 September 2023, Pages 921-954. Available from, https://www.sciencedirect.com/science/article/abs/pii/S1526612523007582

7. [Nakayama, 1988] Nakayama, K., Arai, M., Kanada, T. *Machining Characteristics of Hard Materials*. Annals of CIRP, Vol.37/1/1988, p. 89-92.

8. [Pleniceanu, 2009] Pleniceanu, A-M. *Optimizarea parametrilor constructivi și de fiabilitate a structurilor tribologice turnate și sinterizate din bazalt*. Teză de doctorat, Universitatea Politehnica Timișoara, 2009.

9. [Popp, 2017] Popp, I.O. *Some aspects regarding the static behavior of basalt in the machine building industry*. MATEC Web Conf. 8th International Conference on Manufacturing Science and Education – MSE 2017 "Trends in New Industrial Revolution", Vol. 121, 2017, p. 1- 6.

10. [Sandu, 2008] Sandu I. Gh. *Generarea suprafețelor. Tratat*. Editura Academiei, București, 2008.

11. [Ştefănescu, 2000] Ştefănescu W. *Contribuții la studiul influenței structurii și proprietăților fizico - mecanice ale unor piese realizate din bazalt asupra fiabilității utilajelor agricole*. Teză de doctorat, Universitatea Politehnica Timișoara, 2000.

12. [Valea, 2019] Valea, P. *Contribuții privind îmbunătățirea condițiilor de așchiere la prelucrarea materialelor minerale*. Teza de doctorat, Universitatea Politehnica București, Facultatea IMST, 2019.

13. [Zhang, 2014] Zhang, *D. K., Li C., Jia D., Zhang Y. Investigation into Engineering Ceramics Grinding Mechanism and the Influential Factors of the Grinding Force*. International Journal of Control and Automation, Vol.7, no. 4, 2014, p.19-34. Available from, http://www.sersc.org/journals/IJCA/vol7_no4/3.pdf.

14. [AKS, 2016] AKS. *Technical manual of the plan grinding machine RPO200-AKS, 2016.*

15. ****Diamomd tools catalogs*. Available from,
www.diamondtools.ro
www.diateh-romania.ro
www.diasfin.ro
www.popatools.ro
www.tyrolit.com