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THE GRINDING OF MINERAL MATERIALS WITH DIAMOND DISCS IN CONTEXT OF SUSTAINABLE DEVELOPMENT

Petre VALEA[1], Eugen STRĂJESCU[2],

Rezumat. *Lucrarea prezintă câteva informații privind procesul de rectificare plană a materialelor minerale (granit, bazalt) cu discuri diamantate în contextul dezoltării durabile. Ținta propusă a fost de corelare a parametrilor de aşchiere: viteza de aschiere, avans longitudinal, adâncime de aşchiere, temperatura de aşchiere şi puterea consumată în cadrul procesului de rectificare. De asemenea, lucrarea oferă recomandări privind procesul de rectificare al materialelor minerale cu discuri diamantate fără lichid de răcire.*

Abstract. *The paper presents some information regarding the flat grinding process of mineral materials (granite, basalt) with diamond discs in the context of sustainable development. The proposed target was to correlate the cutting parameters: cutting speed, longitudinal feed, cutting depth and cutting temperature, power used for grinding process. The paper also gives recommendations regarding the mineral materials process of grinding with diamond discs and without cooling liquid.*

Keywords: Grinding, diamond discs, mineral materials, power, sustainable development

1. Introduction

The mechanical machining process by grinding (abrasion) achieved by using sharp, sharpened and fragile granules which are cutting edges. Generally are used silicon carbide, aluminum oxide, cubic boron nitride (CBN) or synthetic diamond [1].

Products from mineral rocks (basalt, granite) are obtained from blocks extracted from quarries or by casting into metallic, non-metallic forms and sintering in the case of the basaltic rock. Parts such as: guides for frameworks of machine tools, dimensional control tables, insulating carcasses, sealing rings, bushings and bearings [2, 3, 4].

In the case of mineral products with toughness and fine grain, splinters formed by grinding, planing, turning etc., have the appearance of scales formed by peeling or sliding in the shear plane as in the case of glass processing.

1.1. Phenomena specific to the cutting of mineral materials

[1]Eng., Phd. Student, Politehnica University of Bucharest, petrevalea@gmail.com
[2]Professor., Phd. Eng. Politehnica University of Bucharest, eugen_strajescu@yahoo.com

The processing by cutting of the mineral products is accompanied by totally different phenomena than those encountered in metal cutting. A first problem with the cutting of mineral and ceramic materials refers to the instability of the geometric and technological parameters of the cutting, which undoubtedly lead to the occurrence of processing defects (cracks, breaks, breakings) of the mineral products, especially in the area of the edges or to the variations of the sections. Remanent induced tensions (or residual internal tensions) [5] can influence the behavior of the semifinished products both at static and dynamic demands. Remanent tensions occur not only in metal parts but in most rigid bodies (made of ceramics, minerals, glass, wood, plastics materials, etc.).
The main phenomena of the splinter formation in the case of the mechanical processing by cutting the mineral materials are:

- The formation of the splinter in the form of scales (small pieces of irregular shapes) by the detachment of particulate material as a result of cracks generated by the cutting force (compression).
- In the cut area there are changes in the state of the material, due to the formation of a hardened layer, in which after the elastic recovery a network of cracks is formed;
- The evacuation of undefined geometrical shape particles after some elastic shocks caused by a penetration or an exit of the tool in the cut layer at the end of the work race ; the degree of the deterioration of the machined edges by cutting increases also the granularity of the processed mineral material from which the workpiece or product is made or the product undergoing processing [6].

Obtaining products or parts from mineral materials without defects is the main element of objective assessment of their their machinability and depends directly on the mode of splinter formation, depending on the nature of the mineral material, the method and parameters of the processing regime, namely the geometry and the tool characteristics, of the mechanical properties of the materials from which the tools (harsh and extraneous materials) are made, the nature of the coolant and the technical characteristics of the machine tools to be machined.
Using the hypothesis that in the case of materials characterized by fragility, the specific phenomena of splinter formation are identical, whatever the nature of the mineral material, it results that the phenomena emphasized in the glass cutting process [6, 7] we can extend them to the processing of mineral products that have a high fragility.
Nakayama and his collaborators [8] investigated the size of the cutting forces for the processing of hard and fragile materials by grinding, first analyzing the formation of saw-toothed splinters and concluded that at the processing of hard and fragile materials isn’t neccesary the development of large cutting forces, with the following arguments:

• there is a relatively small plastic deformation, because the splitting of the splinter is made by the material cracking mechanism in front of the cutting edge;

• the contact surface between the tool and the half-finished is relatively narrow;

• the sliding friction coefficient (μ) between the cutting tool and the workpiece is lower than that of ordinary steel cutting with fast steel tools or metal carbides.

Kun, Z. and Gyurika, I.G. [9] investigated the roughness of the processed surface obtained by grinding several granite types with different granulations. The purpose of his study was to determine whether there is a correlation between the cutting speed and the average roughness of the surface. Thus, they tested five types of five-speed cutting granite. They have concluded that there is a parallelism in changing the two parameters and this is true for each type of granite.

1.2 The sustainability of the grinding process with diamond discs in the context of sustainable development

Technologies for the processing of mineral materials with superabrasive materials can be considered as ecotechnologies [10-13] because the coolants (water emulsion) do not pose a pollution hazard for the environment; splinters and scrap of mineral materials resulting from machining can be easily reintroduced into the environment; tool wear (disc pickups) is not aggressive for the environment. In some situations, classical processing can be replaced by non-conventional processings such as: abrasive jet processing; ultrasonic processing; sound field grinding, etc., but mechanical processing with superabrasives will persist for a long time because it has many advantages and can't be easily replaced by another much more efficient process and productriv.

In the face of ecological thinking and the sustainable and integrated development of the environment, mineral materials such as granite, basalt, marble, diamond, ponce stone are materials of low environmental harm, plus mineral materials similar to ceramic materials a high percentage of recyclability similar to current cardboard, packaging and paper products that have a recyclability percentage of more than 90% [14] in a well-integrated management system in industry and the economy.

The noise pollution of grinding machines, mechanically machined, must comply with the rules laid down by the legislation in force. Due to this goal, the large sections and mechanical processing factories on machine-tools were and are located at the outskirts of the town just to affect the population as little as possible and for sound noise to be acceptable within the approved standards [10, 12, 14].

In an analysis of the mechanical grinding process with superabrasive discs of mineral materials it can be observed that the process complies with the conditions

of environmentally friendly processing (eco-friendly), because the splinters and particles of mineral material are easily reintegrated into the environment.
In the manufacturing process [15] through different processes, mainly through grinding, most specialist research studies are concerning three main directions: an assessment of the manufacturing process, taking into account the major environmental impacts; choosing an environmentally friendly technological flow path; using more friendly environmentally process parameters (the choice of environment-friendly tools and coolants, the parameters of the cutting regime being less polluting, low energy consumption, low tooling, low values for the forces developed during the machining process, a thermal regime low temperature processing) in the context of obtaining prescribed quality.
In the study carried out on the processing of mineral materials (basalt, granite) by flat grinding on the RPO200 - AKS smooth grinding machine with diamond discs, we analyzed: power consumption P [kW], thermal regime T [^{0}C], quality of the surfaces obtained R_a [µm], quantity and shape of resulting splinters W [g]; wear of diamond tools; the forces F [N] developed in the grinding process as well as other relevant aspects not covered by this paper.

2. Design of Experiments

In the factorial experiments 2^3 [16, 17] were used diamond discs with outer diameters of D_1 = 175 mm or D_2 = 200 mm [18]. The resulting cutting speeds (v_1 = 27 m/s and v_2 = 31 m/s) being within a relatively narrow range interval determined that the new set of measurements had a greater range up to v = 47 m / s. It can be argued that the set of factorial experiments 2^3 performed provided conclusive data followed by pertinent conclusions for the relatively narrow interval of the cutting speed (v = 27...31 m/s).
This set of factorial experiments was performed on the RPO200-AKS plane grinding machine from the S.C.Vrancart S.A. mechanical workshop, Adjud, county Vrancea, (standard unit for the recycling of paper and cardboard products), flat grinding [19] with multiple advantages in the pursued research.
Table 1 shows the input and output variables for the program matrix selected for the experiment set.

Table 1. Program matrices for a factorial type experiment 2^3 with output variables R_a, P, T_{max} for grinding of granite and basalt

No. of the exp.	Input variables			Output variables					
				Surface roughness		Output Power / Measured Temperatures			
	Cutting speed v [m/s]	Long. cutting feed f_l[mm]	Depth of cut a_p[mm]	Ra granite [µm]	Ra basalt [µm]	$P_{granite}$ [kW]	T_{max} [^{0}C]	P_{basalt} [kW]	T_{max} [^{0}C]
1.	27	2,775	0,01	1,143	1,335	1,1	31,6	1	25,8
2.	27	2,775	0,02	0,937	1,130	1,2	37,7	1,2	25,4
3.	27	4,446	0,01	0,829	1,015	1	30,9	0,9	24,8
4.	27	4,446	0,02	1,047	1,125	0,9	35,5	0,8	28,4
5.	31	2,775	0,01	0,877	1,180	0,75	31,3	0,65	23,9
6.	31	2,775	0,02	0,927	0,960	0,85	31,9	0,75	25,2
7.	31	4,446	0,01	1,155	1,175	0,7	28,8	0,7	24,4
8.	31	4,446	0,02	1,265	1,620	0,6	37,8	0,45	27,8

2.1. Aspects of quality and power consumption

From the analysis of the performed experiments we can see that the range of variation of the roughness values obtained during the granite processing is in the narrow range of: 0.829 ... 1.265 µm. For basalt the roughness range is: 0.960 ... 1.620 µm. The higher rust obtained at the basalt (with the same cutting, dry) can be attributed to the higher roughness and the voids between the constituent grains. Regarding the power consumed during the grinding process (for the two materials) it can be seen that the condition provided by the RPO200 AKS plane grinding machine:

$$P_{cutting} < 0.8\ P_{M\text{-}T} = 0.8 \text{ X } 2 \text{ kW} = 1.6 \text{ kW} \qquad (1)$$

The machine grinding drive engine has a power of 2.2 kW.

Figure 1 shows the evolution of surface roughness in experiments performed on basalt samples.

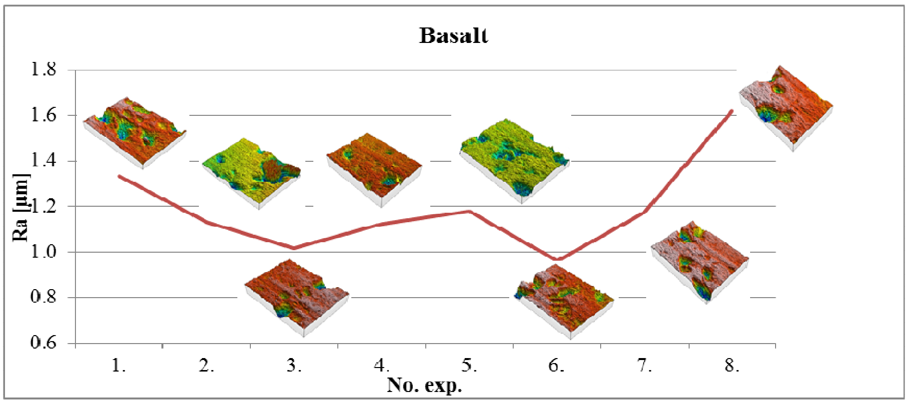


Fig. 1. Evolution of surface roughness in experiments performed on basalt samples

2.2. Flat basalt grinding (roughness aspects)

The function Ra = f(v, fl, ap) is of the politropic type with the exponential general form [20]:

$$R_a = C_R v^{\alpha_x} f_t^{\beta_x} a_p^{\gamma_x} \quad (2)$$

With the help of the DATA FIT version free 9.1.32 program, the following law of variation of the regression function resulted:

$$R_a = 0{,}178048 \cdot v^{0{,}570089} \cdot fl^{0{,}172189} \cdot t^{0{,}0551639} \text{ [µm]} \quad (3)$$

Table 2 shows the measured and modeled values for Ra as well as the relative error.

Table 2. Measured data, modeled for Ra, and relative error for basalt experiments 2^3

Exp. run	**Cutting speed v [m/s]**	**Long. cutting feed f_l[mm]**	**Depth of cut a_p[mm]**	**Ra basalt [µm]**	**Ra basalt modeled [µm]**	**Relative error**
1.	27	2,775	0,01	1,335	1,0777	5,7378
2.	27	2,775	0,02	1,130	1,1197	-19,5021
3.	27	4,446	0,01	1,015	1,1688	-41,0796
4.	27	4,446	0,02	1,125	1,2144	-15,9885
5.	31	2,775	0,01	1,180	1,1660	-32,9580
6.	31	2,775	0,02	0,960	1,2115	-30,6421
7.	31	4,446	0,01	1,175	1,2646	-9,4910
8.	31	4,446	0,02	1,620	1,3139	-3,8663

Figure 2 shows the aspects of measured variation - modeled for the regression function of the roughness parameter Ra for tests performed on basalt samples.

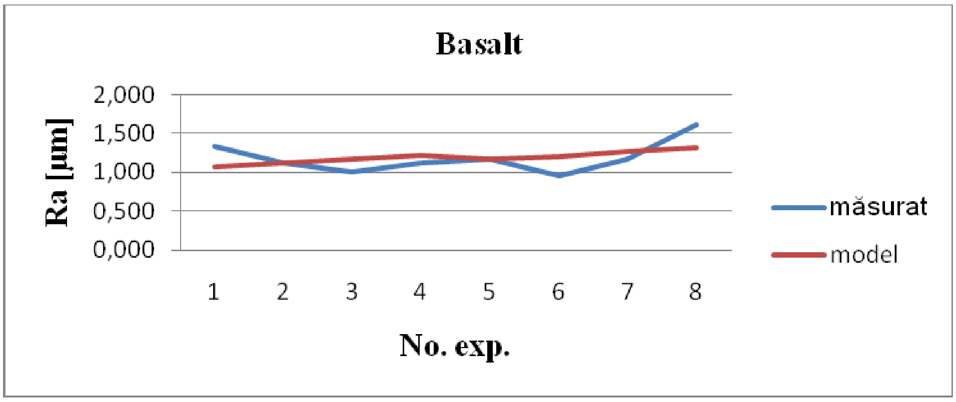


Fig. 2. Measured variation - modeled for the regression function of the roughness parameter Ra for tests performed on basalt samples.

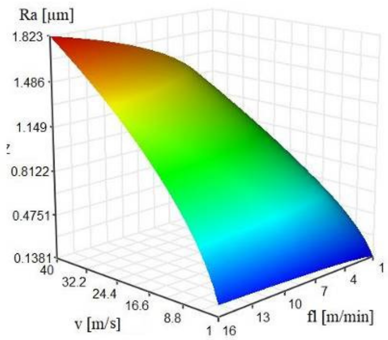


Fig. 3. The response surface corresponding to the model Ra = f (v, fl) for ap = 0.01 mm, basalt

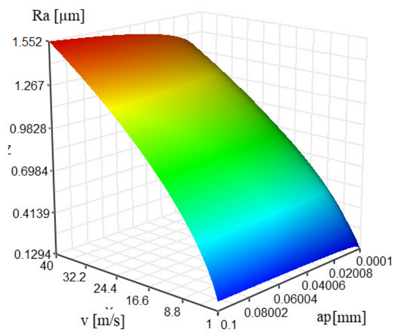


Fig. 4. The response surface of the model Ra = f (v, ap) for fl = 2,775 m/min

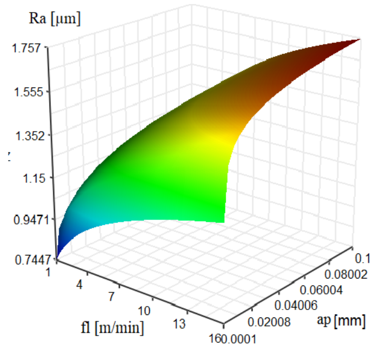


Fig. 5. The response surface of the model Ra = f (fl, t) for v = 27 ... 31 m/s (basalt grinding)

2.3. Flat grinding of granite (roughness issues)

The general relationship for the fixed roughness function has the exponential shape:

$$R_a = C_R v^{\alpha_x} f_t^{\beta_x} a_p^{\gamma_x} \tag{4}$$

The regression function obtained is exponential polytropic type:

$$R_a = 0{,}1566 \cdot v^{0{,}55968} \cdot fl^{0{,}23543} \cdot t^{0{,}07177} \ [\mu m] \tag{5}$$

Figure 6 shows the evolution of surface roughness in experiments on granite samples

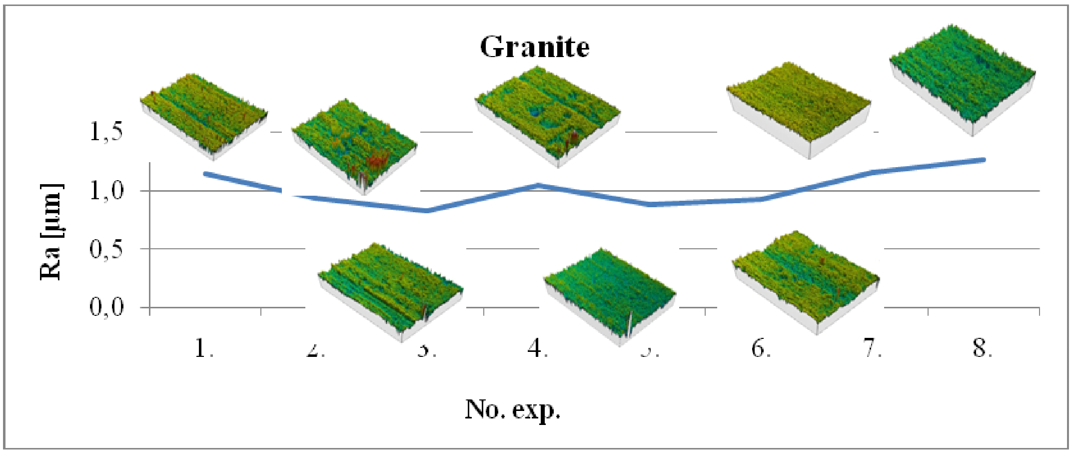


Fig. 6. Evolution of surface roughness in experiments on granite samples

Table 3 shows the measured Ra, the Ra modeled and the relative error.

Table 3. R_a Measured, Modeled, and Relative errors to granite experiments 2^3

Nr.	**Cutting speed** v [m/s]	**Long. cutting feed** f_l[mm]	**Depth of cut** a_p[mm]	**Ra granite** [µm]	**Ra modeled** [µm]	**Relative error**
1.	27	2,775	0,01	1,143	0,9051	20,8334
2.	27	2,775	0,02	0,937	0,9513	-1,5267
3.	27	4,446	0,01	0,829	1,0114	-22,0721
4.	27	4,446	0,02	1,047	1,0630	-1,5236
5.	31	2,775	0,01	0,877	0,9779	-11,5051
6.	31	2,775	0,02	0,927	1,0278	-10,8316
7.	31	4,446	0,01	1,155	1,0927	5,3966
8.	31	4,446	0,02	1,265	1,1484	9,2173

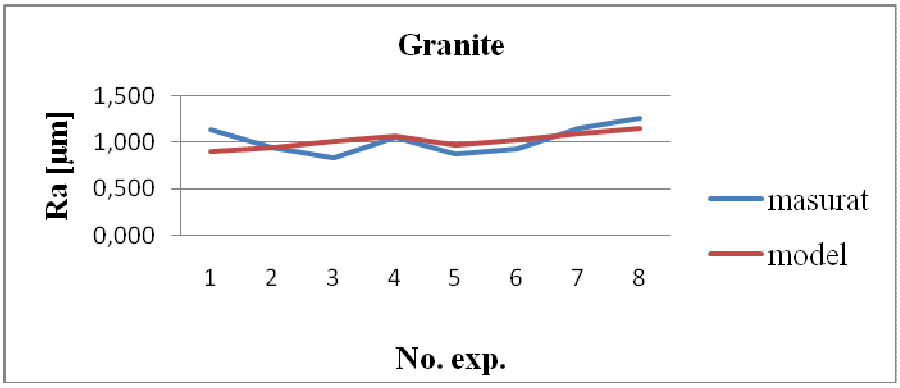


Fig. 7. Measured- modeled variation for the regression function of the roughness parameter Ra obtained for the tests performed on the granite samples.

Figure 7 shows the variation measured and modeled for the regression function of the roughness parameter Ra obtained for the tests performed on the granite samples. It is found that the measured values of Ra follow the modeled values.

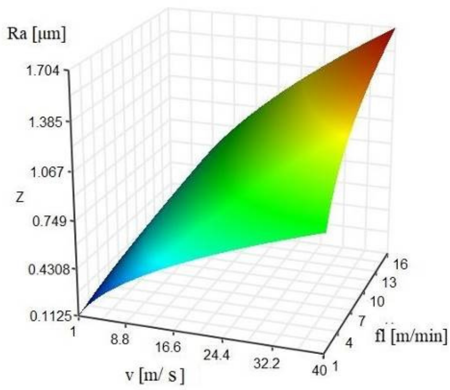


Fig. 8. The response surface of the model Ra = f (v, fl) for ap = 0.01 mm

In Figure 8 it can be seen that the roughness Ra increases with the increase of the longitudinal feed fl as compared to the increase of the cutting speed v.

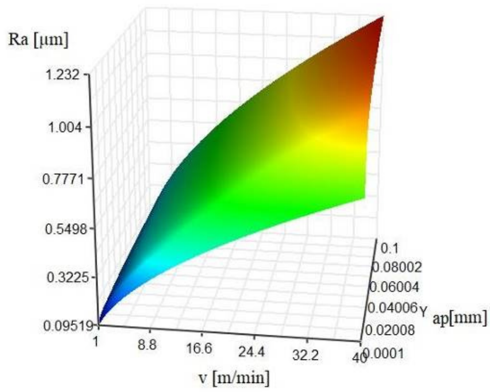


Fig. 9 The response surface of the model Ra = f (v, ap) for fl = 2,775 m/min

In Figure 9 it can be noticed that the roughness Ra, increases with the increasing of the depth of cut ap in comparison with the increase of the cutting speed v.

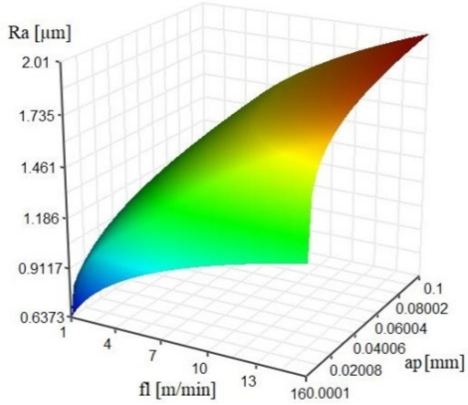


Fig.10. The response surface of the model Ra = f (fl, t) for v = 31 m / s

In Figure 10**,** it can be seen that Ra increases more when increasing the depth of cut ap treatment compared to increasing the longitudinal cutting feed fl.

3. Aspects of power P [kW] consumption the processes of mineral material grinding

In the proposed paper it was considered useful to analyze the power consumed during the process of grinding of mineral materials within the set of factorial experiments 2^3.

Thus, the power regression function P [kW] obtained after the experimental data processing with the DATA FIT free version 9.1.32 program is of the form:

$$P = 12710 \cdot v^{-2.675} \cdot fl^{-0,4179} \cdot ap^{0,0153} \qquad (6)$$

Table 4. Program matrix for a factorial experiment type 2^3 with output variables Ra and P for granite and basalt grinding

Nr.	Input factors (independent variables)			Output factors			
				Surface roughness		Consumed power	
	Cutting speed v [m/s]	The cutting advance f_l[mm]	Depth of cut a_p[mm]	Ra granite [μm]	Ra basalt [μm]	P granite [kW]	P basalt [kW]
1.	27	2,775	0,01	1,143	1,335	1,1	1
2.	27	2,775	0,02	0,937	1,130	1,2	1,2
3.	27	4,446	0,01	0,829	1,015	1	0,9

4.	27	4,446	0,02	1,047	1,125	0,9	0,8
5.	31	2,775	0,01	0,877	1,180	0,75	0,65
6.	31	2,775	0,02	0,927	0,960	0,85	0,75
7.	31	4,446	0,01	1,155	1,175	0,7	0,7
8.	31	4,446	0,02	1,265	1,620	0,6	0,45

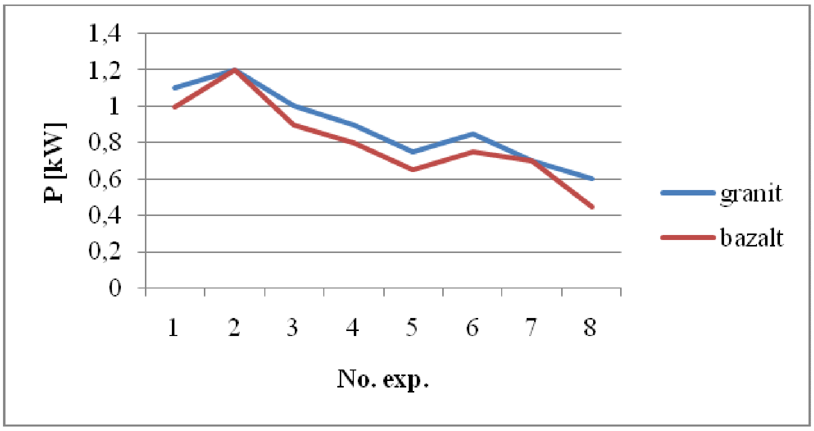


Fig. 11. The evolution of the power output variable P [kW] to the grinding of granite and basalt samples in the eight experiments

From Table 4 and Figure 11 it can be seen that the output variable P [kW] has the highest value in the experiment with the number two for both the basalt grinding and for the grinding of the granite (v = 27 m / s, fl = 2,775 m / min, ap = 0,02 mm), respectively the lowest values are found in the eighth experiment (v = 31 m / s; fl = 4.446 m / min; ap = 0.02 mm). The fact verified in the workshop practice, at high cutting speeds the forces decrease, implicitly the amount of power consumed is much lower.

3. 1. The power conspumtion at the grinding of the granite

Table 5 shows the measured and modeled values for power function P [kW].

Table 5. Measured Power, Modeling Power and Residual to Granite grinding.

v [m/min]	fl [m/min]	ap[mm]	Measured P	Modeled P	Residue
27	2,775	0,01	1,1	1,146643	-0,04664
27	2,775	0,02	1,2	1,158865	0,041135
27	4,446	0,01	1	0,941619	0,058381

27	4,446	0,02	0,9	0,951656	-0,05166
31	2,775	0,01	0,75	0,792371	-0,04237
31	2,775	0,02	0,85	0,800817	0,049183
31	4,446	0,01	0,7	0,650692	0,049308
31	4,446	0,02	0,6	0,657628	-0,05763

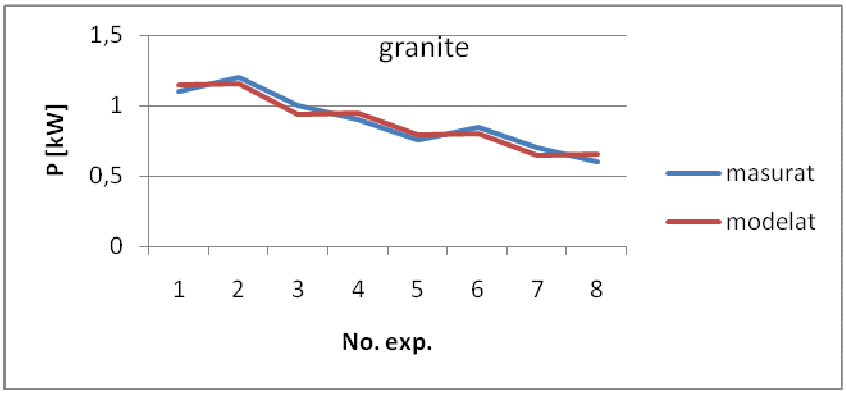


Fig. 12. Measured-modeled variation for the regression function of the power P [kW] variable for the grinding of the granite samples.

In Figure 12 it can be seen that the measured values follow the modeled values in the presented graphs.

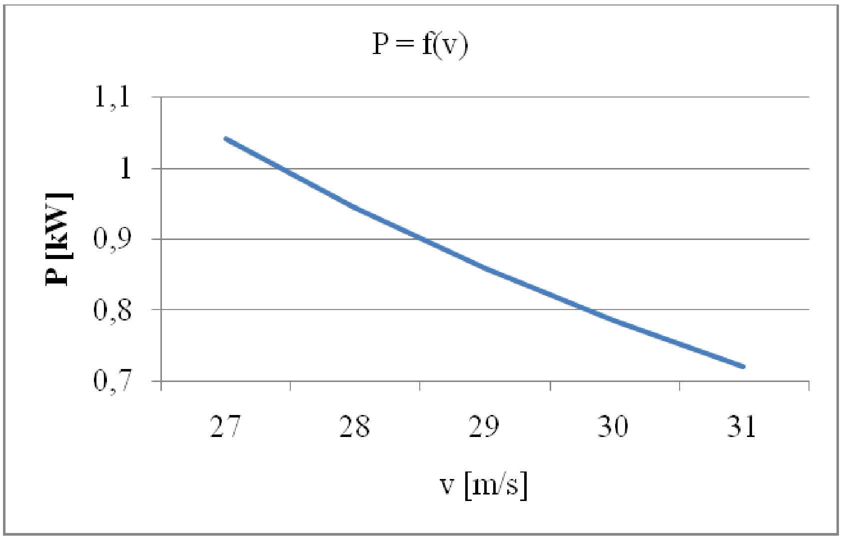


Fig. 13. The variation of the power variable P [kW] according to the regression function for different values of the cutting speed considered for the grinding of the granite (v = 27-31 m / s)

Figure 13 shows that the highest value for the grinding of the granite according to the cutting speed is at the ceramic velocity (v = 27 m/s) with a decrease to the speed v = 31 m / s.

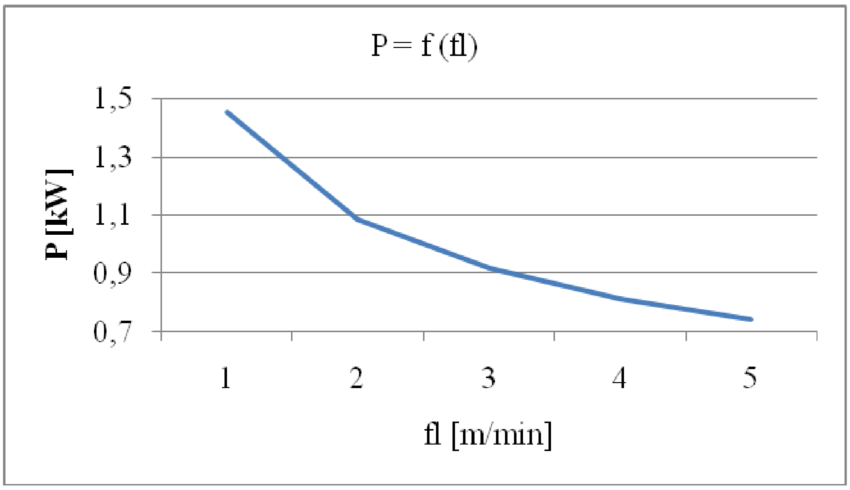
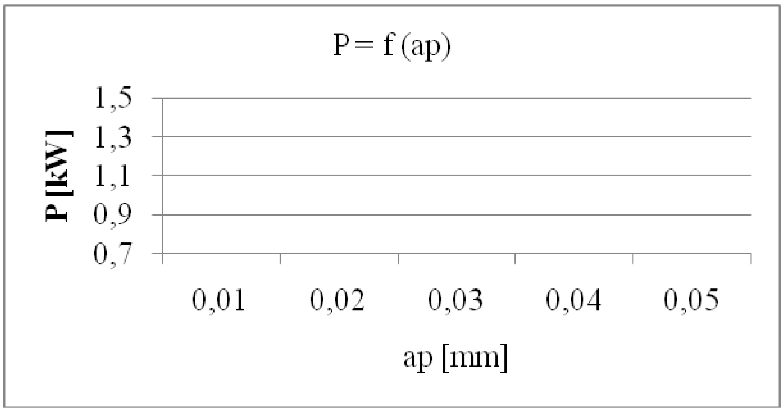


Fig. 14. Variation of the power variable P [kW] according to the regression function for different values of the longitudinal cutting advance considered for the grinding of the granite.

From Figure 14 it can be seen that the power variation according to the longitudinal feed represents higher values at low feed and lower values at higher longitudinal advance.



Fig, 15. Variation of the power variable P according to the regression function for different values of the depth of cutting considered for the grinding of the granite.

In the graph of Figure 15 it can be seen that the power has a slow increase with the increase of the processing addition.

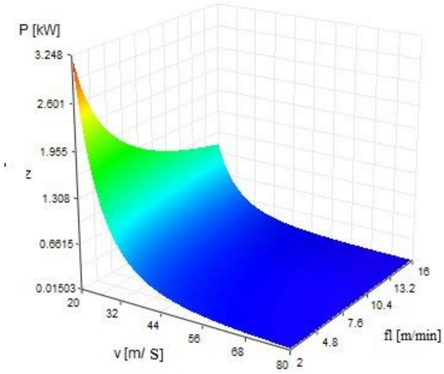
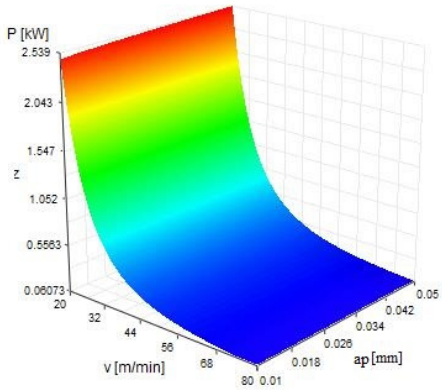


Fig. 16. The surface response corresponding to the P = f (v, fl) model for t = 0.01 mm for the granite grinding

Figure 16 shows the power variation P [kW] depending on the longitudinal feed fl and the cutting speed v. It is noted that the cutting speed has a greater influence compared to the longitudinal feed.



Fig, 17. The response surface corresponding to the model P = f (v, ap) for fl = 2,775 m/ min for the grinding of the granite

In figure 17 it is showed the variance of the power P [kW] in relation to the cutting speed v [m/s] and the depth of cut ap. It is noticed that the cutting speed as well as the machining depth of cut ap have a considerable influence approximately the same on the power consumed.

3. 2. The power consumption at the grinding of the basalt

Regression function P [kW] usinge *Data Fit* program has the following form:

$$P = 59840 \cdot v^{-3.108} \cdot fl^{-0,513} \cdot ap^{0,0337} \qquad (7)$$

Table 6. Measured, modeled power and residual data for basalt grinding

v [m/s]	fl [m/min]	ap [mm]	Measured P	Modeled P	Residue
27	2,775	0,01	1,1	1,146643	-0,04664
27	2,775	0,02	1,2	1,158865	0,041135
27	4,446	0,01	1	0,941619	0,058381
27	4,446	0,02	0,9	0,951656	-0,05166
31	2,775	0,01	0,75	0,792371	-0,04237
31	2,775	0,02	0,85	0,800817	0,049183
31	4,446	0,01	0,7	0,650692	0,049308
31	4,446	0,02	0,6	0,657628	-0,05763

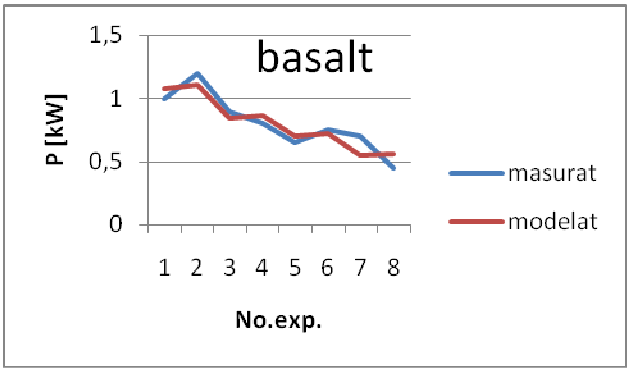


Fig. 19. Measured variation modeled for the regression function of the power variable P obtained for the basalt sample grinding

In Figure 19 we can see small variations of the graph compared to the one that modeled and due to the non-homogeneity of the tested material.

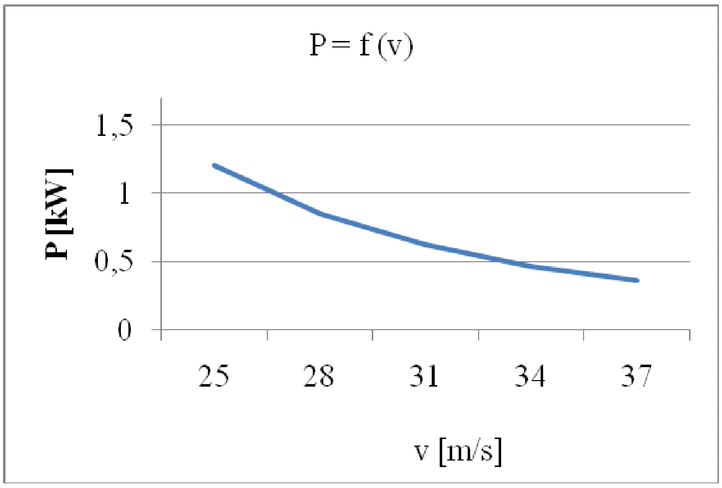


Fig. 20. Various variable power P according to the regression function for different values of the cutting speed considered for the basalt grinding

In figure 20 it can be seen that even in the case of basalt grinding, the power has higher values at low cutting speeds and much lower values at higher cutting speeds.

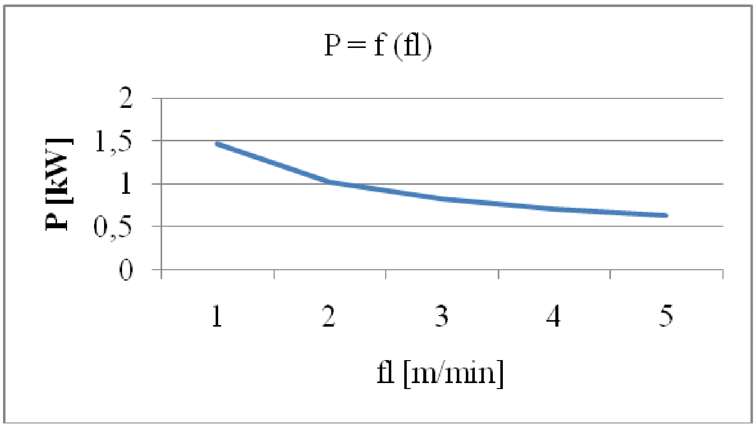


Fig. 21. Variable variation power P [kW] according to the regression function for different values of the cutting advance considered for the basalt grinding

Figure 21 may show that the power has a decrease from the small longitudinal processing advances to the large longitudinal processing advances.

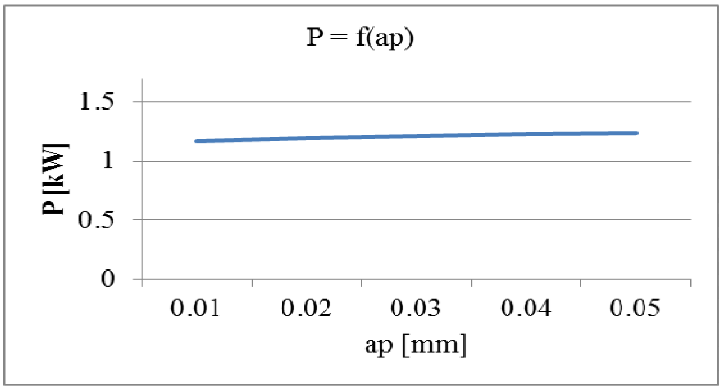


Fig. 22. Various variable power according to the regression function for different values of the depth of cutting considered for the basalt grinding

In Figure 22 it can be seen that the function P may have a slightly increase with the increase of the processing additions ap.

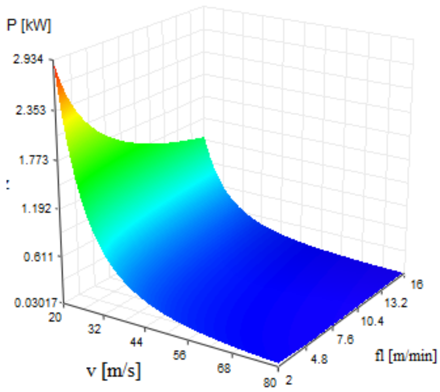


Fig. 23. The response surface corresponding to P = f (v, fl) for t = 0.01 mm for basalt grinding

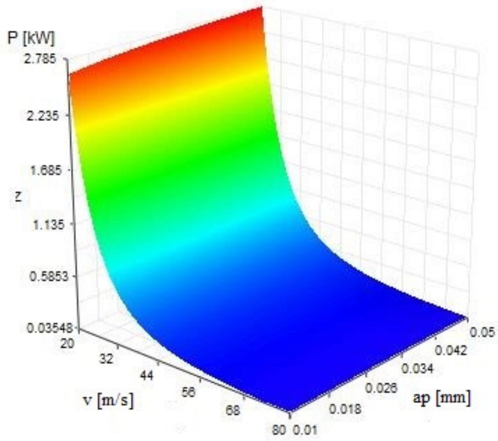


Fig. 24. The response surface corresponding to the model P = f (v, t) for fl = 2.775 m /min for the basalt grinding

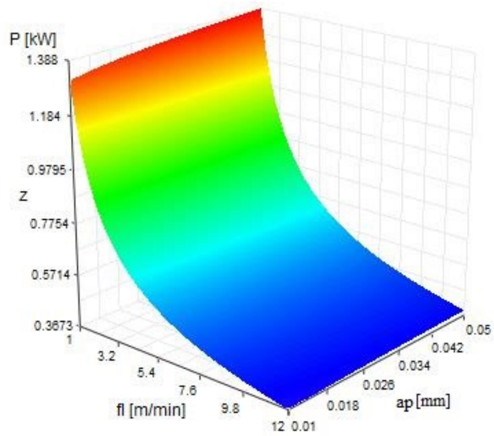
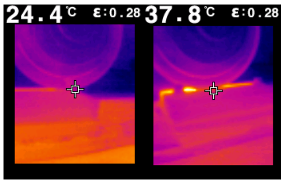


Fig. 25. The response surface corresponding to the model P = f (fl, ap) for v = 31 m/s for the basalt grinding

4. Thermal regime

In the experiments analyzed, the measured temperature range is relatively small (24.4 - 37.8 °C). This fact can also be attributed to the relatively large porosity of the mineral materials (granite, basalt) subjected to the processing, on the cutting regimes used, and to the fact that a relative focus in the cutting of the FLIR 45 thermal imaging chamber used, of the temperature conditions in the workshop where the grinding machine was located etc.

Figure 26 shows two images captured by the FLIR type 45 thermal imaging camera for processing mineral materials (basalt and granite) in factorial experiments 2^3 (minimum and maximum temperatures).



a b

Fig. 26. Temperature measurement at the processing coupler: a) basalt; (b) granite

Notations and / or **Abbreviations**

f_l [m/min] = longitudinal cutting feed
v_d [m/s] = disk speed
a_p[mm] = depth of cut
N [kW] = power
R_a[μm] = rougness

5. Conclusions

This paper highlights the main aspects of the integration of the flat grinding procedure within the concept of sustainable environmental development. The flat surface grinding process of the mineral materials is an eco-friendly process, both the machining splinters and some fragments, plate debris can be easily reintroduced into the environment, all of which have a high degree of recyclability. Coolant (emulsion, water) does not creat any problem in terms of recycling and re-integration into the environment.

By analogy with granite and ceramics [21, 22] we propose the use of basalt aggregates mixed with poisonous resins in the redesign of frames, iron and iron bars from machine-tools, presses and other gauge equipment under another generic name called *basaltan*. These are an economical and environmentally friendly way of re-incorporating the scrap of mineral materials into the industrial manufacturing circuit of the various machine tool assemblies.

The paper also presents aspects of regression functions for roughness, Ra [μm] and power P [kW] in the flat grinding of mineral materials with Romanian diamond discs with great importance in the workshop practice as well as for the future researches.

It has been demonstrated that the power consumed in flat basalt and granite grinding has relatively low values, just as the forces, F [N] developed in the grinding are low (the forces being measured with the Kistler model 9257B dynamometer located on the electromagnetic plate of the grinding machine).
Although the interval of the cutting speed was narrow within the set of factorial experiments 2^3 it was observed that at high speeds the consumed power is low for the two tested materials. The temperatures in the heat treatment mode shown are low in a small interval, which can be caused by the unevenness of the rectified materials, or by a less successful focusing with the FLIR 45 thermal imaging chamber. The shape of the resulting splinters and their texture don't present any inappropriate reintegration into the environment.
The factors influencing the roughness of Ra of the processed surfaces have the following decreasing order: v, ap, fl. Factors of influence on the consumed power P [kW] are in the recurrent order: v, fl, ap. Increasing the peripheral speed of the disk from v = 27 m/s to v = 31 m/s causes a decrease in power P [kW] from 1.2 kW to 0.75 kW (with an average percentage of 37.5%).
In conclusion, grinding of mineral materials is an eco-friendly process with a high potential of time-to-life. The splinters and shavings of the mineral materials resulting from the mechanical processing have a high degree of recyclability. Moreover, the basalt in various forms (natural, cast, sintered) is a genuine substitute for the ferrous and non-ferrous materials in the machine building industry, being quite large in various areas of the world and in our country (Racoş and Hoghiz county Braşov, Detunatele county Alba, Limpedea county Maramureş).

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