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ORIGINAL ARTICLE

Effects of the granite-forming minerals on the surface roughness in the milling processes

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Abstract
Milling of granite surface is getting increasingly important in the industry. A major problem is that the effect of granite minerals on surface roughness is currently unknown. The research in this article aims to examine these effects. During the experiment, six surfaces with different cutting speeds were examined on the surface of three different granite samples. The color of the various minerals was determined by light microscopy, and a scanning electron microscope (SEM) and X-ray diffractometer (XRD) were used to analyze the composition of the samples, and a confocal microscope was used to measure the surface roughness of each mineral. From the results of the investigations, we deduced different correlations between the minerals forming granite and the surface roughness. Area-based surface roughness was used in this study because it results more accurate data. From the results, we conclude that the roughness of different surface-forming minerals varies greatly. This causes a high average surface roughness value.

Keywords Granite · Surface roughness · Minerals · Milling · Investigation methods

1 Introduction

People have been using rocks for a long time. One of the most important rocks is granite. It is a material that not only is used in architecture or in our everyday life (e.g., gravestones) but also is being used in the industry as a bed for precision machining and workbench for CNC coordinate measuring machines these days.

With high usage, the quality is increasingly important. A major problem is that the effect of granite minerals on surface roughness is currently unknown. The aim of the research is to investigate these effects. If we know these properties of the minerals, we can suggest the most effective granite types based on customer needs.

A light microscope was used for the examination of the colors of various minerals, scanning electron microscope (SEM) and an X-ray diffractometer (XRD) for the determination of the composition, and a confocal microscope for the determination of the surface roughness value of each mineral.

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As a result of our research, we got an answer about the effects of the investigated minerals on the surface roughness.

People have been using rocks for a long time. One of the most important rocks is granite. It is found in architecture, as a material for kitchen worksheets or as a base material for gravestones. It has also appeared in the industry as a workbench for precision machining.

Numerous investigations deal with the processing of rocks, including granites. Schunnesson [1] used percussive drill monitoring. The measured data, i.e., hole length, the thrust, and the penetration rate, were normalized. The analysis showed the importance of using the normalized data. This analysis facilitates the classification of stone blocks by their geological or mechanical properties (strength, fracture).

The mechanical properties of the minerals were studied by the density function theory. These minerals were siderite and hematite. Zhang et al. [2] used their results for selective grinding.

Granite consists of variable surface-forming rocks, but they can become dangerous, if they become unstable.

Pérez-Rey et al. [3] examined the stability of granite stones in Galicia (Spain). The rocks were found to be stable in the present circumstances, but an earthquake could remove them from their stable position.

In contrast, Bobji et al. [4] have already been exploring for the extracted rocks. During the hardness measurement, a known geometry was pressed into the rock surface. The result was burdened by scattering due to the surface roughness and the different compositions of minerals. Nonetheless, as a result of numerical simulations, the researchers found that surface roughness is higher where rock is harder.

Not only Bobji, but also Delgado et al. [5] research the hardness of stones. They examined the Pink Porrino granite. It was found that sawing is not primarily influenced by the quartz content but by the granite hardness, because hardness is a characteristic of the whole sample and can be used to obtain more accurate results. Thus, a low increase in material hardness results in a significant increase in saw speed. However, hardness is affected by the grain size and the cracks.

Three types of granite specimens containing two non-coplanar fissures were examined by Tian et al. [6]. It was concluded that the ligament angle and the grain size may influence the stress-strain curves of the pre-fissured granite. At a ligament angle of 60 to 150°, both peak strength and peak strain increases. Wing cracks start at different angles in case of coarse granite and fine granite specimens. The cracks are easy to contact in the case of fine grains, whereas they are not common in the case of coarse grains. It has also been found that if the ligament angle is constant and the angle between the principal stress and the crack increases, the grain size decreases. Also, further research result shows that the cracks in coarse granite are more difficult to start than in the case of fine granite.

The crack start was examined by Homand et al. [7]. Same specimens are tested at the same pressure and temperature but at different stress values. The study showed that when a crack appeared, a new crack is usually formed and not the old one is grew/broadened. And the new cracks often come together.

Wang et al. [8] focused on the temperature. Results showed that the micro-cracks induced by high-temperature and high-speed heating but they may close due to cooling. According to Zhang et al. [9], the change in temperature affects the mechanical properties. Hartlieb et al. [10] radiated the granite with a low-power (3.2 kW) microwave. Measurements showed that the granite heated slowly and did not show strong physical changes, because the granite contained small amounts of microwave absorbers.

Besides that, Li et al. [11] and Huang et al. [12] investigated the appearance of the cracks. The geometry of cavities in rocks was studied by Huang et al. The short (b) and long (a) axis ratio (b:a) of the rocks was examined. The b:a ratio was changed from ¼ to 1/1, so the cavity form changed from oval to circle. If the b:a ratio increased, the uniaxial compression, the crack initiation stress, and the peak stress of cavity decreased linearly.

Fracture toughness was investigated by Han et al. [13] and Nasseri et al. [14]. Nasseri et al. used five granite samples. Their results showed a good correlation between the density and length of the micro-crack and the strength. The results showed a very good correlation between fracture strength and average micro-fracture length.

A triaxial compression test was performed by Golshani et al. [15], and it was concluded that compression below 10 MPa causes surface failure only when high density of micro-crack is numerous.

Brittle cracks and fractures were simulated by Klichowicz et al. [16]. With a chisel, granite specimens were stressed under an increase pressure. This experiment was monitored by a high-speed camera. The results showed that the new fracture test is suitable for validating 2D DEM simulation of a mineral fracture process. However, the paper showed that the difficult processes can be simulated by simple models.

Prikryl [17] focused not on hardness but on the strength of rocks. The grains size, shape and the shape-preferred orientation of rock-forming minerals, grain size distribution, and mineral composition were examined. He found that for magmatic rocks (granite), the strength variation is dependent on the grain size. The strength increases as the grain size decreases.

Knowledge of surface roughness is an important parameter not only in use but also in machining. After the machining process, the next step is polishing. Important information is how much material can be removed to achieve an appropriate surface. Ribeiro and Paraguassú [18] investigated with this problem. Their research showed that the mineral composition and the rock texture are the primary factor in the degree of surface roughness.

The surface roughness of the joints was investigated for rocks 4.2 km deep by Diaz et al. [19]. They found that the minimum and maximum JRC ranged from 1.16 to 1.54. This shows notable anisotropy.

Surface roughness is the determining quality of the product and greatly influences the cost of production. Aydin et al. [20] according to the average grain size of rock is a primary factor in determining the roughness of the surface. The fine grains cause greater surface roughness [21]. The surface of the minerals is also affected by the materials used in machining, according to Li et al. [22].

Another important parameter is the machinability of granite. A study by Yurdakul [23] showed that machining rocks with similar properties requires similar amounts of energy. Xu et al. [24] also conducted a research on this topic; however, they approached the experiment from the side of machine. It was found that, during a long-time sawing process, both the tangential and normal force components increased with the decrease of gradual wear of the saw blade.

Xu et al. [25] found that the abrasion of diamond grains is dependent on the high temperature in the contact zone, the machining parameters, and their combination. In addition, the geometry and the structure of diamond are another important criterion.

Li et al. [26] suggested a new type of machining method for granite rocks. They try to achieve more cost-effective machining by keeping tribological interactions to a minimum. Huang et al. [27] showed that the size of the diamond grain was reduced, which caused the formation from the brittle mode to the ductile mode. The surface roughness of the granite increased, while the degree of plasticization decreased.

Wei et al. [28] did not study hardness, but quartz content. As a result, it was found that sawability depends on the quartz content, the quartz grain size, and the hardness, compressive strength, and abrasiveness of granite. The effect of quartz was investigated with similar results by Lang et al. [29], but in the case of marble.

Buyuksagis [30] examined the effect of cutting on granites. The study showed that specific wear rate and specific energy values obtained in the up-cutting mode are less than those obtained in the down-cutting mode.

Not only granite cutting but also grinding was studied. Xie and Tamaki [31] examined the micro-hardness distribution in granite. The results showed that micro-hardness deviation in granite and the bulk value decrease with the increase of abrasive machining efficiency.

The surface of granite was dryly polished by Saidi [32]. His experiment showed that the speed of the spindle and the average feed rate of the polishing tool greatly influence the quality of the surface. He also found that processing produced ultrafine dust, which is dangerous to health [33, 34].

Zhang et al. [35] used the Taguchi design application to optimize surface quality. Tests verified that it was successful.

Bin et al. [36] developed a novel fixed abrasive lapping (NFAL) tool, which ensures the correct surface quality. Results showed that the surface roughness Ra and Rz values decrease when the feed rate increases.

Granite is a popular and versatile rock. Not only the piece of stone but also the waste generated during machining can be used [37]. In many researches, granite waste is recycled as an additive in concrete [38], paint [39], or cement [40].

In our research, the surface roughness of the minerals that make up the various granites was investigated. These minerals were processed with different cutting speeds. From this data, we would like to set up a prediction system to assist in evolving the appropriate surface quality of the granites of different compositions. These are the primary test for setting up a scale of typical granite constituents, obtained from the characteristics of minerals that influence machining.

Another possibility is the use of this material in the case of granite.

In the studies, the mineral composition, the hardness, the grain size, the mineral orientation, the appearance and spread of cracks, and the surface roughness as a function of the working temperature were examined.

Based on the literature analysis, it appears that the closed segment of our research area is still unexplored. The data can be used for additional research, such as a prediction system that would help to form the right quality of granite surface or could provide information for setting up a proportional scale.

Our main goals are (1) to rank the minerals in granite samples based on their effect on surface roughness, (2) to develop a prediction system that determines surface quality based on material structure, and (3) to suggest material structure composition based on desired surface quality and ergonomic requirements.

2 Material and methods

2.1 Selection of granite

Three different granite samples were examined (Fig. 1.a) In our research, different minerals forming granite were examined in 6 lines with different cutting speeds. The 3 granite samples have different grain sizes (fine, medium, and coarse), so all the groups of the international standards are covered by these 3 types of granite.

2.2 Production of sample surfaces

When machining the granite blocks, we used an Italian Prussiani Golden Plus–type machine tool (NC) with a maximum power consumption of 15 kW. Its range of motion along the *XYZ*-axis was 3300 × 1600 × 250 mm. Its spindle speed could be varied between 0 and 10,000 rotations/min.

A face milling tool with 8 segments was used for milling and the tool diameter is 60 mm. During the formation of the lines, the depth of the cut, i.e., 1 mm, was set. During the experiment, machining with diamond grains embedded in a Co-based binder resulted in a geometrically indeterminate edge of the tool.

Six lines were formed on the surface of each granite specimen by milling. While numerous parameters are constant (1 mm cutting depth, 40 mm cutting width, and 0.1 mm/tooth feed rate), the rotational speed of the spindle was changed and the cutting speed was calculated (37.7 m/min, 75.4 m/min, 113.1 m/min, 150.8 m/min, 188.5 m/min, 226.2 m/min) based on this rotational speed.

Stairs were formed with down-milling in the granite samples, so we were able to create 40-mm strips.

The examined surfaces were located between the endpoints of the strips, starting at a tool radius distance from the ends as in this range, there are stable conditions.

The milling process was based on the tool and the machine economical cutting range.

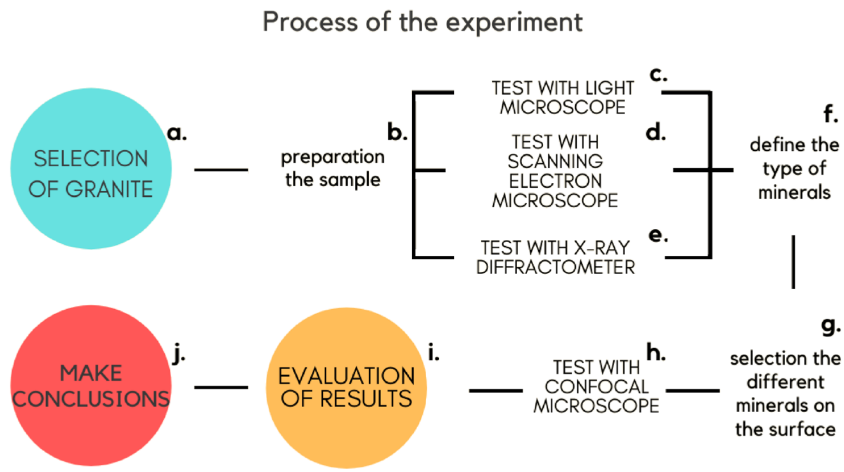


Fig. 1 Flowchart of the process of the experiment

2.3 Test with the light microscope

A KEYENCE VHX 2000 ultraprecision light microscope was used with large depth-of-field and super resolution. It has 2D/3D imaging and measurement capability, including automated measurement tools and a 54-MP 3CCD camera. Every mineral has different colors, so they are thus distinguished (Fig. 2). The granite samples contained black-, gray-, white-, light-rose-, and greenish-rose-colored minerals.

In *granite 1*, four different colors of minerals were observed: black, light rose, white, and gray. A small piece of sample was cut off from the full specimen (Fig. 1.b), and it was examined with a light microscope (Fig. 1.c) and then with a scanning electron microscope (Fig. 1.d).

2.4 Test with the scanning electron microscope

The type of the scanning electron microscope (SEM) is FEI/Thermo Fisher Apreo S; Philips XL 30 ESEM. The microstructure was tested with a resolution of 20 Å in a low vacuum mode (Fig. 1.d). Besides determining the crystal boundaries,

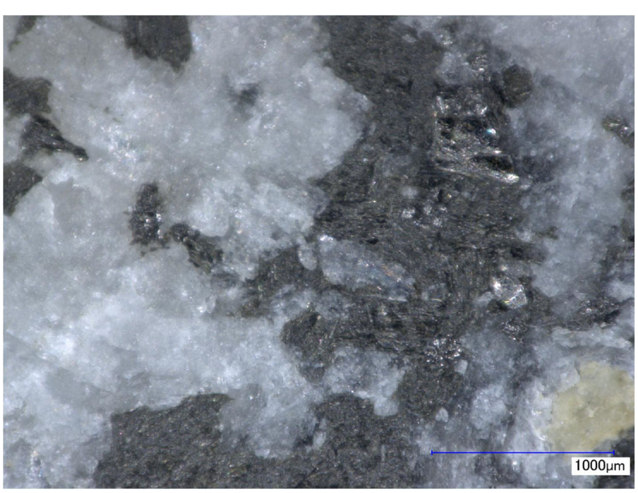


Fig. 2 Light microscope recording of the *granite 1* sample

we performed elemental analysis, too (Fig. 4 and Table 1) as Huang et al. [41].

After evaluating the data in the areas shown in Fig. 3, we determined that *granite 1* contains biotite, K-feldspar, and albite and naturally, large quantities of quartz-forming minerals are also present (Fig.4).

The colored minerals were examined with the light microscope and they were identified easily by their unique color.

2.5 Test with the X-ray diffractometer

The table of elements was obtained by SEM [42], but it was not 100% exact. To get the exact results, we powered and tested the sample with a Philips PW 3710 X-ray diffractometer (Fig. 1.e).

The device makes the determination of the phase composition of the crystalline materials possible by qualitative and quantitative analysis [43]. The results of this measurement confirmed the previously obtained SEM results.

Results are as follows (Fig. 1.f):

- Black: biotite (*selected area 1*)
- Light rose: orthoclase (*selected area 2*)
- White: albite (*selected area 3*)
- Gray: quartz (*selected area 4*)

Granite specimens 2 and 3 were tested with the same test method as the *granite 1* sample, so the method is not described here again; only the results are presented.

In the *granite 2* sample, four different colors of minerals were also distinguished by the light microscope (Fig. 5). These colors are black, greenish rose, off-white, and gray.

According to the results obtained by SEM (Fig. 6), the sample contains quartz, microcline, plagioclase, and biotite. After an X-ray diffractometer test, the plagioclase area showed albite.

Table 1 The atomic percentage composition of the granite-forming minerals in the granite 1 sample

Elements\atomic%	Selected area 1	Selected area 2	Selected area 3	Selected area 4
O	60.35	61.31	59.31	67.80
Mg	4.98	-	-	-
Al	7.51	8.04	9.67	-
Si	14.97	22.56	22.05	32.20
Cl	0.24	0.05	-	-
K	4.89	6.04	0.22	-
Ti	1.30	-	-	-
Fe	5.76	-	-	-
Na	-	1.99	7.32	-
Ca	-	-	1.44	-

The results were as follows (Fig. 1.f):

- Black: biotite (*selected area 4*)
- Greenish rose: albite (*selected area 3*)
- Off-white: microcline (*selected area 2*)
- Gray: quartz (*selected area 1*)

In the *granite 3* sample, only three different colors of minerals were isolated (Fig. 7).

This result (Fig. 1.f) was supported by the measurements (Fig. 8):

- Black: biotite (*selected area 1*)
- Dark gray: albite (*selected area 2*)
- Light gray: quartz (*selected area 3*)

Taking the results of the measurements into consideration, we can state that there are five different minerals in these three samples. We examined and analyzed the surface roughness of the five, above-mentioned minerals. The surface is formed by these minerals. The surfaces were formed at room temperature and so was the surface roughness tested. However, the material composition tests (SEM, XRD) were performed under tempered conditions. The temperature in the tempered room was 20 °C.

These five minerals are the basis of our research.

2.6 Test with the confocal microscope

The area-based average surface roughness of the minerals was measured in the granite. These component minerals were quartz, mica, and feldspar. Quartz, albite, and biotite were constant components in each sample. However, in the first two specimens, orthoclase and mica were observed along with albite. For exact surface roughness, measurements were made at the beginning, middle, and end of the line (Fig. 1.g). The parameter we used was Sa (arithmetical mean height) and the unit of Sa was micrometers. Sa is the extension of Ra to a surface. It expresses, as an absolute value, the difference in height of each point compared to the arithmetical mean of the surface. The other parameter is Sz (maximum height). Sz is defined as the sum of the largest peak height value and the largest pit depth value within the defined area [44].

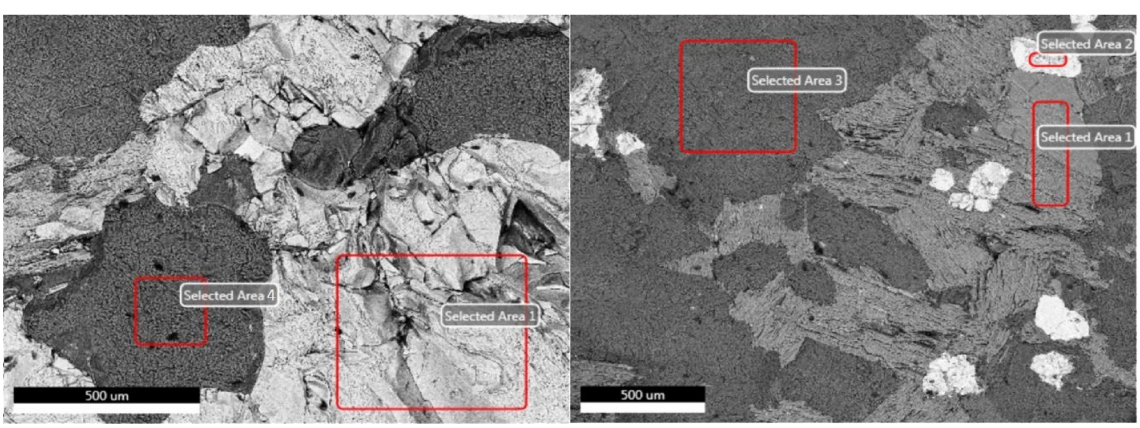


Fig. 3 Scanning electron microscope recording of *granite 1* sample

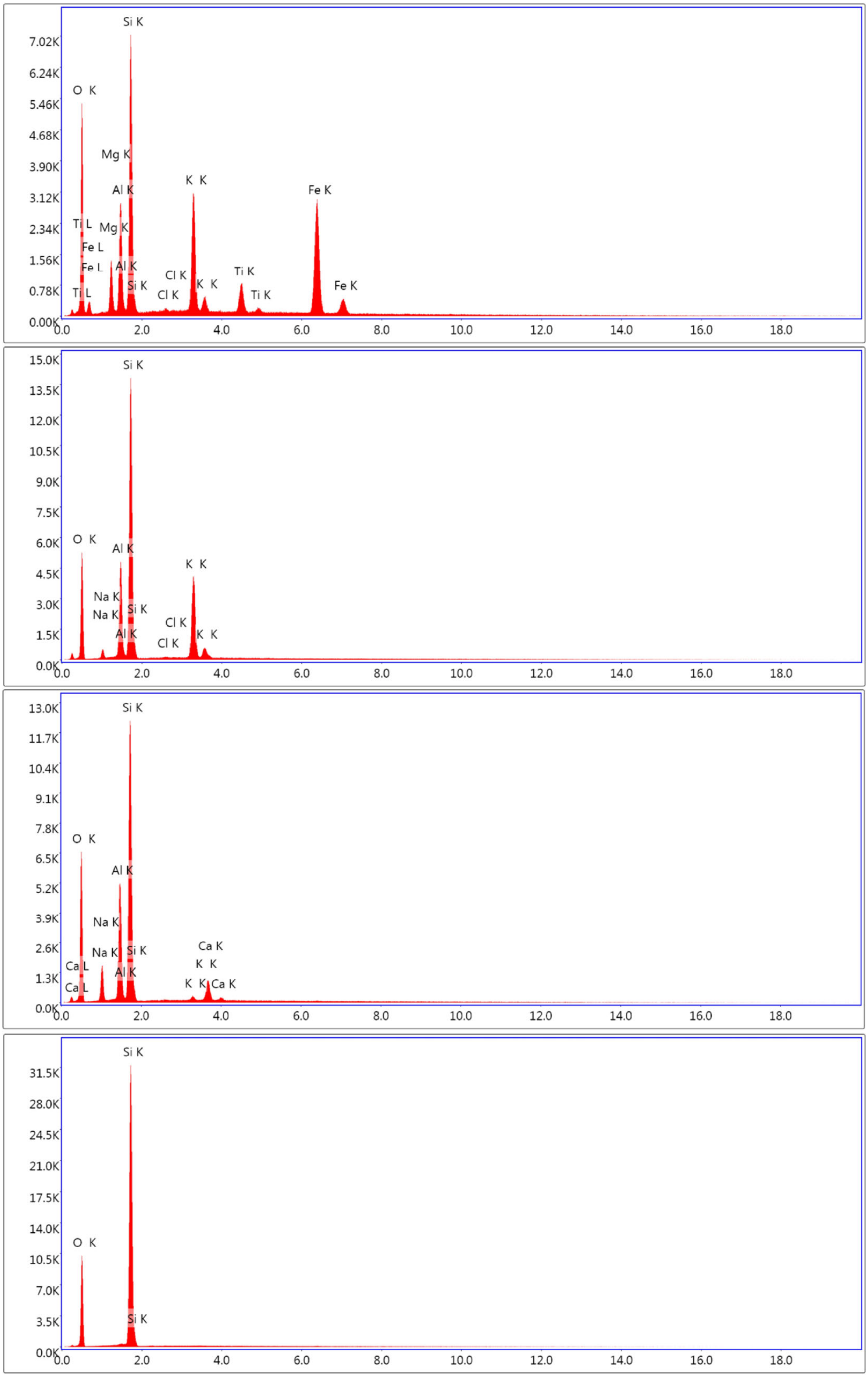


Fig. 4 SEM micrographs of the *granite 1*–forming minerals

The surfaces of the samples were cleaned with high pressure air. Then, the specimens were put under the microscope of *Alicona InfiniteFocus IFM G4*. *InfiniteFocus* is a fast and flexible optical 3D surface measurement system. The machine has a color focus sensor (1624 × 1236 3D points) without a filter. Alicona InfiniteFocus G4 is using the principal of focus variation for the "capturing" surface and 3D reconstruction of the data.

The device has a resolution of 10 nm, which is very beneficial as it has a relatively large working space, so the sample does not need to be cut [45].

During the measurement, information on both the color of the test area and its surface roughness can be obtained.

During the 3D study, the focus was set to include the roughness peaks and roughness valleys.

The examined area was 28,404 mm × 21,551 mm and the spatial extent is 19.93 μm (Fig. 9).

If the focus is poor, the surface roughness cannot be evaluated. Precise measurement is also supported by the precise movement of the *InfiniteFocus* object-slide.

The surface roughness of the selected minerals was calculated by the evaluation software of the microscope. During the experiment, area-based roughness was measured instead of line-based roughness to obtain more accurate results (Fig. 1.h).

Our granite samples were chosen so that the surface roughness of numerous minerals could be examined. Besides the quartz and biotite, the surface roughness of orthoclase, microcline, and albite was measured.

3 Results and discussion

3.1 Statistical analysis of granite 1

After the measurements, we evaluated the results by using the MATLAB R2019b software (Fig. 1.i). We performed

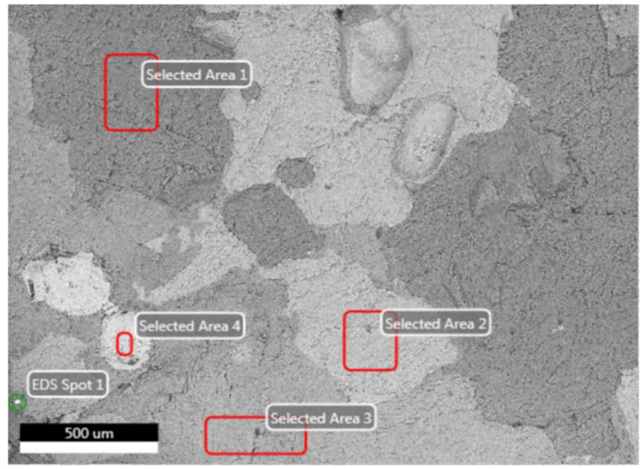


Fig. 6 Scanning electron microscope recording of the *granite 2* sample

statistical analysis on the surface roughness of the above-mentioned minerals, and then, we determined the significance of the quadratic regression curve with analysis of variance.

All three samples are deep magmatic granite rock; however, their results need to be treated separately because the conditions at which they occur are not well known. As a result, they have different percentages of composition and micro-hardness, so they have different physicochemical properties that affect the surface roughness of minerals.

Figure 10 shows that the area-based surface roughness values of the minerals in the sample decrease if the cutting speed increases, except for albite mineral, whose surface roughness decreases gradually to 188.5 m/min and then it slightly increases. This increase can be caused by two factors: (1) at higher cutting speed values, the individual grains will be torn out of the material; (2) the selected minerals do not have the corresponding orientation during cutting. We think if the mineral is machined in its corresponding orientation, it has a much lower surface roughness. The goal of our later research

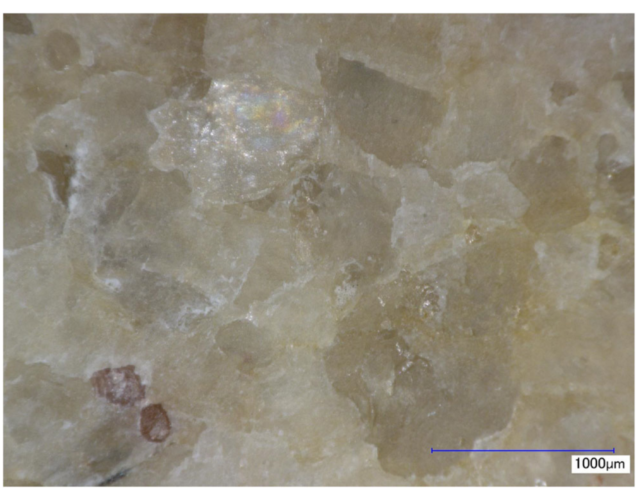


Fig. 5 Light microscope recording of the *granite 2* sample

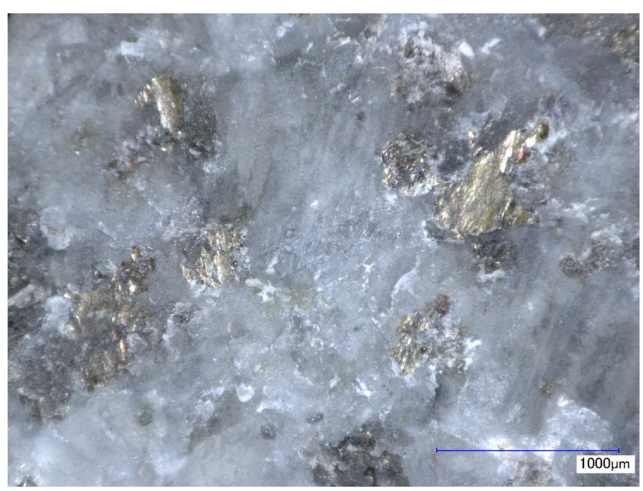


Fig. 7 Light microscope recording of the granite 3 sample

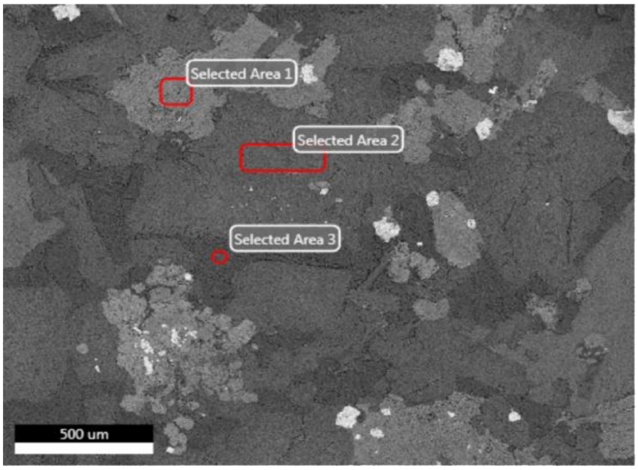


Fig. 8 Scanning electron microscope recording of the granite 3 sample

is to examine this probability. The results were analyzed with statistical analysis, and there is a strong correlation between all minerals in the sample: $R^2_{\mathrm{quartz}} = 0.799$, $R^2_{\mathrm{orthoclase}} = 0.858$, $R^2_{\mathrm{albite}} = 0.851$, and $R^2_{\mathrm{biotite}} = 0.852$.

In addition, the significance value of minerals is also low: $P_{\mathrm{quartz}} = 0.011$, $P_{\mathrm{orthoclase}} = 0.003$, $P_{\mathrm{albite}} = 0.001$, and $P_{\mathrm{biotite}} = 0.003$. In this case, quartz gave the worst result, showing that there is a 1.1% chance that the applied regression curve is not significant with the surface roughness of the minerals. The results of this sample prove that the effect of the cutting speed on the surface roughness of minerals can be effectively approximated by a second-degree regression curve.

With this knowledge, we examine the effect of coarse-grained minerals on the surface roughness. Different curves represent different minerals. The surface roughness of quartz has the largest, that of mica (biotite) has the lowest, and that of the feldspar is between biotite and quartz.

3.2 Statistical analysis of granite 2

The results of granite 2 are showed in Fig. 11 The surface roughness values of the minerals in the sample are inversely proportional to the increase in cutting speed.

The tendency of the line is decreasing, but the different slopes are influenced by the conditions of the formation of the above-mentioned rocks. Considering the statistical evaluation, we can say that there is a strong correlation just like in the first case: $R^2_{\mathrm{quartz}} = 0.879$, $R^2_{\mathrm{microcline}} = 0.855$, $R^2_{\mathrm{albite}} = 0.816$, and $R^2_{\mathrm{biotite}} = 0.834$. The significance values of the minerals are as follows: $P_{\mathrm{quartz}} = 0.015$, $P_{\mathrm{microcline}} = 0.09$, $P_{\mathrm{albite}} = 0.018$, and $P_{\mathrm{biotite}} = 0.007$.

In the sample with medium grain, the quartz shows the largest value of surface roughness and the biotite shows the lowest. The feldspars are between the two values.

3.3 Statistical analysis of granite 3

Specimen 3 shows that the tendencies of the lines are mixed (Fig. 12).

In the case of quartz, surface roughness decreases gradually to a cutting range of 150.8 m/min; then, it stagnates. According to statistical analysis, correlation coefficients of quartz, $R^2_{\mathrm{quartz}} = 0.835$, and albite, $R^2_{\mathrm{albite}} = 0.702$, are strong. However, the value of biotite ($R^2_{\mathrm{biotite}} = 0.351$) shows a weak tendency. This may be caused by the different orientations of the minerals. If we consider the significance coefficients,

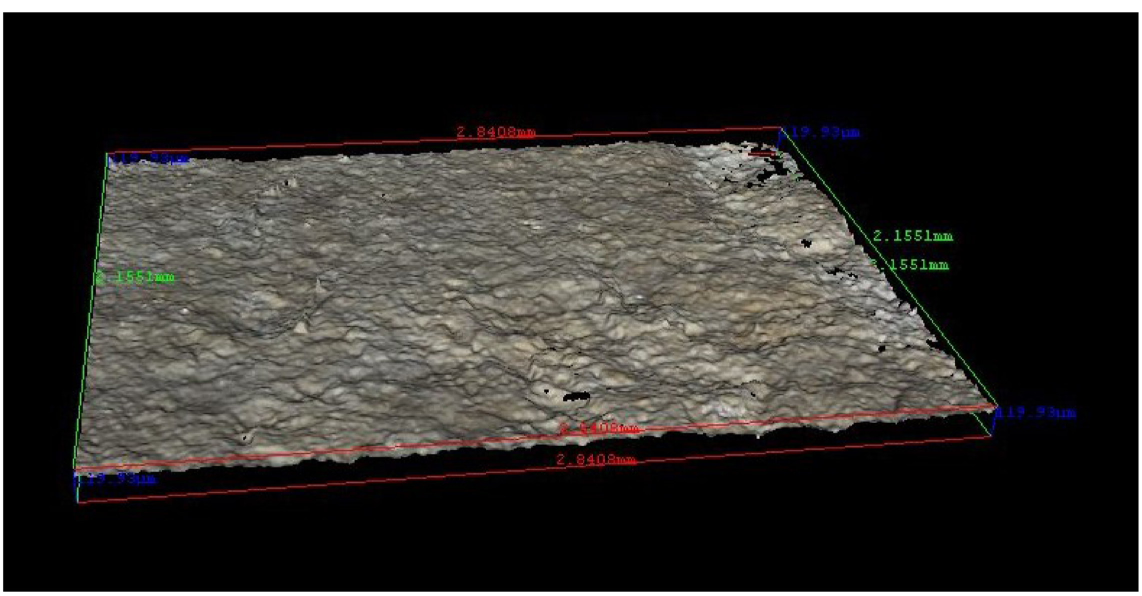


Fig. 9 3D image of the *granite 1* sample

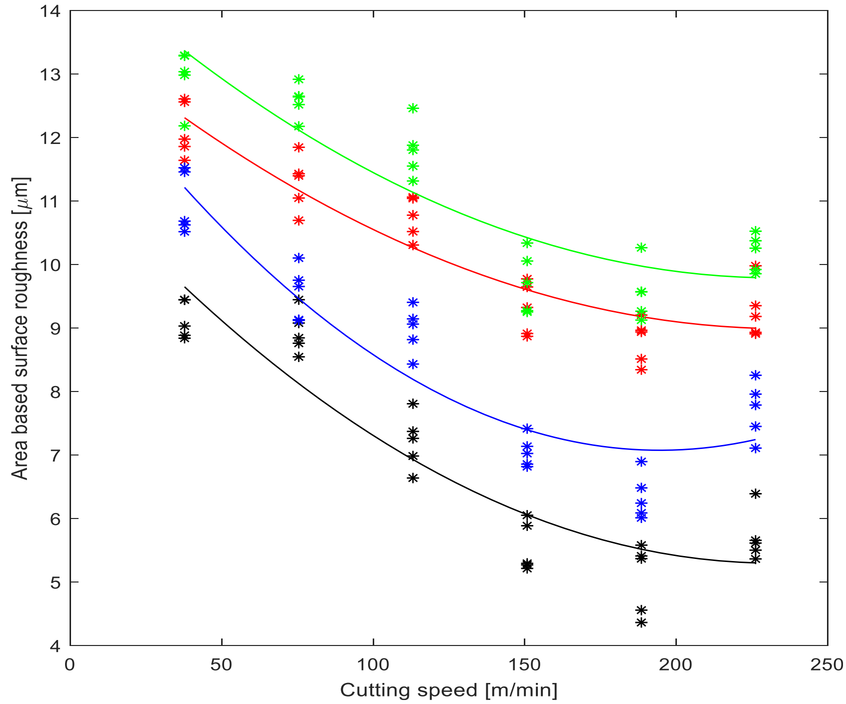


Fig. 10 Relation between minerals forming granite and surface roughness in the *granite 1* sample [46] (light green: quartz, red: orthoclase, blue: albite, black: biotite)

biotite shows an outstanding difference: $P_{\text{quartz}} = 0.007$, $P_{\text{albite}} = 0.007$, and $P_{\text{biotite}} = 0.126$.

In the fine-grained sample, the effects of minerals on surface roughness were similar. The biotite has the lowest value of surface roughness, quartz has the largest, and the surface roughness of feldspar is medium.

Comparing to the previous samples, we found that the biotite mineral has less roughness. I suppose that the location of the examined minerals was in the correct orientation, the grain cracked appropriately, and this resulted in a smoother surface.

4 Conclusions and future perspectives

Although the three samples cannot be evaluated together as they have different physicochemical properties, we can conclude that the biotite minerals have the lowest and quartz minerals have the largest surface roughness with the same cutting speed. Between the two values are the different feldspar minerals.

Granite samples were graded based on average particle size. The surface roughness of the granite-forming minerals was investigated for each of the reference stones in its groups.

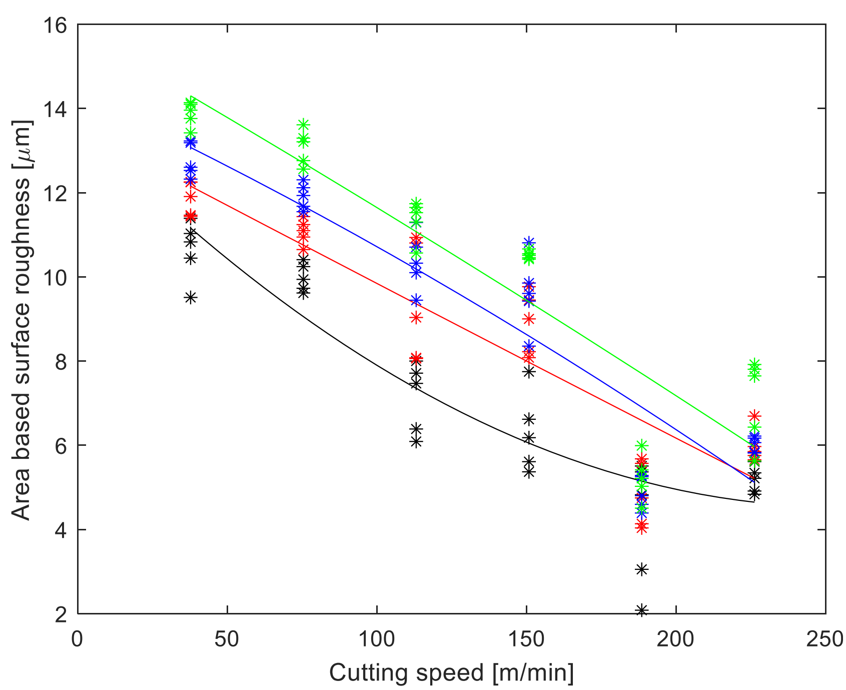
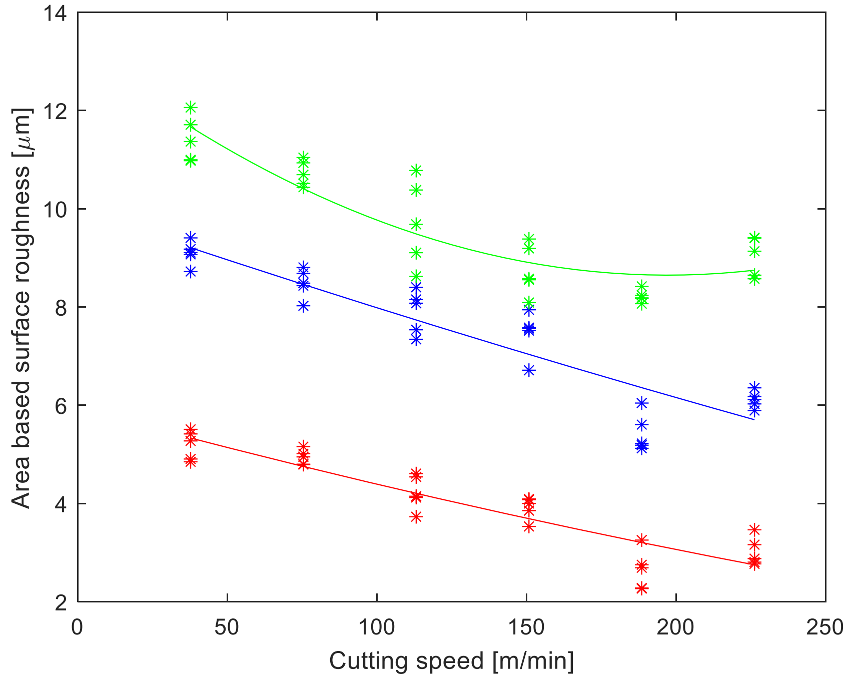


Fig. 11 Relation between the minerals forming granite and the surface roughness in the granite 2 sample [46] (light green: quartz, blue: microcline, red: albite, black: biotite)

Fig. 12 Relation between the minerals forming granite and the surface roughness in the granite 3 sample [46] (light green: quartz, blue: albite, red: biotite)



So, it can be stated that the order of the effect of minerals on surface roughness is the same at all examined cutting speeds and every particle size (Fig. 1.j).

The results may be greatly influenced by the microhardness of the minerals, their different orientations, and the percentage composition of the sample.

The results of the study contribute to setting up a proportional scale that would include the various constituent minerals on the grounds of their workability.

In addition, the effect of neighboring minerals on each other, the roughness of the interface, and possible changes in orientation will be examined.

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Data availability E. Cserta, "Effect of the granite forming minerals on the surface roughness in the milling process," Mendeley Data, v1, 2020. doi: https://doi.org/10.17632/h6t9j5vkj7.1.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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