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THE EFFECTIVENESS OF HYDROABRASIVE, SUSPENSIVE WATERJET CUTTING OF THE ROCKS

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ABSTRACT

The paper presents the results of complex studies on parameters of cutting chosen rocks with a hydroabrasive suspensive jet, whose pressure is reduced to 30 MPa. Such a considerable operating pressure reduction is a result of an original and own construction of BORJET 01 appliance, where advantage of circuitous liquid motion phenomenon has been taken of. The influence of the most important hydraulic and technological parameters on the cutting depth is presented in the paper. Apart from this, coefficients of erosion and proper energy characterizing the cutting process have been compared. The effectiveness of suspensive jet cutting with a pressure reduced to 30 MPa is comparable to conventional hydroabrasive jet cutting with a pressure of 300 MPa.

1. INTRODUCTION

The most serious disadvantage of the so-far existing systems for cutting with a high pressure hydroabrasive jet and working at pressures of 400 MPa [9], is the use of an injector mixer to create the jet - due to its small efficiency, especially in the case of very big differences of working media velocities. An elimination of an injector mixer [10] and the use of the jet's circumferential motion [1, 5] for mixing an initially created hydroabrasive mixture directly under a high pressure can result in a radical change of the situation. Owing to this, similar machining effects are achieved even though the working pressure has been lowered even by an order of magnitude [2].

2. TEST STAND

The test stand [4, 5] has been constructed on the basis of BORJET 01 prototypical appliance. It is of a universal nature and enables a quick change of the configuration of hydraulic connections, which in turns makes it possible to change the mixing manner, the manner to wash out the abrasive bed as well as the change of water supply manner, and the way to carry out an initially formed hydroabrasive jet.

BORJET 01 appliance (cf. Fig. 1) has been built from two containers and four independent hydraulic branches, which enable an adjustment of the basic flow parameters. Each branch consists of the following valves: a cut-off valve, a throttle valve, a non-return valve and a manometer. An overflow valve performs the function of an element preventing an excessive increase of pressure. It is set at the pressure of 30 MPa.

A hydraulic monitor P26 type is the source of a high pressure. It is made on the basis of elements of a plunger pump made by an Austrian WOMA company. It makes it possible to obtain the maximum pressure of 75 MPa with the rate of water flow of 75 dm^3/min.

3. TEST METHOD

The materials were cut by directing the hydroabrasive jet perpendicular to the machined material [4,7], and then a rectilinear traverse speed in relation to the working nozzle. The thickness of the samples was selected in such a way that, with the most effective machining parameters, cutting through these should not occur, which would make it difficult to correctly determine the depth of the cut.

Rocks used for tests: marble, syenite and limestone, they were describing various properties. Marble is metamorphosed limestone, composed of fairly pure calcite (a crystalline form of calcium carbonate, $CaCO_3$). It is extensively used for sculpture, as a building material, and in many other applications. Faux marble or faux marbling is a wall painting technique that imitates the color patterns of real marble (not to be confused with paper marbling). Marble dust can be combined with cement or synthetic resins to make *reconstituted* or *cultured marble*. Places named after the stone include Marble Hill, Manhattan, New York and the town of Marble, Minnesota. The Elgin Marbles are marble sculptures taken from the Parthenon to Britain by the Earl of Elgin.

Syenite is a coarse-grained intrusive igneous rock of the same general composition as granite but with the quartz either absent or present in relatively small amounts. The feldspars are alkaline in character and the dark mineral is usually hornblende. Soda-lime feldspars may be present in small quantities. The term syenite was originally applied to hornblende granite like that of Syene in Egypt, from which the name is derived. Syenite is not a common rock, some of the more important occurrences being in New England, Arkansas, Montana, New York (syenite gneisses), Switzerland, Germany, and Norway.

Limestone is a sedimentary rock composed of the mineral calcite (calcium carbonate). The primary source of this calcite is usually marine organisms. These organisms secrete shells that settle out of the water column and are deposited on ocean floors as pelagic ooze (see lysocline for information on calcite dissolution). Secondary calcite may also be deposited by supersaturated meteoric waters (groundwater that precipitates the material in caves). This produces speleothems such as stalagmites and stalactites. A further form is composed of oolites (Oolitic Limestone) and can be recognised by its granular appearance. Limestone makes up about 10 percent of the total volume of all sedimentary rocks. Pure limestones are white or almost white. Because of impurities, such as clay, sand, organic remains, iron oxide and other materials, many limestones exhibit different colors, especially on weathered surfaces. Limestone may be crystalline, clastic, granular, or dense, depending on the method of formation. Crystals of calcite, quartz, dolomite or barite may line small cavities in the rock. Chert or Flint nodules are common in limestone layers. Bands of limestone emerge from the Earth's surface in often spectacular rocky outcrops and islands. Examples include the Verdon Gorge in France; Malham Cove in North Yorkshire, England; and the Ha Long Bay National Park in Vietnam [8].

4. RESULTS OF TESTS

4.1 Influence of traverse speed and pressure

Cutting was conducted with the following constant parameters:

- abrasive: quartz sand #30,
- inside diameter of nozzle d=2.0mm,
- length of hydroabrasive nozzle l=50mm,
- distance nozzle – material b=6mm,
- abrasive flow rate m_a=60g/s.

The largest depth cut of marble h=48.51 was obtained with the smallest traverse speed υ_p=1mm/s and the highest working pressure p=28MPa (Fig. 2a). Together with a decrease of pressure to 16MPa, the cut depth decreases and, at the same traverse speed, it reaches value h=38.83mm. With an increase of traverse speed to υp=6mm/s, the cut depth decreases for all pressure values and reaches value h=13.73mm for pressure 16MPa [6].
The largest depth of the h=54.79mm cut (rys. 2b.) were reached at smallest traverse speed υ_p=1mm/s and the highest working pressure p=28MPa. With reducing the working pressure, depth of the cut is decreasing, reaching the h=40.34mm value at the 16MPa pressure. The smallest depth of the cut h=10mm was being reached at the lowest working p=16MPa pressure and at biggest traverse speed cutting into the smallest depth by up=6mm/s, were being reached at biggest traverse speed υ_p =6mm/s and the lowest working p=16MPa pressure.
The largest depth cut of syenite h=53.89 (Fig. 2c) was obtained with the smallest traverse speed υ_p=1mm/s and the highest working pressure p=28MPa. With a decrease of pressure to 16MPa, the cut depth decreases and, at the same traverse speed, it reaches value h=42.01mm. Together with an increase of traverse speed to υp=6mm/s, the cut depth decreases for all pressure values and reaches value h=15.71mm for pressure 16MPa [7].

4.2. Influence of abrasive flow rate and pressure

Cutting was conducted with the following constant parameters:

- abrasive: quartz sand #30,
- traverse speed υp=4mm/s,
- inside diameter of nozzle Ø=2.25mm,
- length of hydroabrasive nozzle l=50mm,
- distance nozzle – material b=6mm.

The effects of cutting marble are exemplified in Fig. 3a. The largest cut depth h=40. 06mm is obtained with the highest working pressure p=28MPa and abrasive flow rate m_a=70g/s. A decrease of the depth of the cut in the whole range of working pressures is connected with the change of the abrasive flow rate. A working pressure decrease results in its reduction, as well. The smallest cut depth exceeding h=6mm is obtained with the extreme value of the abrasive flow rate and the lowest pressure p=16MPa.
Exemplifying effects of cutting limestone are exemplified in Fig. 3b. The largest depth of the cut h=27mm, is being obtained at the p=28MPa pressure and the abrasive flow rate from 70g/s, as similarly for the previous cases.

With effect of the change of the value both of parameters is a drop in depth of the cut. The weakest effects were being reached in the form of depth of the h=10.19mm cut for the lowest pressure and the smallest abrasive flow rate.

The effects of cutting syenite are exemplified in Fig. 3c. The largest cut depth h=33.00mm is obtained with the highest working pressure p=28MPa and abrasive flow rate m_a=70g/s. A decrease of the depth of the cut in the whole range of working pressures is connected with the change of the abrasive flow rate. A working pressure decrease results in its reduction, as well. The smallest cut depth exceeding h=18mm is obtained with the extreme value of the abrasive flow rate and the lowest pressure p=16MPa.

4.3. Influence of abrasive flow rate and sizes of nozzles

In order to determine the influence of abrasive flow rate and sizes of nozzles onto the depth of cutting steel a decision was made to conduct a process of cutting with the use of nozzles characterized by the following geometric parameters:

- length l=50, 75 and 100mm,
- diameter d=2.0; 2.25; 2.5 and 2.75mm.

The remaining parameters of the cutting process were as follows:

- abrasive: quartz sand #30,
- traverse speed υ_p=4mm/s,
- distance nozzle – material b=6mm,
- working pressure p=28MPa.

4.3.1. Influence of abrasive flow rate and diameter of nozzle, 50mm length

The depth of marble cutting (Fig. 4a) is less dependent of the abrasive flow rate and the nozzle diameter, as for most of the parameters it ranges from 24 to 32mm. The largest depth of the cut is obtained only while machining with a nozzle of diameter d=2.25mm, reaching a maximum equaling 40mm for the abrasive flow rate m_a=70g/s. The smallest cut depth exceeding h=20,14mm is obtained with the minimum value of the abrasive flow rate and a while nozzle with the smallest diameter is being applied.

The depth of limestone cutting h=26.99mm (Fig. 4b), for the nozzle about the length being obtained when using nozzles about the f=2.25 diameter and the m_a=70g/s expense. Change of the abrasive flow rate and change of the nozzle diameter is causing the drop in depth of the cut like. The smallest depth of the cut is being reached at extreme m_a =50g/s values and m_a=90g/s of the abrasive flow rate.

The depth of syenite cutting (Fig. 4c) is less dependent of the abrasive flow rate and the nozzle diameter, as for most of the parameters it ranges from 24 to 32mm. The largest depth of the cut is obtained only while machining with a nozzle of diameter d=2.25mm, reaching a maximum equaling 33mm for the abrasive flow rate m_a=70g/s. The smallest cut depth exceeding h=20.14mm is obtained with the minimum value of the abrasive flow rate and a while nozzle with the smallest diameter is being applied.

4.3.2 Influence of abrasive flow rate and diameter of nozzle, 75mm length

Typical cutting effects of marble are presented in Fig. 5a. The depth of marble cutting is the largest for the nozzle of diameter d=2.25mm with the highest abrasive flow rate and amounts h=55.3mm.

A reduction of both the nozzle diameter and the abrasive flow rate results in a decrease of the cutting depth. The poorest efficiency of the machining process is to be observed in the range of the abrasive flow rates from 50 to 70g/s for the largest diameters of nozzles. The cutting depth in this range does not exceed 31mm.

Exemplifying effects of limestone are presented in Fig. 5b. For the nozzle about the l=75mm length the biggest h=40.13mm depth is being obtained for the diameter of the d=2.75mm nozzle at the abrasive flow rate has 80g/s. Reducing of the diameter of the nozzle and the abrasive flow rate is leading for reducing efficiency of cutting. The smallest depth of the cut, being h=24.96mm, is being obtained for the nozzle about the d=2.0mm diameter at the abrasive flow rate m_a=50g/s.

Cutting of syenite effects are presented in Fig. 5c. The depth of syenite cutting is the largest for the nozzle of diameter d=2.25mm with the abrasive flow rate 60 g/s and amounts h=42.67mm.

A reduction of both the nozzle diameter and the abrasive flow rate results in a decrease of the cutting depth. The poorest efficiency of the machining process is to be observed in the range of the largest and smallest diameters of nozzles. The cutting depth in this range does not exceed 29mm.

4.3.3 Influence of abrasive flow rate and diameter of nozzle, 100mm length

For marble cutting in the case of this length of nozzles the largest cutting depth (cf. Fig. 6a) is achieved at the 70g/s abrasive flow rate and a nozzle of diameter d=2.25mm, and is h=37,5mm. Together with the abrasive flow changed , the cutting depth decreases, too, and this is so in the case of all working diameters. The largest cutting depth decrease occurs at the reduction of the hydroabrasive jet diameter to value d from 2.0. The abrasive flow rate decrease results in a smaller cutting depth, as well. Its lowest value of 27.23mm is reached, in a similar manner, at the smallest abrasive flow rate, while a nozzle with the smallest diameter is being applied.

For result of limestone cutting in the case of this length of nozzles the largest cutting depth (cf. Fig. 6b) at the value of the diameter of the working d=2.75mm nozzle for the in case of the nozzle about the l=100mm length at the value of the working nozzle diameter f=2.75mm for the abrasive flow rate depth is gaining maximum m_a=80g/s. Cutting depth by reducing is calling both reducing of the diameter of the internal working nozzle how and of abrasive flow rate not less than to reaching the h=16mm minimal value for the nozzle about the f=2.0mm diameter and the abrasive flow rate m_a=50g/s, it was taking place like in case of the previous material.

For efect of syenite cutting in the case of this length of nozzles the largest cutting depth (cf. Fig. 6c) is achieved at the 90g/s abrasive flow rate and a nozzle of diameter d=2.5mm, and is h=39.79mm. Together with the abrasive flow changed , the cutting depth decreases, too, and this is so in the case of all working diameters. The largest cutting depth decrease occurs at the reduction of the hydroabrasive jet diameter to value d from 2.0. The abrasive flow rate decrease results in a smaller cutting depth, as well. Its lowest value of 18.06mm is reached, in a similar manner, at the smallest abrasive flow rate, while a nozzle with the smallest diameter is being applied.

5. STATE OF MATERIAL SURFACE AFTER MACHINING

In order to assess the state of the surface of materials cut, examinations of the surface microstructure were carried out. Its roughness was measured, too.

5.1. Surface microstructure

The microstructure was examined by means of a scanning microscope. Fig. 8 presents the image subject to an analysis by means of a scanning microscope type JSM1 produced by JEOL company. It shows the surface cut in magnification 300.

The exemplifying surface of cut marble was presented in the fig. 7a. She is characteristic of the fragile, crystalline breakthrough with particles being behind on the cut surface of the material crushed out. Small traces are visible of wiping and reliable orientation of working of the stream.

The fig. 7b is presenting the standard surface of the cut limestone. It is like in case of marble fragile, more fine breakthrough. The structure is little developed, don't can be seen on the surface of erosion traces of the material.

A characteristic landscape (fig.7c) was shown to the surface in the figure last of cut materials - syenite. In central his parts can be seen rubbing off by the trace surrounded with the area of the fragile breakthrough. Visible, typical of the coarse-grained breakthrough, the grain structures of the rock are proving it. Such a structure is showing the surface on the synergetic character of the erosive interaction of abrasive grains and streams of water.

5.2. Surface roughness

The roughness of the examined lateral surface of the cut material is a result of the erosive influence of the hydroabrasive jet. The roughness of the material cut with the hydroabrasive jet was defined with parameter R_a, determined in system of lines M (the arithmetic mean of deviation R_a of the average line profile).

Fig. 8a shows the amplitude of marble scratch in relationship to the size of the measuring length. The average surface roughness of marble value is R_a=5.25µm.

The limestone average surface roughness presented fig. 8b. The average surface roughness of limestone value is R_a=5.65µm.

Fig. 9c shows the amplitude of syenite scratch. The value for this rock is R_a=4.40µm.

7. SUMMARY

- The influence of a traverse speed is inversely proportional to the depth of the cut, irrespective of the remaining parameters of the process.
- The working pressure has a direct influence on the depth of the cut and, for most cases, the highest possible pressures should be applied.
- The average surface roughness for rocks is of row R_a=5µm.

The examination results allow one to define the best machining parameters of marble without the necessity to conduct additional examinations, which undoubtedly plays a part in a better understanding of the hydroabrasive cutting process in conditions of a lowered working pressure and will contribute to its wider application.

Further laboratory studies of this technique of separation of materials should be conducted with a view to increasing the working pressure, as its even greater reduction is not able to ensure the preservation of a high machining efficiency, comparable with the effects of machining by means of a high-pressure jet created in traditional injection mixers.

In order to lower the costs of hydroabrasive cutting, studies on decreasing both water and abrasive flow rate should be conducted.

Owing to such procedures, the efficiency of the cutting process should be ever higher, as a result of which there may be a wider practical application of this most interesting technology.

REFERENCES

[1] Borkowski J., Perec A., 1995, Influence of conditions highpressure, suspensive, hydroabrasive jet creation onto metals cutting. XVIII Scientific School of Abrasive Machining. Wroclaw - Szklarska Poreba, Poland.

[2] Brandt C., Louis H., Meier G., Tebbing G., 1994, Abrasive Suspension Jet at Working Pressure up to 200 MPa. 12th Int. Symposium on Jet Cutting Technology. Rouen, France.

[3] Perec A., 1995, Influence of conditions highpressure, suspensive, hydroabrasive jet creation onto cutting materials parameters in lower working pressure aspect.(In Polish). Doctor trial. Technical University of Koszalin.

[4] Perec A., 2001, The surface properties of constructional materials with the high-pressure, hydroabrasive waterjet cutting. XXIV Scientific School of Abrasive Machining. Lopuszna, Poland 2001, pp.137-144.

[5] Perec A., 2003, Some aspects of hydroabrasive suspensive jet cutting of aluminum alloy. 7th Pacific Rim International Conference on Water Jetting Technology. Jeju, Korea 2003.

[6] Perec A., 2003, Some aspects of hydroabrasive suspensive jet cutting of marble. 2003 WJTA American Waterjet Conference. August 17-19, 2003 Houston, Texas, USA, paper 1-C.

[7] Perec A., 2004, Some aspects of hydroabrasive suspensive jet cutting of syenite. 17th International Conference on Water Jetting - Advances and Future Needs. Mainz, Germany, 7- 9 September 2004, pp. 295-306

[8] Wikipedia - http://en.wikipedia.org/

[9] Vijay M.M., 1989, Evalution of abrasive-entreined water jets for sloting hard rocks. 5th American Water Jet Conference. Toronto, pp. 333-342.

[10] Yazici S. Summers D. A., 1989, The inwestigations of DIAJET cutting of granite. 5th American Water Jet Conference. Toronto, pp. 346-350.

NOMENCLATURE

b – distance nozzle – material
d – nozzle diameter [mm],
l – nozzle length [mm],
υ_p – traverse speed [mm/s],
p – pressure [MPa],
R_a – average surface roughness,
m_a – abrasive flow rate [g/s].

GRAPHICS

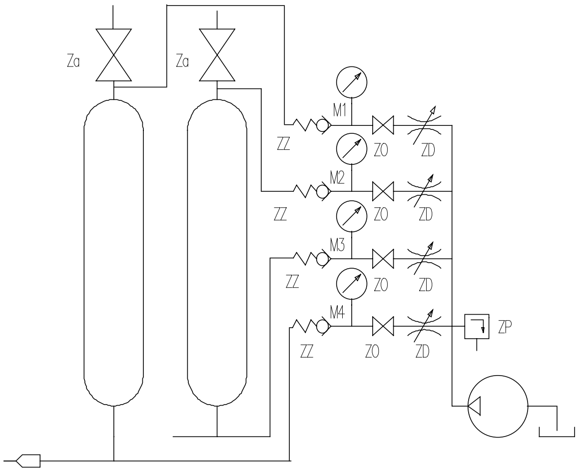


Figure 1. Hydraulic diagram of device BORJET 01

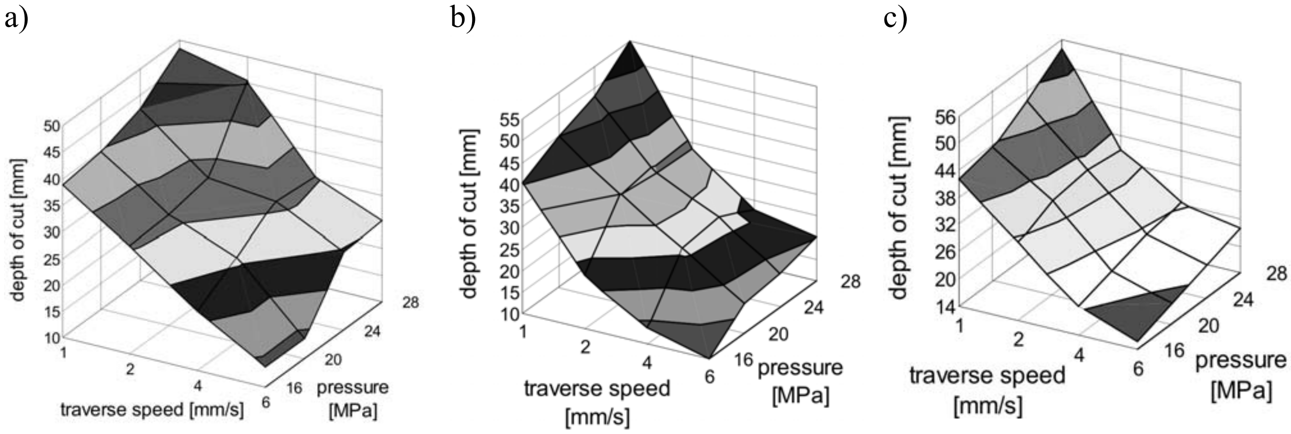


Figure 2. Influence traverse speed and pressures onto depth of cutting:
a)marble, b)limestone, c)syenite

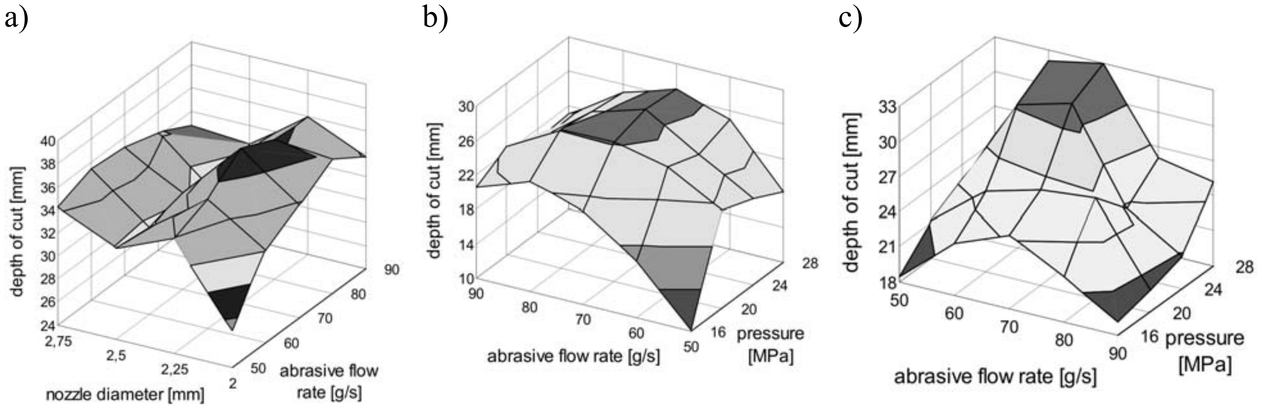


Figure 3. Influence abrasive flow rate and pressures onto depth of cutting:
a)marble, b)limestone, c)syenite

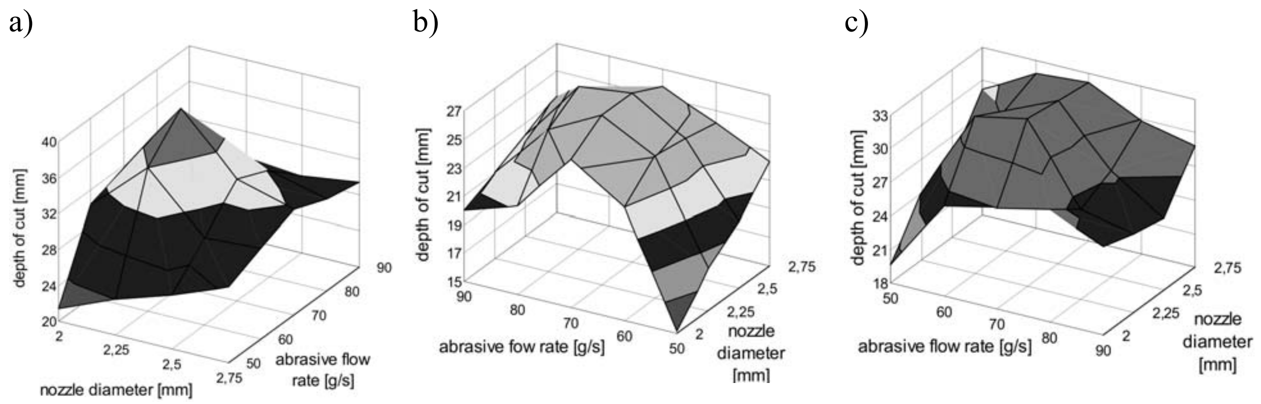


Figure 4. Influence abrasive flow rate and nozzle diameter about length 50mm onto depth of cutting: a)marble, b)limestone, c)syenite

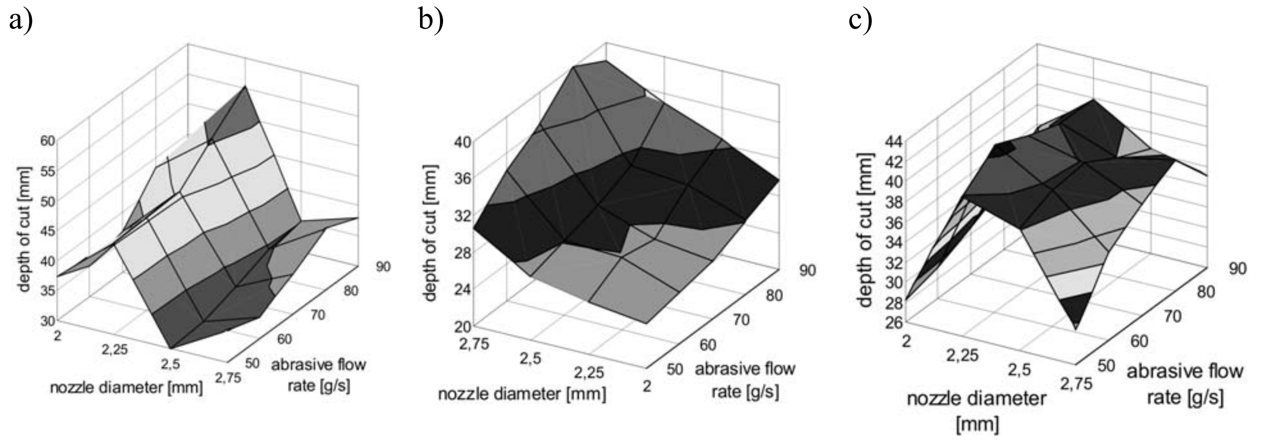


Figure 5. Influence abrasive flow rate and nozzle diameter about length 75mm onto depth of cutting: a)marble, b)limestone, c)syenite

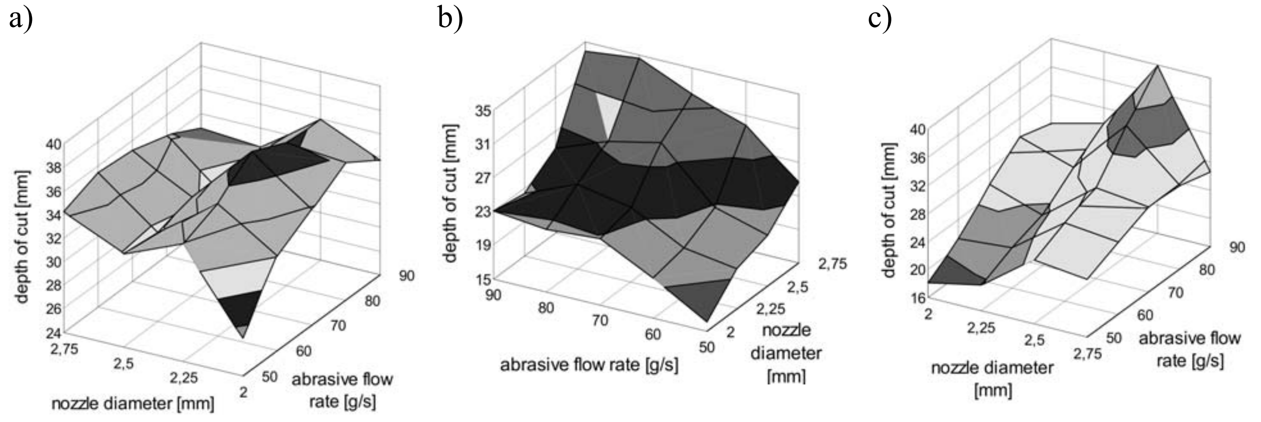
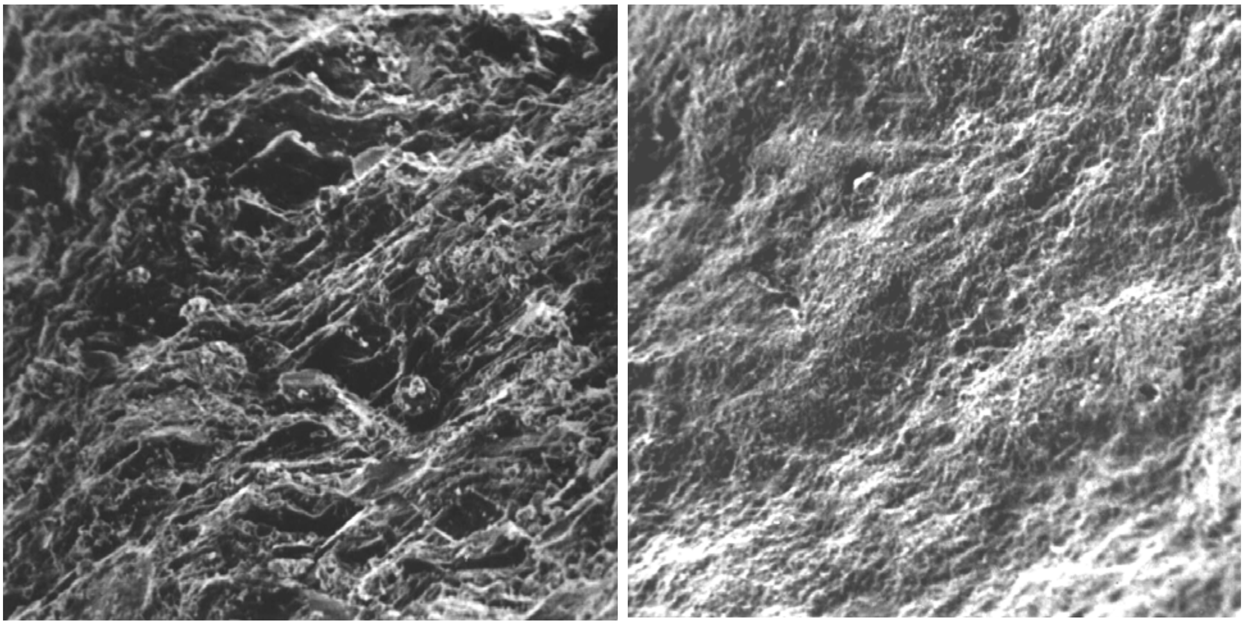
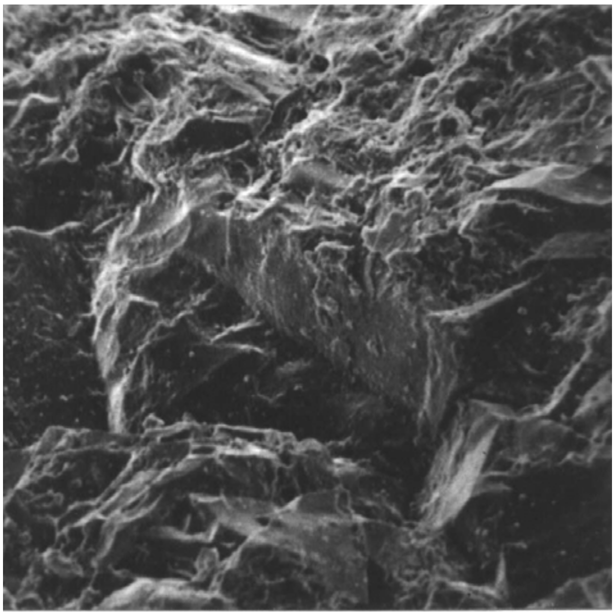


Figure 6. Influence abrasive flow rate and nozzle diameter about length 100mm onto depth of cutting: a)marble, b)limestone, c)syenite



a) marble b) limestone



c) syenite

Figure 7. Microstructure cutting surface (300x):

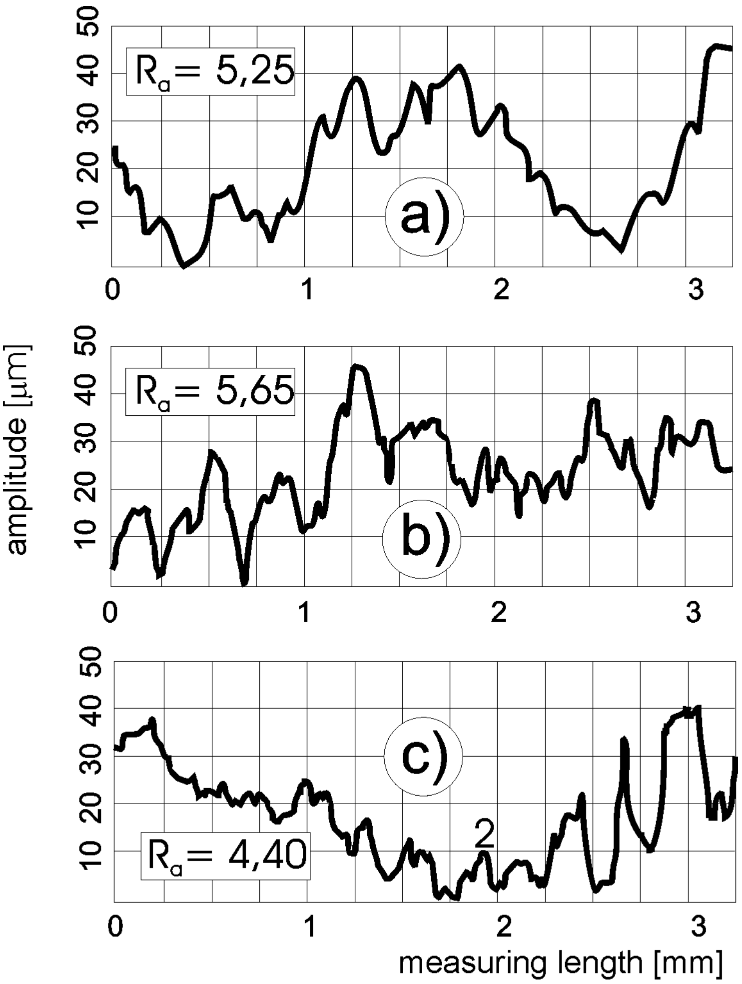


Figure 8. Outline amplitude of cut surface: a)marble, b)limestone, c)syenite