ANALYSIS OF THE CUTTING PROCESS FOR MILLING OF MARBLE AND SANDSTONE WITH AN END MILL CUTTER

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ABSTRACT

Research has shown that it is possible to machine natural stone materials using end mill cutters with geometrically defined cutting edges as they are used in metal cutting processes. The milling process can be used as an energy efficient alternative to the well-known grinding processes. A study of Fraunhofer IPK investigates the cutting process for Postaer Sandstone and Carrara Marble using an end mill cutter. A high speed video camera was used in order to analyze the cutting process. The produced stone particles ("chips") were sorted according to their size distribution and the resulting surface roughness was measured in order to identify possible influences of different cutting parameters. For the study, the depth of cut a_p, the feed per tooth f_z and the cutting speed v_c were varied. For the influence on the surface roughness, results show that all three parameters have a significant influence when machining marble. For the machining of sandstone, no significant influence has been identified. The distribution of sandstone particles after the milling process is independent from the cutting parameters as well, only the depth of cut shows an influence for marble. The high speed videography of the cutting process shows obvious differences between the two investigated natural stone materials. The chip formation for Carrara Marble is a rather continuous process whereas for sandstone the cutting process is rather random and can hardly be influenced by altering the process parameters.

KEYWORDS

Stone Milling, influence of cutting parameters, end mill cutter, high speed video analysis, particle distribution analysis, Postaer Sandstone, Carrara Marble

INTRODUCTION

In recent years many researchers have investigated the cutting process for natural stone machining. Most of the work is based on the use of abrasive diamond tools as they are mainly applied for the cutting of natural stone. The most well-known and referenced work in this area is the work of Wagner [1] who divides the chip formation process into two different steps, stating that the cutting process leads to crushed material on the one hand and discontinuous chips on the other hand. Clausen and Meding [2] use single grain diamonds and perform scratch tests to investigate the cutting process which they divide into three different process steps. The primary chip formation occurs in front of the cutting edge where micro and macro-cracks occur due to the compressive stresses induced by the diamond grain. They state that the cutting process depends on the grain size and the mineral distribution of the workpiece material. For fine grained materials a plastification of the surface occurs under the diamond. The plastified zone is then separated from the surface. This step is called secondary chip formation. For coarse materials, the secondary chip formation is characterized mostly by transcrystalline cracks. The cutting process model of Tönshoff and Asche [3] is almost the same as Clausen's and Meding's. The main difference is the use of a diamond cutting wheel and a coolant instead of a single diamond grain. Reichenbächer [4] also states that the cutting process of natural stone materials is characterized by a primary and secondary chip formation process. Except Tönshoff and Asche, who use a rotating tool, all of the authors use single diamond grains or tools to perform linear scratch tests. This paper aims to contribute to a better understanding of the cutting process and the influence of the cutting parameters when using a rotating end mill cutter for the machining of natural stone.

1. EXPERIMENTAL SET UP

Two different natural stone materials were selected for the tests: Postaer Sandstone and Carrara Marble. Postaer Sandstone is a sedimentary rock and is mainly used for façade elements of buildings [5]. Carrara Marble, a metamorphic rock, is one of the most well-known natural stone materials in the world. Besides its use for sculptor work and monuments, it is often used as decorative flooring or tiles [6].
A 3-axis milling machine was used in all test presented in this paper. A single bladed end-mill cutter with a diameter of 16 mm was used to investigate the influence of the cutting parameters on the particle size distribution of the chips. After each test run, the particles remaining in the working area of the machine were collected and separated according to their size by using a sieve shaker. Six different sieves with grit sizes of 600 µm, 150 µm, 125 µm, 100 µm, 75 µm and 50 µm were used. Remaining, smaller particles were collected in a pan. For the tests, the cutting speed v_c, the feed per tooth f_z and depth of cut a_p were varied according to table 1. An orthogonal design was used to define the values of the parameters and a regression analysis allowed identifying significant and insignificant influences of the parameters. The value $\alpha = 1.28$ was calculated based on the criterion for an orthogonal design according to Kleppmann [7]. The design of experiments leads to a total of 48 different factor combinations. Each of the factor combinations was tested three times. In order to analyze the results, a factor was introduced which allows to compare the size distribution of the stone particles. The factor is called particle size factor (PSF) and is calculated based on the percentage of mass distribution multiplied by the grit size for each sieve. The lower the factor is, the higher the percentage of small particles is and vice versa. For the video analysis, a high speed video camera using a frame rate of 1000 frames per second. Besides the single blade end mill cutter, other tools have been tested in order to find out if the tool geometry and cutting material have a noticeable influence on the cutting process. All tests are performed without coolant in order to be able to separate the particles and to record the cutting process clearly.

Table 1: Parameters and parameter values

Parameter		Parameter value				
		- α = -1.28	-1	0	1	α = 1.28
A: cutting speed v_c	m/min	53.78	62.8	94.2	125.6	134.62
B: feed per tooth f_z	mm	0.13	0.15	0.225	0.3	0.32
C: depth of cut a_p	mm	0.86	1	1.5	2	2.14

2. PARAMETER INFLUENCE ON THE SURFACE ROUGHNESS

After each test, the roughness of the machined surface was analyzed with a tactile surface measuring device. The roughness average Ra is used to rate the influence of the parameters. The Ra value is the arithmetic average of the profile heights of the surface and hence is hardly influenced by peaks within the measurement distance. This allows investigating the influence of the parameters rather than the influence of the material structure.
In order to identify parameters with a significant influence on the roughness of the natural stone surfaces, regression coefficients and confidence levels were calculated. The results for both Postaer Sandstone and Carrara Marble are shown in figure 1.

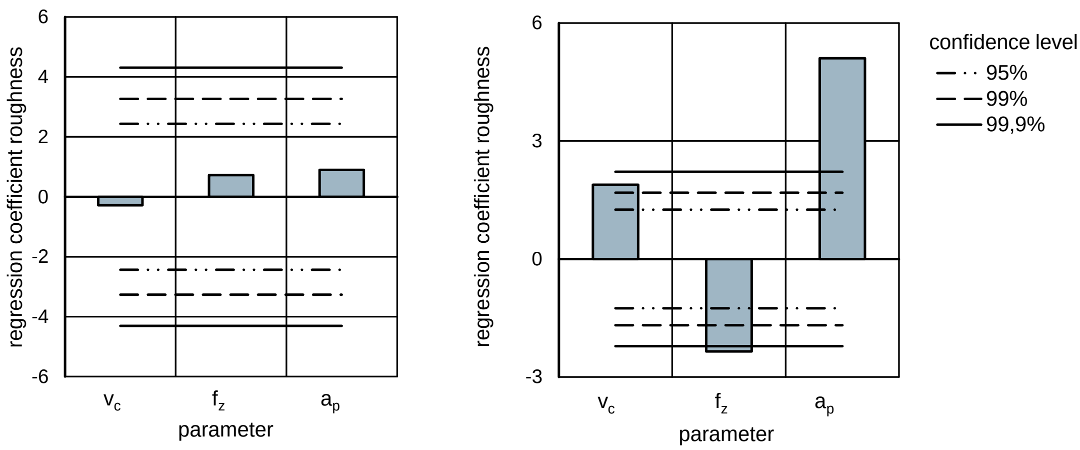


Fig. 1: Regression coefficients for the surface roughness for Postaer Sandstone (left) and Carrara Marble (right)

According to the results of the regression analysis, no significant influence of the cutting parameters on the surface roughness value Ra can be identified for milling Postaer Sandstone. That means a specific manipulation of the resulting surface roughness by altering the milling parameters is not possible. When looking at the results for each parameter combination, the surface roughness seems to be completely independent from the parameters within the investigated range. It is more likely the material influences the results. In several cases, large holes on the surface can be observed. These holes occur when single quartz particles break out of the surface as a result of the milling process.
For Carrara Marble, all three parameters have a significant influence on the surface roughness. The regression analysis shows that the value of the roughness average can be minimized by using low cutting speed v_c, high feed per tooth f_z and a low depth of cut a_p. The influence of all three parameters is linear within the investigated range.

3. PARTICLE DISTRIBUTION ANALYSIS

The stone particles are collected from the working space of the machine after each test run. Figure 2 shows the particles of a test run with Postaer Sandstone for the different sieve sizes. Particles mostly look the same for each sieve. For the large sieve > 600 µm most particles show a footprint area of about 1 mm², but individual, significantly larger particles with a footprint of up to 1 cm x 1.3 cm have been found. A representative image for the particle distribution of marble is given in figure 3.

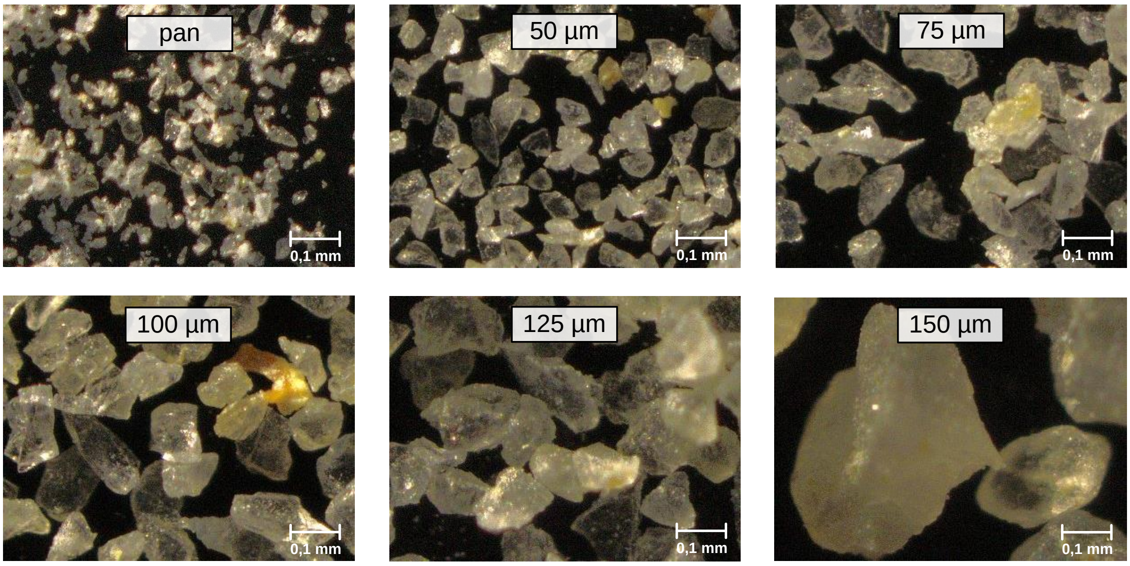


Fig. 2: Particle distribution for Postaer Sandstone

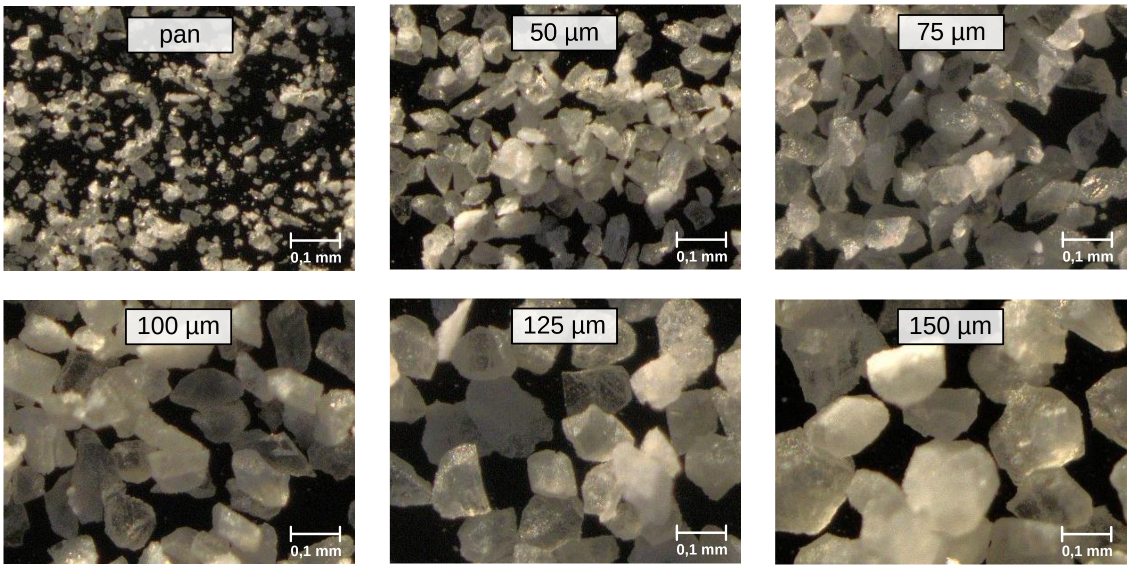


Fig. 3: Particle distribution for Carrara Marble

When comparing the particles in the figures, they look similar besides the fact that two materials with different properties have been used. The macroscopic analysis of the particles with sizes > 600 µm shows some differences. When milling sandstone, whole material grains are removed from the workpiece. The particles are literally pulled out of the surface. For marble, most of the large resulting particles have a rather two-dimensional shape, the process seems to work more like a chipping process.

The results of the regression analysis for the cutting parameter influence on the particle size factor PSF are shown in figure 4. For Postaer Sandstone, no significant influence has been found, though the feed per tooth shows a tendency to influence the PSF when further increasing it beyond the value that has been used as maximum within this study. When machining marble, parameter C, the depth of cut, has a significant influence on the PSF. Moreover the surface roughness and the

PSF seem not to be linked to each other, as the roughness is influenced by all three parameters and the PSF just by one. The influence of the depth of cut on the PSF is linear, that means a low value for a_p leads to smaller particles and a high value to larger particles.

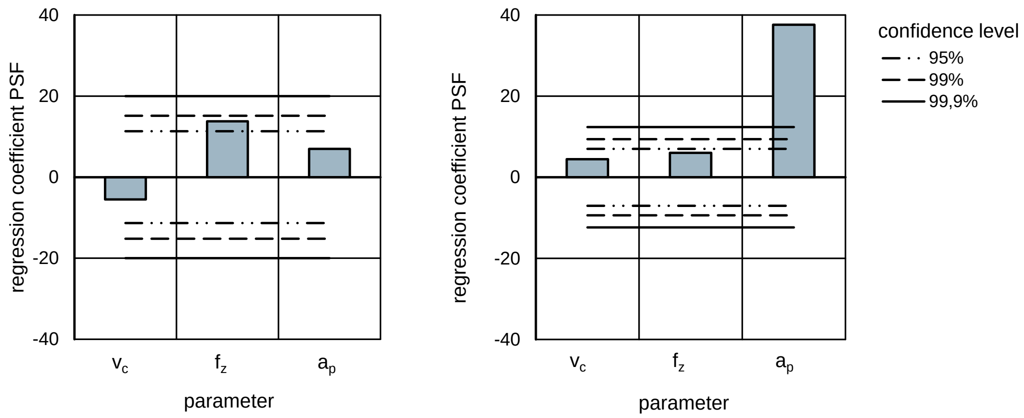
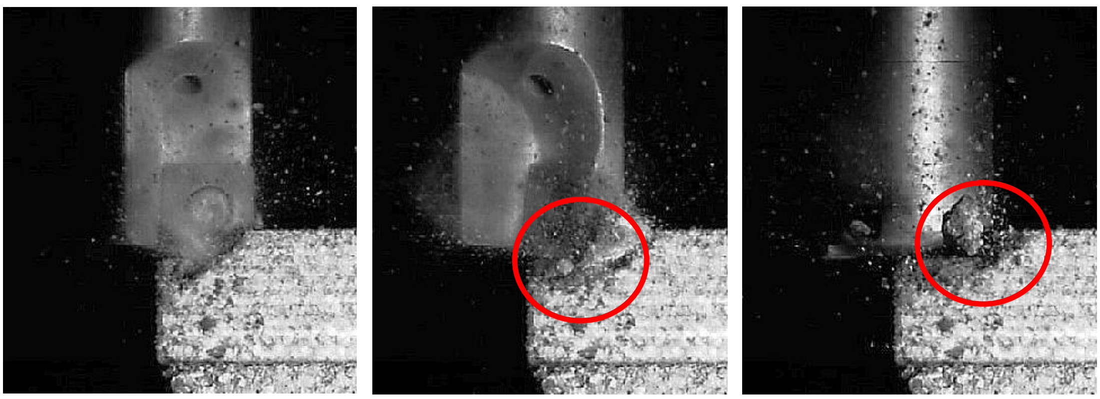


Fig. 4: Regression coefficients for the particle size factor for Postaer Sandstone (left) and Carrara Marble (right)

4. HIGH SPEED VIDEOGRAPHY

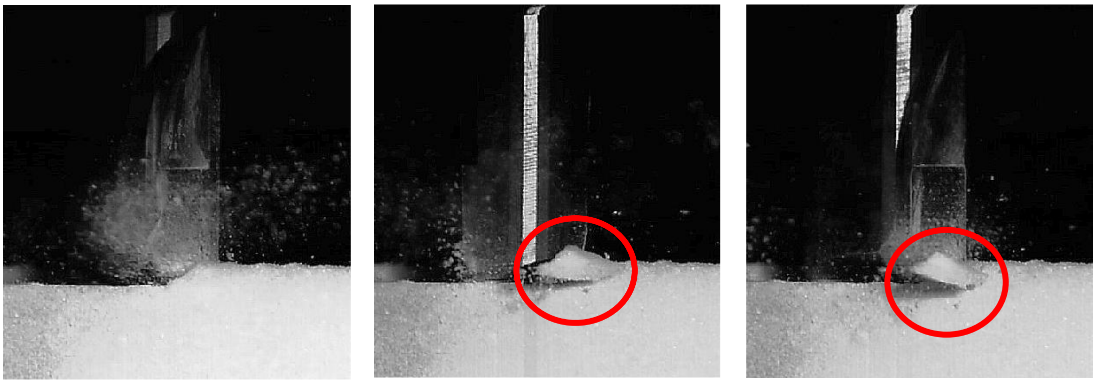
The following figures are snapshots from the high speed videos that were recorded during the test runs. For each parameter combination, small and larger particles are removed from the workpiece. The occurrence of larger particles seems to be random, no correlation with the cutting parameters can be identified. This verifies the previous results regarding the surface roughness and the particle size distribution: The cutting process for milling Postaer Sandstone depends on the material properties and its grains rather than on the cutting parameters. Figure 5 shows an example of the cutting process for Postaer Sandstone. Snapshots were taken at the beginning and after 10 ms and 20 ms. Most of the resulting particles are small-sized, but after 10 ms a pull-out of a significantly larger particle can be seen. The large particle has a footprint area of roughly 4 x 2 mm².



a) 0 ms b) 10 ms c) 20 ms

Fig. 5: Snapshots of the machining of Postaer Sandstone

Figure 6 shows exemplary snapshots from the cutting process of Carrara Marble. The images support the results of the particle distribution analysis. On the one hand, small, “dusty” particles occur during the whole process and on the other hand rather two-dimensional chips can be found. The chips usually do not occur directly at the cutting edge but mostly just in front of it and in some cases behind the cutting edge. The reason for that might be that the cutting forces lead to compression stress within the workpiece material. If the stresses are too high, material failure occurs and the chips are removed from the workpiece material in front of the cutting edge. In case of the chip formation right behind the cutting edge, a resilient material behavior seems to be a possible reason for the chip formation.



a) 0 ms b) 5 ms c) 10 ms

Fig. 6: Snapshots of the machining of Carrara Marble

5. SUMMARY AND CONCLUSIONS

The results show that the cutting and hence the chip formation process for the milling of natural stone materials mainly depends on the workpiece material. For Postaer Sandstone, which can be characterized as a coarse grain material, the cutting process is rather random. The tested parameters, cutting speed v_c, feed per tooth f_z and depth of cut a_p show no significant influence on the chip formation. The material removal depends on the grain composition which leads to a pull out effect of whole grains due to compressive stresses induced by the tool. A repeatable machining of Postaer Sandstone is not possible for the tested parameters. Even when a test with a defined parameter set up is repeated, the results concerning the surface roughness and the PSF may differ strongly. The high speed videography shows that the process leads to two different kinds of particles and hence confirms the cutting process models by the authors mentioned in the introduction of this paper.

When machining the fine graining Carrara Marble, test results are repeatable and the cutting parameters show an influence on the roughness and the particle size factor. To reach a low surface roughness, a low cutting speed and depth of cut should be used in combination with high feed per tooth. A low depth of cut a_p also helps to produce rather small chips. The formation of large chips occurs mainly at the edges of the workpiece and can be reduced by slot cutting. Stone materials are natural materials, hence their properties differ from material to material or even within the same material. The results show that using end mill cutters for machining and especially shaping of natural stone materials is an effective way for a fast near net shaping of workpieces. Suitable cutting parameters and machining strategies have to be investigated beforehand for each workpiece material.

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