INVESTIGATION OF PROCESS FORCES OF ULTRASONICALLY ASSISTED SCRATCH TESTS

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ABSTRACT

Due to their abrasive qualities, machining of hard and brittle materials is predominantly performed using tools with geometrically indefinite cutting edge. However, these processing methods offer only low productivity, which often can be increased by superimposing ultrasonic vibrations to the process. At the same time this hybrid process design involves great uncertainties, as influencing factors and the mechanism of action are not sufficiently described yet. In order to close this knowledge gap, firstly the occurrences on the scale of single abrasive grains shall be observed. This should increase the overall process understanding and reveal fundamental interrelations of machining with geometrically indefinite cutting edge. To achieve this, scratch tests with well-defined boundary conditions will be performed, analyzed and compared. As a result of the experiments the interdependencies of process forces, cutting speed, ultrasonic amplitude and depth of cut will be presented.

INTRODUCTION

Using stone as material is extremely varied and has a long tradition. Applications range from sculpture to horticulture and interior decoration to industrial applications. The widespread applicability of stone is a result of its distinguished properties, which often cannot be attained by competing individual or combined materials. [1]

Whereas the aesthetic aspects of stone are important in art, the outstanding technical properties are to the fore in industrial applications. Granite is often chosen as material to produce measuring components thanks to its temperature stability and wear resistance [2]. It is, however, difficult to machine this natural stone due to its great hardness and abrasive material properties so that it is indispensable to use diamond tools.

In principle, material removal can be divided into cutting and abrasive processes according to DIN 8589. The remarkable features of cutting processes are generally their high productivity, a great accuracy of the manufactured products and an efficient use of the process energy input [3]. These numerous advantages are opposed by an enormous tool wear in stone machining, making the cutting of hard, brittle materials uneconomic despite the advantages mentioned. For this reason, processes with diamond-tipped grinding tools are preferred by industry to manufacture stone products. The tool attains a continual sharpness due to the constant breakaway of worn diamonds and the exposure of new grains [4]. The productivity of abrasive machining processes is, however, low owing to little material removal rates and great frictional heat.

Hybrid machining methods broaden the existing process boundaries of conventional production processes in material removal technology. Especially the superposition of a mechanical vibration in the ultrasonic range has proved to be favourable in the machining of hard, brittle materials and hence is increasingly used in industry [5]. Different effects can arise, depending on the action direction of the ultrasonic vibration. Microhammering is an important working mechanism in vibration-assisted machining and comes particularly into effect in the case of machining processes with parallel feed and vibration directions [6]. The hard, brittle material properties of stone are used here to achieve the smashing of the material by applying varying loads. Due to a lower tensile strength of hard, brittle stone, the resilience of the loaded material induces great tensile stresses so that the material splinters. In addition, pulsed loads onto the tool cutting edges lead to the microsplintering of diamonds so that new, sharp cutting edges arise and the tool always remains sharp [7]. Apart from microhammering, the cleaning effect is another phenomenon of vibration-assisted machining. It is assumed here that the ultrasonically excited tools show a self-cleaning effect in connection with a coolant. Because the tool is lifted briefly, the coolant directly reaches the machining zone and removes the cut particles better. Hence the cutting edges and the chambers remain empty, which improves the efficiency of the grinding tools. Another effect of ultrasonically assisted machining is supposed to be the reduction in Coulomb friction [8]. The decrease in mean friction here results from the periodic change in direction of the relative speeds between tool and workpiece. Hence the ratio between base speed and directed speed amplitude is crucial for how high the Coulomb friction is. Friction is completely missing in the borderline case of an insignificant speed ratio.

In principle there are several possibilities for how a conventional machining process can be superimposed by vibrations in the ultrasonic range [9]. The most widespread application here is to add vibrations via a tool excitation. Compared with a vibration excitation of the workpiece, the advantages of this excitation form are the discretely distributed antinodes and nodes as well as the independence of the vibrational system characteristics from the machining position and the mass of the workpiece. Compared with an excitation of the whole spindle unit, a tool excitation can be realised more economical and energy-efficient. In this way it is not necessary any more to design the spindle individually for each application, and the accelerated masses can be kept small.

Vibrating systems are usually designed for a no-load operation. It is intended here to reach a resonant-near operation with discretely distributed nodes and antinodes. The important influencing parameters are the material-related properties, defining the stiffness of the system, and the distribution of the inert masses. Systems designed in such a way change their vibration properties if they are affected by process forces [10 - 11]. Especially the forces directed parallel to the vibrations affect the stiffness of the system by distorting or stretching the actuator unit like a spring. Consequently, the nodes and antinodes are shifted, and the system becomes off-resonance [12].

The vibration system thus must be designed individually for each application to realise an optimum operation. It is not sufficient here to examine only the process kinematics by taking all process-relevant parameters into account. The design process of a vibrating system rather requires that the interactions between tool and workpiece are taken into consideration permanently. The iterative feedback of the resultant forces arising is central to the design process here. Concerning tools for cutting processes, it is relatively easy to determine both the amount and the direction of the loads arising. By machining cylindrical specimens with different diameters, it is even possible to identify resultant forces on individual cutting edge segments [13]. Establishing the loads on tools for abrasive processes is fundamentally different. Both the shape and the number of simultaneously engaged cutting edges are unknown here. Hence it is impossible to reliably determine the resultant forces for the entire tool. In addition, it is sensible to restrict the process loads to one grain at first. Thus scratch tests with a single grain were carried out to permit evaluation of process forces and observation of the interaction between workpiece and the vibrating tool as well. This, in turn, can serve as a first step towards process-oriented design of ultrasonic tools.

SET-UP AND PROCEDURE

The scratch tests were carried out with a linear test stand, which is used by the Institute for Machine Tools to examine the true machining characteristics of single teeth. This test stand consists of an adjustable vertical table, which is fastened to the stationary frame, and a movable slide unit, which can perform a uniaxially directed movement underneath the portal-shaped frame. The portal frame is prestressed in order to achieve a great static and dynamic stiffness. Hence, this test stand is ideally suited to carry out single grain cutting tests. Thanks to a linear direct drive it is possible to achieve cutting speeds of up to v_c = 200 m/min, which is within the usual cutting speed range of v_c = 60 - 180 m/min in the machining of hard stone [14].

A scratch was produced here by moving a stone specimen that was fastened to the slide unit at a defined cutting speed under the stationary tool. The depth of cut a_p was set at the tool by changing the vertical position of the table (z-axis). In addition, a fine adjusting element was fitted to the workpiece to compensate for tilting errors of the test specimens so that it was possible to attain accuracy within the micrometre range. Figure 1 shows an illustration of the equipment used as well as the entire flow of information.

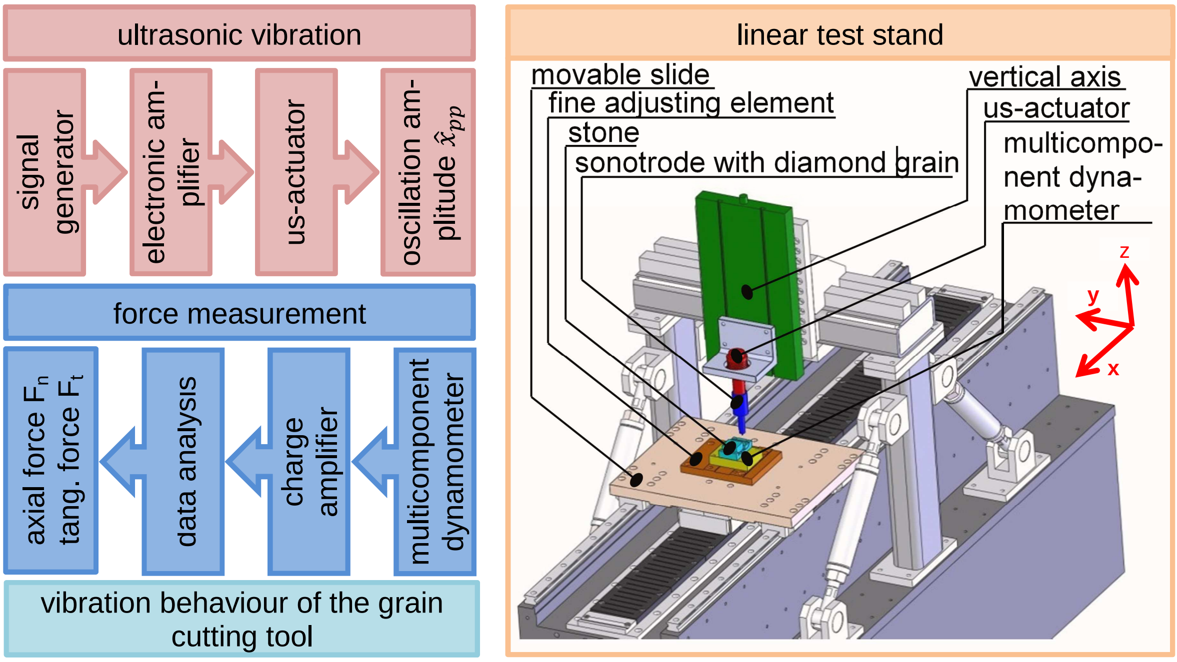

Figure 1: experimental setup and flow of information

Different tools were necessary to establish the measuring data and control the ultrasonic actuator. The process forces were measured with a multicomponent dynamometer by Kistler and an accompanying charge amplifier. The components of the resultant force are measured in a quasi-static way here, since the dynamics of the process at an ultrasonic vibration frequency cannot be established with this measuring technique. A digital phase control unit (dPLL 500/100k) developed by the Institute of Dynamics and Vibration Research was used for driving the ultrasonic actuator. This unit permits a resonant operation of the actuator due to an appropriate phase control. In addition constant amplitude of current and displacement respectively is achieved by an integrated closed-loop amplitude control. Furthermore, the vibration behaviour of the grain cutting tools were monitored with a 3D one point laser vibrometer by Polytec by means of focusing on a measuring point on the grain cutting tool near the shear zone and measuring its spatial shifting. The high dynamic properties of the measuring system make it possible to visualise the technical vibration behaviour of the grain cutting tools in every detail.

EXPERIMENTAL DESIGN

To be able to represent the effects of the three test parameters of cutting speed v_c, depth of cut a_p and the peak-to-peak value of the ultrasonic vibration $\hat{x}_{pp}$ as response surface a procedure was worked out by using design of experiments (DOE). Every single test was repeated at least three times to compensate for the scattering in the composition and the material properties of the stone specimens. The values of the single parameters here range between the limits listed in Table 1.

Table 1: parameter variation

depth of cut a_p [µm]	cutting speed v_c [m/min]	oscillation amplitude $\hat{x}_{pp}$ [µm]
10 – 50	15 - 180	0 - 40

A three-level experimental design in accordance with Box-Behnken [14] was used in the first test step. In this first experimental design, it was intended to quickly create a preliminary, rough database in only a few single tests, in order to detect nonlinear dependences on the forces of the influencing factors and to decide on the further design of experiments. Assessing this first test stage leeds to the conclusion, that additional support is required for a future utilisation in the complete kinematic model. In addition, it is also necessary to make a finer grading than the three levels per influencing factor as used in the Box-Behnken experimental design.

In the next two steps the experimental design was consequently expanded by two intermediate levels per each influencing factor. A D-optimal design was selected both times, which contains the preceding results and is supplemented with new points. Using this refined experimental design, it is possible to generate response surfaces of sufficient accuracy.

TOOLS

There are no restrictions in the design of tools for carrying out scratch tests in stone regarding conventional grain cutting without ultrasonic superposition. Central requirements here are not only a sufficient static strength but also a fast exchangeability of worn diamond grains and a resource-saving design. In highly dynamic processes, these requirements fade into the background because they do not take account of the dynamic structural properties of tools at varying high-frequency loads. The essential aspects in ultrasonically assisted scratching are to transmit energy to the cutting region with as little loss as possible and to maximise the vibration amplitude at the tool tip.

With respect to an efficiency of resources, it was sensible to carry out the conventional as well as the ultrasonically assisted scratch tests with a modular tool. Consisting of a base and a diamond-tipped grain holder, the modular design enables a fast and easy exchange of grain holders if the diamond grains are worn out or broken off. The two tool parts were connected by an M6 thread, making a good compromise as it presents a slip-free connection with a great tightening torque. The diamond grains were fixed to the grain holders by vacuum soldering with silver solder. This method provides a good connection of the single grains to the grain holder at a moderate temperature below the oxidation temperature of diamond. Alternate methods such as bonding and mounting were ruled out in preliminary tests as the load-carrying capacity of the joint proved to be insufficient.

The above-mentioned requirements on a dynamic vibration system were met by designing the grain cutting tool with the λ/2 method. In this method all members of a vibration chain are tuned to half the length of a sound wave axially propagating in the medium or to a multiple of half its length. In this way a standing wave with constructive interference characteristics is formed, so that a tool which is excited at the base has maximum amplitude at its tip. The vibration amplitude was amplified by tapering the tool geometry. The system has to be operated in or at least close to the resonant frequency of the desired natural mode to guarantee that energy is transmitted as completely as possible. Vibratory systems have the highest values of flexibility in this resonant-near frequency range and hence can absorb higher amounts of energy. Figure 2 shows the geometric and vibrational characteristics of the designed grain cutting tool.

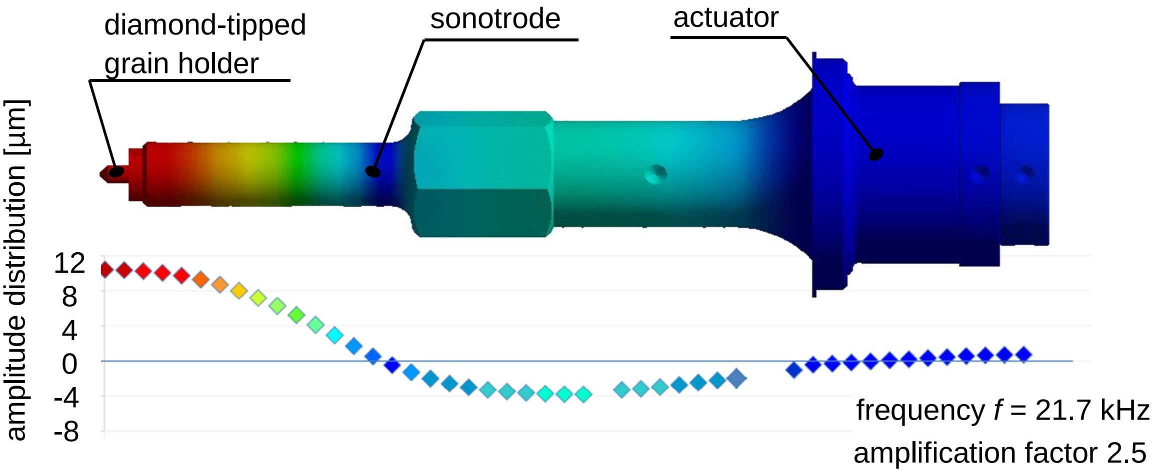

Figure 2: geometric and vibrational characteristics of the ultrasonic system

All diamond grains differ fundamentally from each other in shape and size. As a rule, the shape of a grain growing without being disturbed varies between a cube and an octahedron, but all intermediate forms can occur. Before the scratch tests were conducted, all diamond grains were classified and selected from a representative amount of grains with roughly the same geometric properties, so that these geometric shapes have as little effect as possible. Figure 3 presents the statistical distribution of the measured diamond grains with respect to the shape and the size of a single grain.

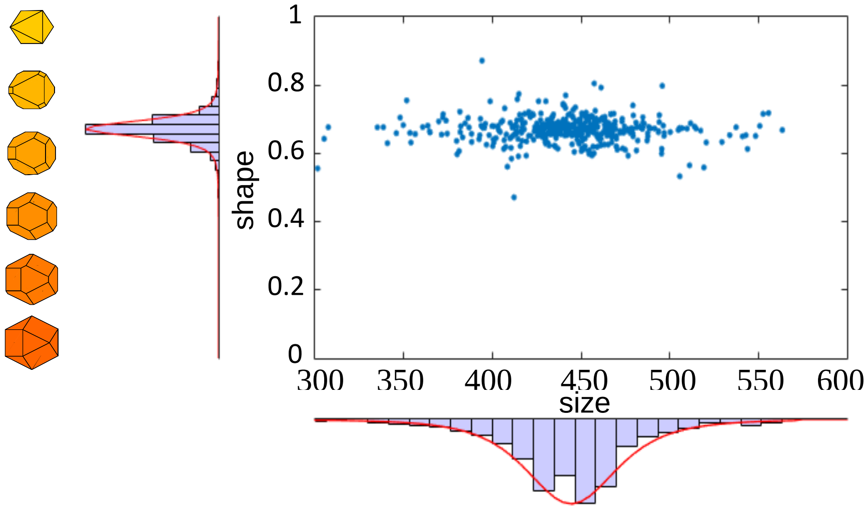

Figure 3: statistical distribution of shapes and sizes of single grains

RESULTS

The resultant force is analysed depending on the depth of cut of the diamond grain a_p, the cutting speed v_c and the peak-to-peak amplitude of the tool $\hat{x}_{pp}$, in order to find out how the boundary conditions affect the arising process forces. These are measured here component by component, in the direction of primary motion F_t and of depth setting F_n as well as orthogonally to both directions and then summed as medians. Since only dependences on two parameter variables can be sensibly represented by a three-dimensional graph, the third parameter has to be constant each time.

The results of the scratch tests without vibration superposition can be seen in Figure 4. As expected, the medians of both process force components F_n and F_t rise as the depth of cut

a_p of the diamond grain as well as the cutting speed are increasing. With growing depth of cut, the chip cross-sectional area and the resistance on the diamond grain penetrating the material are greater. The increase in force components with rising cutting speed is based on a greater material removal rate, which requires more cutting energy.

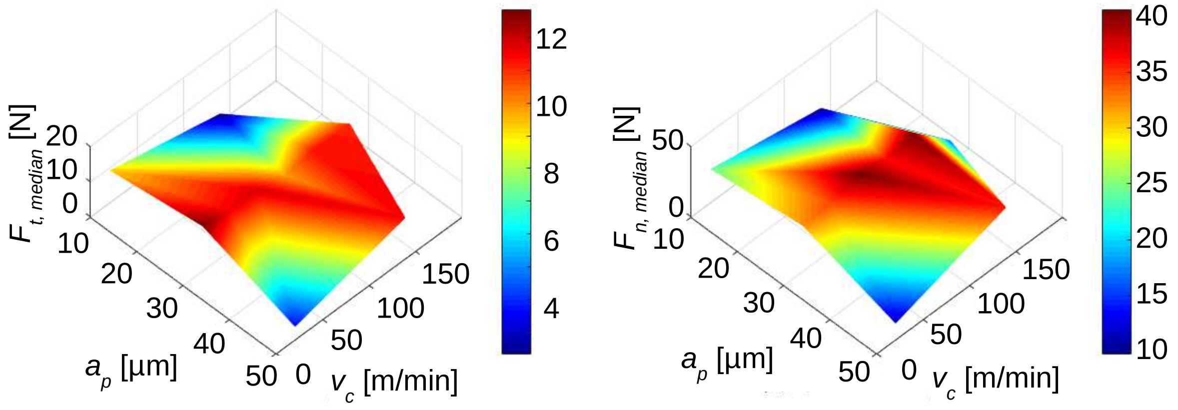

Figure 4: dependency of tangential (left) and normal force (right) on the cutting speed and the depth of cut for x_{pp} = 0 µm

The fact described above can also be detected in vibration-assisted scratch tests with a vibration amplitude of $\hat{x}_{pp} = 20$ µm (Figure 5). The represented response surfaces show that the two components of resultant force depend on the parameter variables of depth of cut a_p and cutting speed v_c as well. In contrast to conventional scratch tests, the two force components here increase with growing depth of cut if speed is low. If cutting speed is increased, the effect of the depth of cut is getting less until there is none at all in the case of high cutting speeds. The cutting speed affects the amount of the resultant force components much greater. The individual components of the resultant force increase with rising cutting speed, reaching their maximum at the highest examined cutting speed.

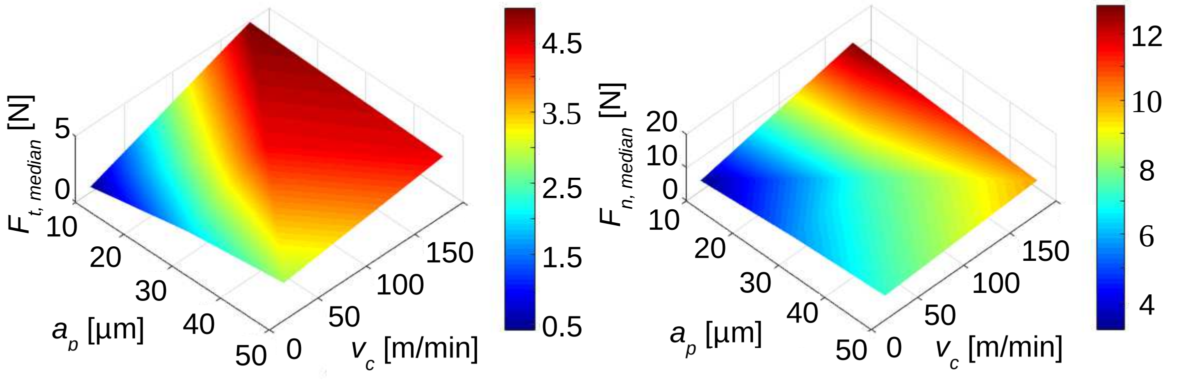

Figure 5: dependency of tangential (left) and normal force (right) on the cutting speed and the depth of cut for x_{pp} = 20 µm

It is obvious that the amplitude of the superimposed vibration affects the amount of the arising process forces as well. As an example, Figure 6 shows this correlation for a constant depth of cut of a_p = 30 µm.

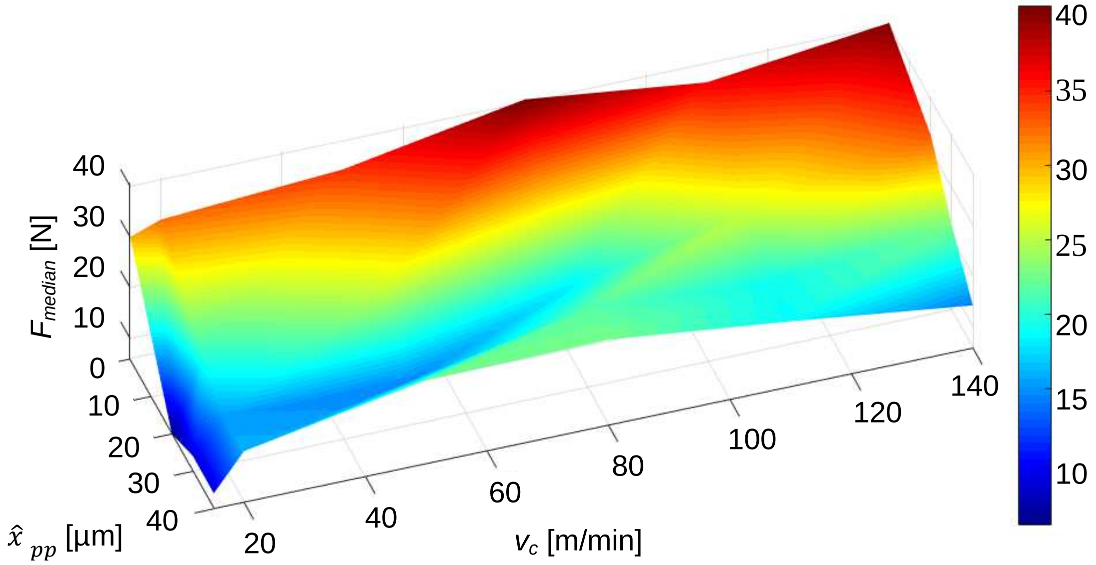

Figure 6: dependency of the cutting force on the cutting speed and the oscillation amplitude for a_p = 30 µm

It follows from this diagram that the mean process force is reduced down to 20 % of the initial value due to the vibration superposition. For example, the maximum reduction in process force is already reached at lower vibration amplitudes in the case of lower speed ranges (v_c = 15 - 80 m/min). If the vibration amplitude is increased further, the process forces rise in the case of low cutting speeds. The maximum reduction in resultant force occurs at high vibration amplitudes regarding the examined upper ranges of cutting speed (v_c = 110 -140 m/min). It is remarkable here that process force gradually decreases with increasing vibration amplitude.

At first, the kinematics of the grain cutting process have to be examined more closely to clarify the correlations described. In the case of scratch tests without ultrasonic assistance, the diamond grain moves parallel to the surface of the stone specimen and exerts continuously increasing compressive stresses on the material in front of and under the cutting edge. If a critical material value is exceeded, these compressive stresses lead to material failure and the forming of primary chips. Due to the continual contact in the shear zone this process is characterised by great friction, which, together with the grain cutting process characteristics, leads to high loads on the diamond grain. The established medians of the resultant forces are comparatively high in scratch tests without ultrasonic superposition. In contrast to this, the continual contact between the diamond grain and the stone specimen is periodically interrupted due to ultrasonic superposition, which reduces the average friction in the shear zone. This is also the reason for the generally lower level of the determined medians of resultant force. Moreover, the contact period becomes shorter with growing vibration amplitude and constant operating frequency. Hence, a further reduction in friction is to be expected at higher amplitudes. But at the same time, the rising vibration amplitudes increase the effective depth of cut of the diamond grain. This is the sum of real depth of cut and vibration amplitude and counteracts the effect of friction reduction, diminishing resultant force. It can be clearly seen how these two contrary effects interact in the lower range of cutting speeds (v_c = 15 - 80 m/min). At first, the effect of friction reduction is predominant in the case of low vibration amplitudes thus the resultant forces decrease with increasing amplitude. If the vibration amplitudes are high, the effectively greater depth of cut becomes noticeable by a renewed increase in process forces. In the examined upper ranges of cutting speed (v_c = 110 -140 m/min), the maximum reduction in resultant force is reached at high vibration amplitudes. It is obvious here that the force-reducing effect of the superimposed ultrasonic vibration predominates the counteractive influence of the increasing chip cross-sectional area. Hence, the medians of the process force gradually decrease despite a greater effective depth of cut.

Apart from the medians of the measured resultant force, the examination of the individual force components (normal and tangential force) should provide more insight into correlations prevailing in the process. For that purpose, the ratio of tangential force to normal force has also to be analysed for a constant depth of cut of a_p = 30 µm, depending on cutting speed and vibration amplitude (see Figure 7).

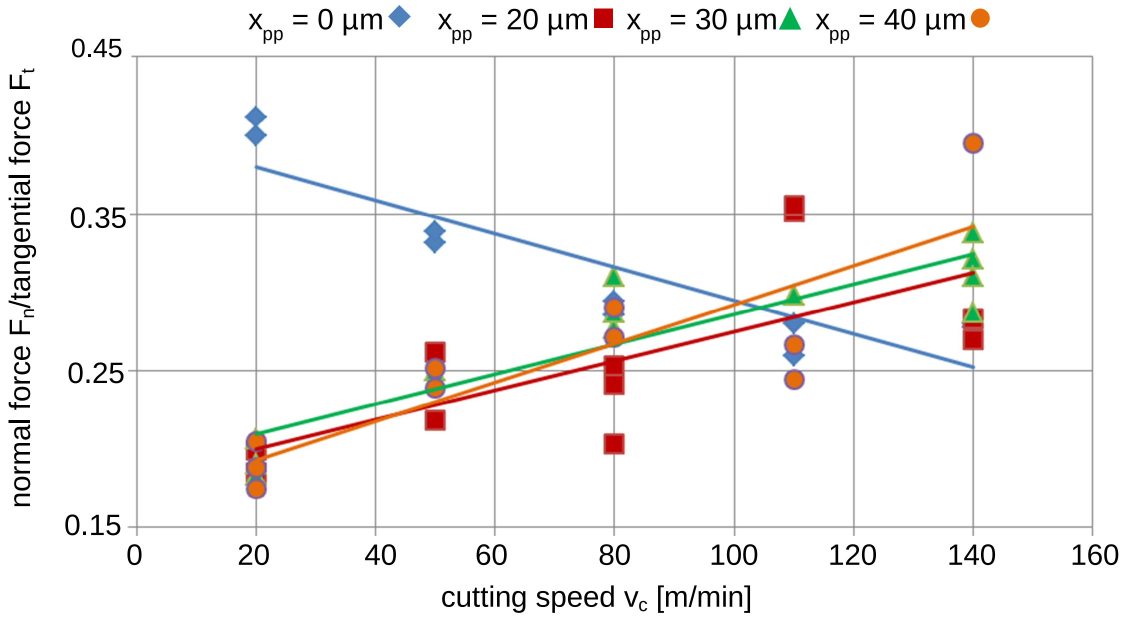

Figure 7: ratio of tangential (left) and normal force (right) for a_p = 30 µm

The trend lines presented in the diagram above visualise the direction towards which the behaviour of the ratio between the resultant force components tends and are calculated from the minimum sum of error squares. It can be seen from this that the gradient of the trend line shows higher values in the case of greater vibration amplitudes. The trend line of conventional scratch tests have a negative gradient.

The different trend line gradients can be accounted for with diverse material removal mechanisms prevailing in the respective series of tests. In conventional grain cutting, the material is largely cut by a pushing movement due to a linearly increasing load in the contact zone. In ultrasonically assisted grain cutting by contrast, the surface splinters predominantly due to the pulsed hits of the diamond grain. Especially the tangential force here depends on the speed ratios prevailing in the contact zone. If the ratio of vibration speed to cutting speed is sufficiently high, the diamond grain hits the stone surface almost vertically and smashes the material underneath. The two components of resultant force result almost entirely from the geometric boundary conditions in the contact zone so that material removal can be attributed exclusively to microhammering. As the ratio of vibration speed to cutting speed decreases, the material to be machined exerts a force on the diamond grain so that the tangential component of the resultant force rises. Consequently, there is a mixed material removal mechanism. In conventional grain cutting, however, the entire tangential force results from the cutting energy produced.

CONCLUSIONS

This paper presents the results of the conducted scratch experiments, machining stone with single diamond grains. Thereby, the occurring machining forces, with and without ultrasonic superimposition, were determined and analyzed in dependence of the depth of cut, the cutting speed and the vibration amplitude of the tool.

The presented examinations show, that an increase in cutting speed and the depth of cut results in an increase in process forces. These observations originate in the increase in cutting work due to higher material removal rates. The superimposition of ultrasonic vibrations has a categorically positive effect on the process forces. The occurent cutting force was reduced by up to 80% during the scratch tests. An augmentation of the vibration amplitude didn't necessarily entail a reduction of the cutting force, since changing the amplitude also altered the effective cut of depth. Another fundamental influence on the force reduction was the ratio of ultrasonic velocity to cutting speed. With increasing ratios of the two velocities the cutting force did always decrease. This is founded in the different dominant separation mechanism in the machining zone.

The influence of ultrasonic vibrations on machining precision will be one topic of further examinations. For this purpose the relation of removed material and the process forces will be examined under varying parameter settings. This will increase the understanding of the complex interdependencies in ultrasonically assisted machining of stone. The influence of process forces on the vibration characteristics of the ultrasonic system will be another topic.

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