Vibration-Assisted Machining Research at Fraunhofer IPT – Diamond Turning and Precision Grinding

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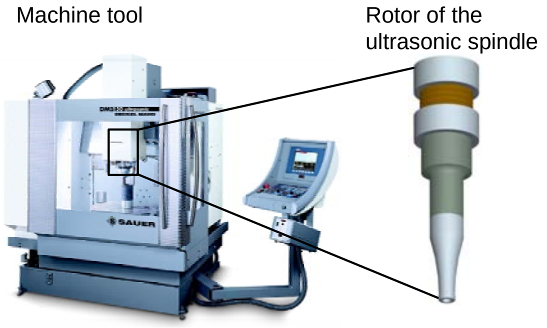
INTRODUCTION

First investigations on ultrasonic assisted grinding were published in 1956 by Colwell [1] and on ultrasonic assisted turning in 1964 by Dohmen [2]. Since then a lot of approaches were made regarding oscillation assisted manufacturing processes. Either the tool or the workpiece were superimposed with an ultrasonic oscillation. All these approaches showed significant advantages regarding reduction of tool wear for ultrasonic assisted turning and achievable surface qualities [3, 4, 8] or reduction of process forces regarding ultrasonic assisted grinding [5, 6, 7].

Nevertheless, most of these results were gathered through experimental setups, which were not capable for batch production. Developments in the past concentrated on the transfer of the gained know-how to industrial applications. In case of ultrasonic assisted grinding robust machine systems for form flexible manufacturing of hard and brittle materials, from Dama Technologies AG, Sauer GmbH, Sonic-Mill® etc., are available since the 90s of last century. These machine tools opened new application areas and markets for ultrasonic assisted grinding. Furthermore, workpieces with complex geometries (e.g. double curved or even free form surfaces) in hard and brittle materials could be machined for the first time. In case of ultrasonic assisted turning Fraunhofer IPT developed within several public funded research projects machine systems for process stable ultrasonic assisted turning. These systems were integrated on precision turning machines. These integrated systems enable process stable ultra-precision machining of glass and ferrous materials by defined cutting edge with mono-crystalline diamond.

ULTRASONIC ASSISTED GRINDING

For the investigations on ultrasonic assisted grinding Fraunhofer IPT owns the ultrasonic assisted grinding machine DMS50 ultrasonic from the company Sauer GmbH (FIGURE 1). This machine tool is based on a conventional NC-controlled three axes milling machine, with perpendicular axes. The lengths of the guideways are x = 500 mm, y = 400 mm and z = 400 mm. The drives allow a maximum feed rate of v_f = 5 000 mm/min. Furthermore, the machine tool features two manual rotational axes (b and c), which are not NC-controlled and can be used for workpiece alignment.



Source: Sauer GmbH

FIGURE 1. Ultrasonic assisted grinding machine DMS50 ultrasonic from Sauer GmbH.

The ultrasonic system consists of the oscillation assisted spindle and the generator (FIGURE 2). The generator sends electrical high frequency signals to the piezo crystals, which are part of the rotor of the spindle. The piezoelectric elements transform the electrical energy into mechanical vibration. These are transmitted to the booster and the sonotrode, which clamps the grinding tool. The booster as well as the sonotrode amplify the mechanical oscillation due to the reason, that the piezo crystal is just able to generate a maximum ultrasonic amplitude of A = 5 µm (= oscillation width S = 10 µm), but more than A = 10 µm are needed at the tip of the grinding tool. The whole rotor oscillates in its longitudinal harmonic oscillation with approximately f = 20 kHz. This means that the active rotating part of the grinding tool can oscillate axially with A = 5 to 25 µm ultrasonic amplitude and a frequency of f ~ 20 kHz.

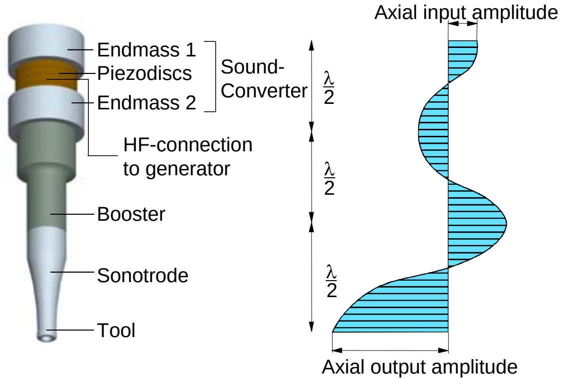


FIGURE 2. Configuration of the rotor of an ultrasonic assisted grinding spindle.

The results, which are described in the following, were gained within a public funded research project. This project aims on the economical rough grinding of spherical glass lenses by ultrasonic assisted rotational side grinding (FIGURE 3). The kinematics allows fast and precise machining of spherical shapes through a linear movement of the grinding tool and an angle between the rotational axes of the grinding tool and the rotating workpiece.

To integrate this kinematics in the DMS50 ultrasonic a rotary table was installed. This table is able to overlay the glass lens with a rotational speed up to $n_w = 550\ \text{min}^{-1}$. Furthermore, a coordinate transformation was implemented in the NC-control unit to enable an easy feed movement of the grinding tool parallel to the rotational axes of the workpiece. Additional, a force measurement device from Kistler was mounted between the machine table and the rotary table. This allows the measure of process forces acting between the workpiece and the grinding tool. Using a measuring computer the acting process forces could be visualized in real time, to enable fast and direct optimization of the process.

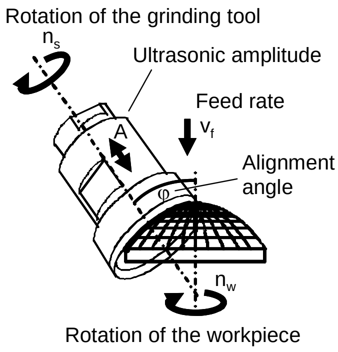


FIGURE 3. Kinematics of ultrasonic assisted side grinding of spherical glass lenses.

For the investigations the optical glass N-BK7 was machined. Besides the influence of process parameters feed rate v_f, rotational speed of the grinding tool n_s and rotational speed of the workpiece n_w the content of the investigations was focused on the influence of the ultrasonic oscillation and the tool specification on the process force and on the tool wear.

It could be shown that activation of ultrasonic assistance with increased ultrasonic amplitude leads to significant reduction of process forces. In most cases maximum achievable material removal rate (MMR) is limited by a maximum process force (F_{max}) to avoid damage of the grinding wheel, machine tool or the workpiece. Therefore, reduction of process forces due to ultrasonic oscillation can be used to increase feed rate v_f respectively material removal rate (FIGURE 4).

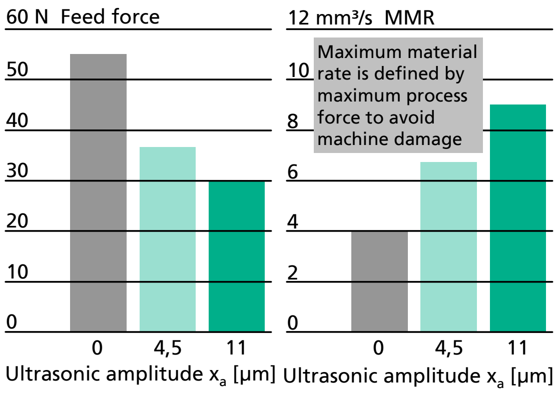


FIGURE 4. Influence of ultrasonic amplitude on feed force and on achievable MMR.

The reduction of mean process forces can be explained by effects on both the workpiece and the grinding tool. On the one hand due to the oscillation micro cracks are generated into the subsurface region of the workpiece. Investigations on subsurface damage showed that the SSD-value of a conventional ground lens is ~ 20 µm (feed rate $v_f = 4$ mm/min, cutting speed $v_c = 14$ m/s, rotational speed of the workpiece $n_w = 500$ min^{-1}, average diamond size D = 46 µm). By activation of ultrasonic oscillation to an amplitude of A ~ 5 µm a SSD-value of ~ 26 µm and to amplitude of A ~ 12 µm a SSD-value of ~ 31 µm could be observed. These micro cracks weaken the workpiece material and reduce its resistance to be removed by the rotation of the grinding tool. On the other hand ultrasonic oscillation leads to slivering at the diamonds of the grinding tool. SEM-pictures of used grinding wheels showed clearly diamond grains with slivered areas. This behavior leads to a sharp tool and therefore lower process forces. Furthermore, it is easier to achieve self-sharpening mode in comparison to a conventional process. Nevertheless, ultrasonic oscillation increases significantly tool wear.

Reduction of process forces and increase of tool wear due to ultrasonic oscillation can be decisively influenced by grinding tool specifications. As stated above ultrasonic oscillation leads predominantly to brittle wear mechanisms at the diamond grains. The overall impulsive load by virtue of ultrasonic oscillation is spread on all active diamond grains. By increasing the number of active grains through raised diamond grain concentration the load on each grain is decreased. Furthermore, a reduction of bonding hardness usually leads to a higher elasticity. Therefore, the whole tool can be deformed stronger due to ultrasonic oscillation and the overall load is decreased. Both variations of grinding tool specifications lead to less load on the diamond grains and therefore less appearance of brittle wear of the diamonds. This results in a lower cutting ability and consequently in higher process forces, because the probability of brittle wear mechanism at the diamond grains as well as self-sharpening mode is reduced. Nevertheless, tool wear is much lower (TABLE 1). Thus, grinding tools with low grain concentration and high bonding hardness should be used for roughing and grinding tools with high grain concentration and low bonding hardness for finishing.

	Process force	Tool wear
Increase of bonding hardness	↘	↗
Reduction of diamond grain concentration	↘	↗

TABLE 1. Influence of bonding hardness and of diamond grain concentration on process force and on tool wear

Ultrasonic assisted grinding offers a wide range of advantages like reduced process forces or increased maximum material removal rate. Nevertheless, increased subsurface damage as well as increased tool wear have to be taken into consideration. But adapted process strategies can take advantage of increased productivity without suffering the disadvantages.

ULTRASONIC ASSISTED TURNING

Compared to the described vibrational assisted rotating grinding tools the ultrasonic assisted turning technology works with a fixed transducer. On top of the mounted sonotrode and booster system a mono-crystalline diamond tool tip is clamped. As written before the aim is to utilize mono-crystalline diamond tools for the manufacture of ultra-precise hardened steel parts, which can be applied for injection molding of plastics or precision molding of glass optics. Usually the diamond tip underlies excessive tool wear while machining ferrous materials due to the affinity of carbon (tool) and iron (workpiece).

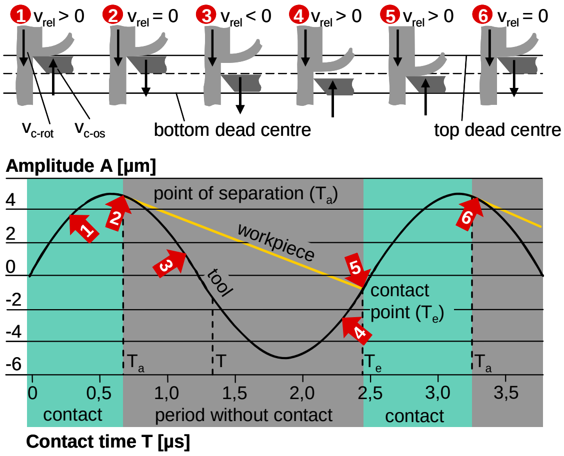


FIGURE 5. Kinematics of US assisted process.

In several publications it was shown that the diamond tool wear can be reduced by the superimposed vibration. This was applied for the first time by Moriwaki for ultra-precision machining purposes [2, 3].

Two different principles of tool vibrations are known, whereas one works with elliptical [3] and the other one with unidirectional [4, 8] tool movement. In this paper the results are shown for the unidirectional tool movement. The vibration acts here in cutting direction as shown in FIGURE 5.

It is essential for the transition from the conventional to the vibration-assisted process, that the maximum oscillation speed reached in the zero-crossing, is bigger than the constant workpiece speed (FIGURE 5). Only when this condition is met the tool does detach itself from the chip during the downward motion (Point 2, relative speed $v_{rel} = 0$). The contact occurs again during the upward motion after the vibrational direction has changed at the lower dead center (Point 5).

Accordingly, the effective contact time between the part and the cutting edge is reduced by the high frequency excitation of the tool. As previously demonstrated, this modification in the kinematics of the turning process has a considerable impact on the efficiency of ultra-precision operations conducted on critical materials such as steel or glass [8]. The positive characteristics of this technology are

- reduction of effective contact duration between tool and workpiece,
- decrease of average process forces
- better inflow of coolant for a decreased cutting temperature and
- reduced friction.

This all leads to a reduction of tool wear as well as an improved ductile cut.

The relationships shown, permit mathematical interrelationships to be derived for the exact calculation of time, position and speed of the workpiece (s_{rot}, $v_{c\text{-}rot}$) and of the tool (s_{os}, $v_{c\text{-}os}$) as well as of the associated relative values (v_{rel}). The derivation of the mathematical relationships illustrates the complex kinematics correlations involved in vibration-assisted machining. It is evident that the variables of vibration amplitude and vibration frequency, used to describe the tool movement, are closely related to the parameters rotational speed n, and workpiece radius r, which determine the cutting speed in conventional turning operations.

In accordance with the description of the operating cycle, the cutting speed in the machining zone $v_{c\text{-}rel}$, is dependent not only on the workpiece motion caused by the spindle rotation, but also on the oscillation of the tool (see FIGURE 5):

$$v_{c\text{-}rel}(t) = v_c = v_{c-rot} + v_{c\text{-}os} \tag{1}$$

Rübenach tried to determine the exact times regarding the contact Te and separation Ta of workpiece and tool. His calculations showed that a complete analytical solution is not possible due to occurring transcendent equations [8]. However he could derive the parameters which have the greatest influence on the process:

- entrance duration ED: relative contact time between workpiece and tool within one vibrational cycle and
- entrance speed v_{in}: relative velocity between workpiece and tool in the moment of contact $v_{c,rel}(t{=}Te)$.

However, these parameters have to be transformed into set-up parameters for the workpiece speed $v_{c,rot}$ and amplitude A of the ultrasonic transducer. The relationship between parameters was derived numerically and its results are illustrated in FIGURE 6.

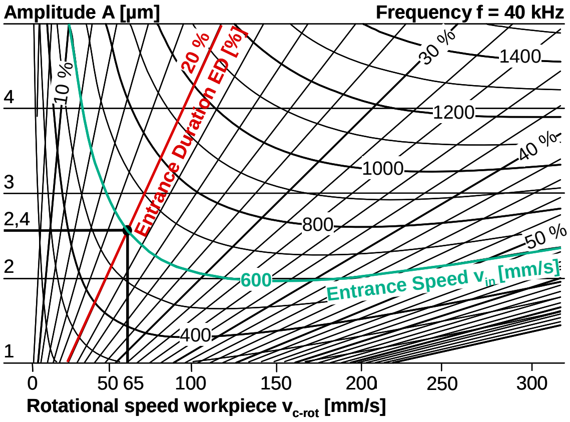


FIGURE 6. Field of parameters for f = 40 kHz for the ultrasonic assisted turning process.

Exemplarily a point is shown with an entrance duration of ED = 20% and a entrance speed v_{in} = 600 mm/s which leads to a rotational speed

$v_{c,rot}$ of 65 mm/s and tool amplitude A = 2,5 µm. This parameter set was chosen as a starting point for the test series.

Beside the theoretical derivation of appropriate parameters several successful machining tests were conducted on different glass materials by Rübenach [8].

The results shown here are related to the ultrasonic turning of plane hardened steel cylinders with a diameter of D = 22 mm. The ultrasonic tool system was mount on an ultra-precision lathe from the company Rank Pneumo. The applied steel material is the commonly known mold and die steel 1.2083 (STAVAX® ESU, X42Cr13) which was hardened and annealed in four discrete configurations (35, 40, 45, 53 HRC).

The conducted machining tests focused on the variation of classical machining parameters like depth of cut a_p and feed rate f. Furthermore, an investigation of the influence of the derived kinematical parameters entrance duration ED and entrance speed v_{in} is mandatory to characterize the process in detail.

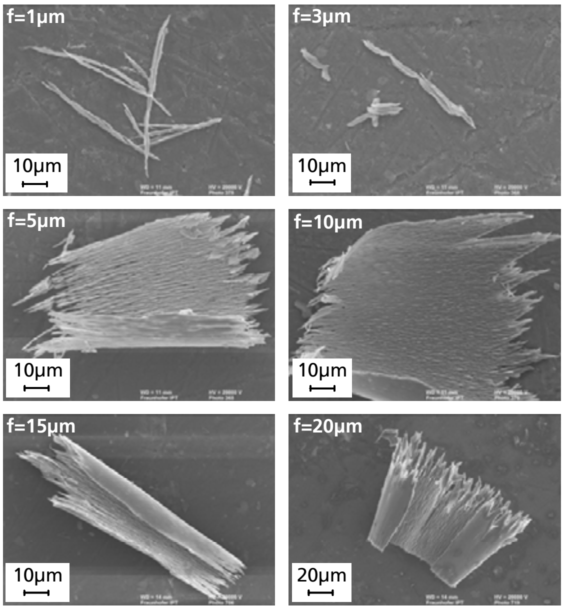


FIGURE 7. Chip formation at varying feed rates (workpiece hardness: 45 HRC).

The discrete variation of the depth of cut a_p = 1, 3, 5, 10 µm (f = 5 µm) and feed rate f = 1, 3, 5, 10, 15, 20 µm (a_p = 5 µm) could show that the results are comparable to classical ultra-precision machining of non ferrous materials. In detail, the depth of cut and the various material hardness have no significant influence on the reachable surface roughness Ra, which is in a range of Ra = 6 - 10 nm. In opposite to these results the variation of the feed rate f has considerable influence on the surface roughness which was for all material configurations at Ra < 10 nm at feed rates between f = 5 - 10 µm. Below and above these feed rates classical effects like the »size effect« respectively the kinematical roughness $R_{t,theo}$ affected the roughness negatively. Additionally, the achievable surface roughness tends to decrease in quality at higher material hardness.

The chips which were collected during the test series (FIGURE 7) show classical sawtooth geometry for a feed rate greater than f = 3 µm which are commonly known from the high precision hard turning process with cubic boron nitride (cBN) tools. Usually this chip form is generated for a material hardness above 50 HRC and is caused by the low material deformation capability – at lower material hardness a continuous chip is generated. Due to the intermitting cut of the ultrasonic tool vibration the sawtooth chip is generated at lower material hardness. The backside of the chips look smooth which indicates the ductile cut. Furthermore, it can be clearly seen that the chip segments coil up at higher feed rates due to the higher energy input. At low feed rates f < 5 µm the generated needle chips experience a lower energy input and thus a typical welded zone between the chip segments can not be generated which is characteristic for saw tooth chips.

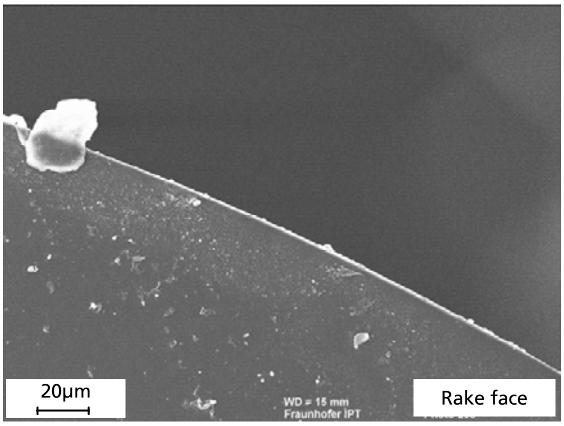


FIGURE 8. Cutting edge after 400 m length of turning (f = 1 µm, material hardness 45 HRC).

Considering the diamond tool wear it can be stated that the tool wear after a turning length of l = 400 m (f = 1 µm at D = 22 mm) was not detectable with a scanning electron microscope (SEM). Except some adhering workpiece particles could be found on the rake face (FIGURE 8).

The following results show the variation of the ultrasonic specific parameters entrance duration ED and entrance speed v_{in}. The discrete variation of the entrance duration ED = 20, 30, 50 % (v_{in} = 600 mm/s, f = 5 µm, a_p = 5 µm) show a significant influence.

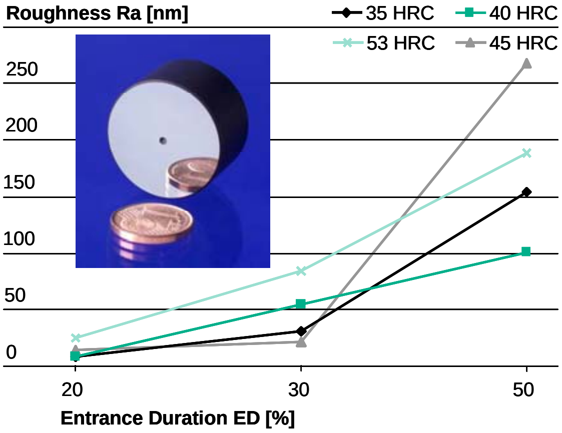


FIGURE 9. Influence of ED on Ra.

At higher entrance durations the quality of the achieved surface roughness decreases (FIGURE 9). One reason for this effect can be seen in the kinematics of the process. A higher entrance duration ED can be adjusted by higher rotational speed $v_{c,rot}$ with a minor decrease of the amplitude (FIGURE 6). This implies a faster transit of one workpiece point through the vibration zone of the tool. Thus, at lower entrance durations a workpiece point can be machined twice or three times per workpiece revolution. In contrast at higher entrance durations a workpiece point is machined once per revolution. Combined with the effect of radial vibrations of the tool, caused by the axial contraction and expansion of the sonotrode, the workpiece surface quality will decrease. In contrast, if a workpiece point is machined twice or three times the generated kinematical roughness will be smoothed. Additionally, a second effect occurs. The tool wear, which is at low entrance durations justifiable by diffusion and oxidation (no chipping or abrasion) is at higher entrance durations justifiable by abrasion and chipping. The discrete variation of the entrance speed v_{in} = 400, 600, 700, 800 mm/s had no significant influence on the achieved surface roughness. A ductile cut with a roughness of Ra = 5 - 15 nm occurred for all speeds. However, a further increase (test have to be conducted) presumably will show a higher surface roughness and a non ductile cutting behavior.

One of the most neglected parameters for the ultrasonic assisted turning technology is the tool frequency. All in the literature known investigations have been performed with 20 or 40 kHz. Higher frequencies have not been considered yet. The Fraunhofer IPT developed in co-operation with industrial partners a new ultrasonic tool device, which can work at f = 60 kHz in the unidirectional mode. The advantages are discussed here theoretically and will be verified in future machining tests. As explained above the unidirectional excitation of the tool causes vibrations which are orthogonal to the axis of the sonotrode. These undesirable vibrations work directly in passive direction of the tool and thus into the surface of the workpiece which leads to lower surface qualities. The reason for this behavior can be seen in the assumed volume constancy of the sonotrode during the vibration, which leads also to a contraction and expansion of the sonotrode in radial direction. The new 60 kHz transducer was developed with the aim to minimize the radial sonotrode vibrations.

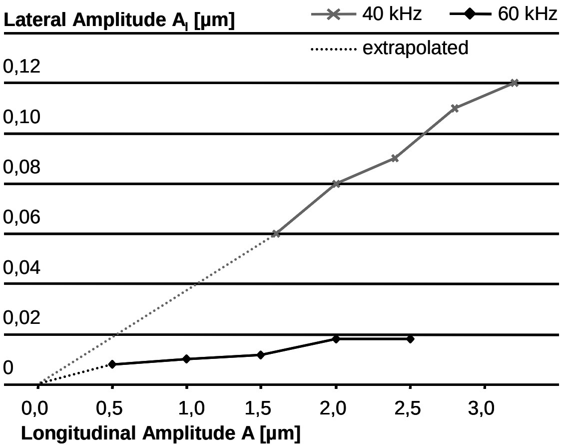


FIGURE 10. Comparison of lateral vibrations between new developed 60 kHz and current 40 kHz transducer.

A comparison of the radial sonotrode vibration of the current (40 kHz) and new System (60 kHz) is shown in FIGURE 10.

The vibrations were measured with a non tactile capacitive Sensor. Obviously the radial sonotrode vibrations are significant (factor 4) lower for the 60 kHz system which should have a positive influence on the workpiece roughness.

However, beside the dynamical considerations an increase of frequency leads to new kinematical boundary conditions.

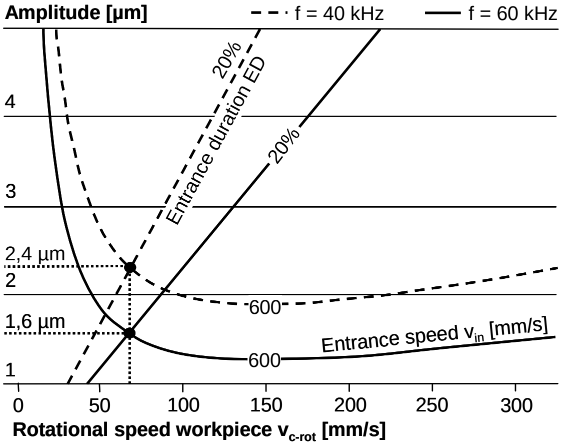


FIGURE 11. Comparison of 40 kHz and 60 kHz parameter field for equal working points.

Figure 11 illustrates the influence on the parameter field for an increased frequency. Considering equal working points for 40 kHz and 60 kHz (ED = 20%, v_{in} = 600 mm/s) leads to a decrease of 33% in amplitude for the higher frequency of 60 kHz. Thus, this effect will also lead to an additional decrease of radial sonotrode vibrations.

Finally it can be stated that the superposition of the general lower radial amplitude of the 60 kHz transducer and the decreased working amplitude will presumably lead to better surface qualities.

SUMMARY AND CONCLUSION

The potential for ultrasonic assisted tools with undefined and defined cutting edges is shown for grinding and turning, whereas the cutting mechanisms are different.

Ultrasonic assistance for grinding tools is applied to exceed the fracture toughness and thus to induce cracks in the workpiece material. This effect can be used to increase maximum material removal rate or to lower process forces compared to a conventional grinding process at comparable process parameters. Beside the advantages unfortunately the SSD is higher for the ultrasonic assistance which has to be taken into consideration of the process strategy's design.

Ultrasonic assistance for ultra-precision turning is applied to decrease the excessive diamond tool wear for ductile machining of hardened steel. The kinematical consideration is the key to achieve appropriate surface conditions as well as reduced tool wear. The investigations show that the conventional parameters like depth of cut a_p and feed rate f lead to similar results compared to conventional ultra-precision machining. However, a consideration of the kinematical parameters entrance duration ED and entrance speed v_{in} is likewise mandatory and show the massive influence of the entrance duration ED regarding the surface roughness.

Theoretical investigations show also the potential of higher frequencies for the ultrasonic assisted turning process.

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