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INDIRECT APPROACH TO ULTRASONIC SUPERPOSITION IN MICRO-EDM

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ABSTRACT

Micro Electro Discharge Machining is a well known process for machining microstructures with highest precision in hard and brittle or tough materials. The deeper the structures and therefore higher the aspect ratio, the more difficult it is to remove the ablated particles from the discharge zone and keep the process in stable condition. Flushing can be aided by vibration of either tool or workpiece. Thus, applying ultrasonic vibration to micro EDM has proven to enhance the process significantly. The vibration is most efficiently induced via the tool or workpiece directly to the discharge zone. However, to achieve an ultrasonic vibration of the tool or workpiece, a complex vibration system that operates in resonant mode is needed. Any crucial change of the vibrating parts results in a demanding and therefore expensive adjustment of the vibrating system. With this setup, the application of ultrasonic vibration is only profitable for large scale serial production. In this work a different approach of ultrasonic superposition to the EDM is proposed. A highly focused ultrasonic vibration is induced into the dielectric in a way to directly influence the discharge zone. This indirect ultrasonic superposition can be easily applied since it is independent of the tool or workpiece geometry. Experiments are carried out to examine the effects of the indirect ultrasonic superposition on the EDM process. First results show the possibility of enhancing micro-EDM by this approach.

INTRODUCTION

Due to its nature of ablating material through electrical discharges between tool and workpiece, Electro Discharge Machining (EDM) allows a noncontact machining of electrically conductive materials. The process is ideal to machine hard to cut materials of workpieces or structures with high aspect ratios. Because of the almost force free process, EDM is ideally suited for micromachining, since factors like the fragility of tool or workpiece are neglectable [1].

The principle of ED machining is ablating material from the workpiece until the required shape is achieved. The ablation is caused by repeated very short electrical discharges between two electrodes, tool and workpiece, which lead to a melting and vaporization of electrode material. The discharges take place in the working gap between tool and workpiece, which is filled with a dielectric fluid, mostly deionized water or dielectric oil. The molten and vaporized electrode material is flushed away by the dielectric. The discharges occur when the intensity of the electric field is higher than the dielectric strength and therefore lead to a breakdown. The dielectric strength is influenced by many factors, e.g. the local temperature or pollution of the dielectric by the debris. The EDM process itself will influence the dielectric strength locally by enriching the dielectric with ablated particles and heating it up locally by the discharges that occur. Without proper flushing, this can lead to unwanted arc discharges or geometrical errors due to locally decreased dielectric strength and make the EDM process unstable. The instability is one key obstacle of the EDM, especially in the field of micro EDM and the machining of structures with high aspect ratios, where flushing is difficult. For high precision, the need for constant dielectric conditions is high [2].

A homogeneous dielectric guarantees for a stable process and precise ablation of the structures that are machined. To achieve this homogenization, different approaches, for example electrode rotation, planetary motion and internal flushing have proven to enhance the process significantly [2-5], but are limited when using very small tool electrodes.

The superposition of the EDM with ultrasonic vibration is another strategy which improves the process speed, stability and range of machinable structures [3, 4, 6]. The ultrasonic vibration is for highest efficiency directly induced via a vibrating tool or workpiece. This approach has many advances, e.g.:

- the vibration is directly applied to the working zone
- a constant flushing is achieved [8]
- the changing of the gap size between tool and workpiece improves the process with regard to discharge mode and duration [9]

Beside the benefits there are some setbacks of the ultrasonic vibration of the tool or workpiece. Although the amplitudes are only within micrometer range, the high frequencies of 20 kHz and above can only be achieved by a large energy consumption of the vibrating system or a resonant vibration. Any major change of the vibration system, respective tool or workpiece, is therefore demanding for a new analysis of resonance modes and frequencies, adaption of transducers or sonotrodes or, in the worst case, modification of the frequency generator, which is as time consuming as expensive. This work shows a different approach to induce ultrasonic vibration into the EDM process namely into the dielectric, which makes it much easier to apply. It has already been proven that by this approach the achievable aspect ratio can be raised significantly [3]. Whereas often unfocused ultrasonic via vibrating basin walls as in cleaning baths is used, in this study a high-energy, focused system comprising of rod shaped sonotrodes with high amplitudes of up to 100µm peak-peak is chosen. The ultrasonic system that is used is commonly applied for mixing and stirring of liquids or for decomposition of cells for biological analysis. It provides a focused and dense ultrasonic vibration. This allows for ultrasonic superposition which can be precisely orientated to the working zone of the ED-machining process.

In Fig. 1 the different types of the ultrasonic superposition are shown. While the direct superposition needs a vibrating tool or workpiece (a), the indirect superposition can be achieved by an independent sonotrode, making this approach easier to apply (b). The idea is that the ultrasonic vibration is transduced to the working zone by reflection and bending effects of the sound waves. The key aspects that are investigated in this work are the effects of the ultrasonic superposition on processing time and the geometrical accuracy of the created structures.

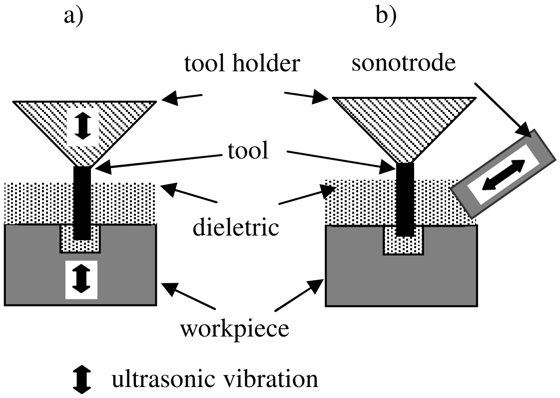


Fig. 1: a) direct and b) indirect ultrasonic superposition

ULTRASONIC PHENOMENA AND THE EDM PROCESS

Although the advantages through ultrasonic superposition have been proven, the effects that lead to those enhancements are not fully understood.

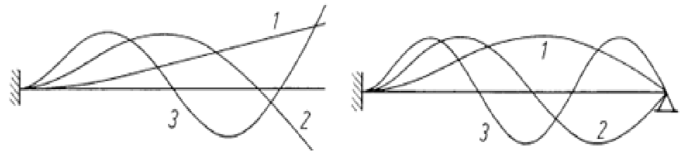
In EDM, the constant creation of ablation particles is contaminating the dielectric, leading to process instabilities, which are minimized by the homogenisation of the ultrasonic vibration [3, 6]. Ultrasonic vibration is used in many cases to homogenise solutions. In EDM, the ultrasonic vibration leads to high velocities in the dielectric, which will change in their direction, bound to the high frequencies of the vibrations. In the following experiments the ultrasonic vibration that is induced leads to velocities of the dielectric that are expected to reach speeds up to 3.4m/s at the tip of the sonotrode that is inducing the vibration. This will lead to intense movements within the dielectric resulting in a strong homogenisation.

Another benefit of the ultrasonic vibration to the EDM process is caused by the changing of the pressure of the dielectric which even leads to cavitation. Cavitation is a phenomenon caused by a cluster of gas bubbles within a liquid. They are generated by a pressure decrease below the vapour pressure of the liquid, leading to a local vaporisation. The local pressure change is caused by the inertia of the dielectric in relation to the high-frequency ultrasonic vibration of the sonotrode. Two effects of the changing pressure on the EDM-process are particularly to be considered.

First of all, the pressure change effects the creation of the discharge and the ablation process. Gas bubbles of the cavitation phenomena are changing the dielectric strength locally. A change of dielectric strength within the working gap caused by cavitation is therefore affecting the creation of discharges. In the case of a pressure drop the evaporation temperature of the electrode material is reduced which leads to a rising amount of evaporated material and therefore an enhancement of the ablation process. Due to the high velocities of the dielectric induced by the ultrasonic vibration, the transport of the ablated material is enhanced, too. Those effects are the opposite in the case of a rise of the pressure. To utilize the effect of the pressure changes on the discharges efficiently, a synchronisation between the ultrasonic vibration and the discharge frequency is beneficial [7].

The second effect of the ultrasonic superposition is caused by the cleaning of the working gap through the cavitation phenomenon. Cavitation occurs much easier when the homogeneity of the liquid is defected by particles. Through the EDM process ablation particles and therefore defects are created which are concentrated within the working gap. Therefore cavitation occurs more likely in the working gap because of the steady output of ablation particles. The gas bubbles of the cavitation phenomenon can become stable gas bubbles, rise and create a stream that flushes particles out of the working gap [3].

When applying indirect ultrasonic superposition, it has to be considered that, because of the orientation of the sonotrode non-coaxial to the feed direction, the tool electrode is also subject to excitation through the pressure waves within the dielectric. Especially in the case of a vibration in the eigenfrequencies of the tool, electrode resonance movement can adversely affect the process. Therefore, this frequency range has to be avoided. For the setup that is used throughout the experiments, two different cases of resonant vibration of the tool electrode have to be considered. The tool electrode is clamped in a collet. Therefore, one side of the tool electrode can be considered as fixed in a solid bearing (case a). When a bore is created, the tool electrode will be forwarded into the bore by the feed system.



a) b)

Fig. 2: eigenforms of a beam a) with solid bearing and free end b) solid bearing and non-locating bearing

When the tool electrode tip is located inside the hole, the thin film of dielectric between the tool tip and the workpiece creates a non-locating bearing, while the other end is still clamped by the collet (case b). With the forwarding of the collet and therefore the tool into the workpiece, the free length of the tool changes, too. To minimize the effort of the analysis, the first step is to check for extreme values. The considered cases of resonance and the first three according eigenforms can be seen in Fig. 2.

In this work, the tools are rods made out of tungsten carbide. The geometrical and material characteristics of the tool electrode can be seen in Table 1.

density [g/cm³]	Young's modulus [kN/mm²]	diameter [µm]	free length [mm]
14.8	630	150	5

Table 1: characteristics of the tool electrode for the vibration analysis

With the values shown in Table 1, the eigenfrequencies for both investigated cases can be seen in Table 2.

eigenfrequencies [kHz]			
	λ1	λ2	λ3
case a	17.4	108.3	303.5
case b	56.6	246.2	513.4

Table 2: resonance frequencies of the tool electrode

The calculated frequencies are partly in the same magnitude as the ultrasonic vibration frequency (f_{us}=24kHz) that is used in the experiments. Especially the first resonant frequency of case a) is critical because it is below the frequency of the ultrasonic vibration. When the process starts to drill the hole, the free length of the tool electrode is reduced. The feed of the tool electrode into the created bore alters the electrode bearing from case a) to case b). Both changes influence the tool electrode, resulting in a rise of the resonance frequency and therefore increasing the probability of a resonant vibration until an eigenfrequency which is distinct above the ultrasonic frequency is reached. A resonant vibration of the tool electrode leads to a measurable enlargement of the created structures. Thus, to reveal any resonant vibration of the tool electrode, the dimensions of all manufactured structures are measured. A comparison between structures that are manufactured with ultrasonic superposition and structures that are manufactured conventionally is performed. Because of the rise of the eigenfrequencies when case b) is reached, no further analysis of the tool vibration is performed because no resonant vibration is expected when the tool is advancing deeper inside the workpiece. A resonant vibration is expected to appear at the start of the drill and therefore reveals itself in a rise of the entrance size of the machined structure.

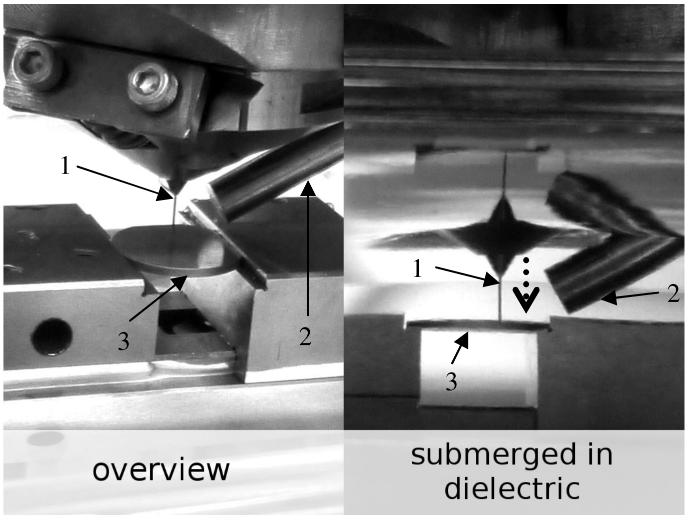
EXPERIMENTAL SETUP

The experiments are carried out using a Sarix T1-T4 micro sinking EDM machine. This machine type is equipped with a relaxation type generator. All structures that are machined during the experiments are microbores. Table 3 shows important machining parameters.

Open circuit voltage U_0	Maximum pulse current I_{max}	Discharge duration t_i	Tool electrode polarity
160V	8A	100ns	negative

Table 3: EDM – machining parameters

All bores are made as through holes. Tool electrodes with a diameter of 150µm made out of cemented tungsten carbide are used. The workpiece material is 18CrNi8. The thickness of the workpiece is 1mm.



1	collet and tool electrode
2	sonotrode
3	workpiece
⇣	feed direction

Fig. 3: setup for ultrasonic assisted micro-EDM

Deionised water is used as dielectric, which is held in a small tub surrounding the working zone. Here, the ultrasonic vibration is induced. The ultrasonic vibration is generated by an Ultrasonic transducer, see Fig. 4. The transducer is vibrating in the resonance frequency of the sonotrode at 24kHz. A sonotrode with a diameter of 5mm is used. The amplitude of the ultrasonic vibration can be altered continuously between 15µm and 45µm. Due to the fact that higher amplitudes lead to high sonotrode wear and need a thick water film in which the sonotrode can induce the vibration without hurling the water away, the amplitude level is set to 15µm (30µm peak-peak) throughout the experiments.

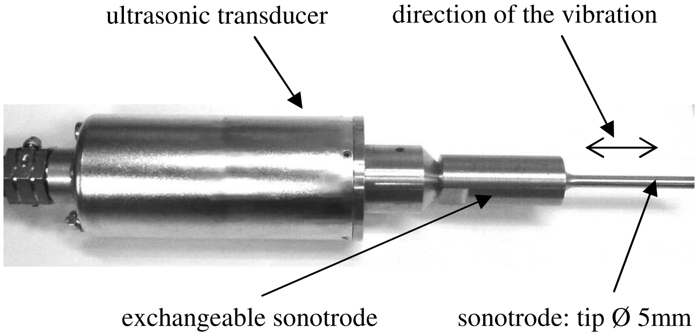


Fig. 4: ultrasonic vibration system

The ultrasonic transducer is providing a dense and focused ultrasonic irradiation. The velocities at the tip of the sonotrode create the cavitation phenomenon which can be observed as gas bubbles near the sonotrode tip. The bubbles are concentrated in a conical area starting at the tip of the sonotrode, see Fig. 5. The spread of the ultrasonic vibration allows a directed superposition of the EDM process with the ultrasonic vibration. To achieve the strongest effect of the ultrasonic vibration possible, the tip of the sonotrode is placed as close to the working zone as possible, only restricted by the machine setup.

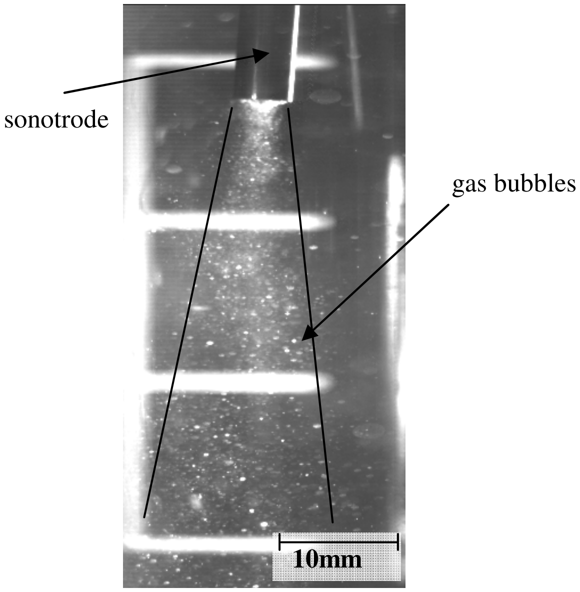


Fig. 5: sonotrode and cavitation in the dielectric

The effects of the ultrasonic vibration on process time and process stability are investigated during the experiments. To compensate the tool wear, the electrode feed is continued for further 50% of the bore depth after the bore exit is machined. Measuring the process time shows the effect of the ultrasonic on the process speed. The diameters of the entrance and exit of each bore are measured to characterize the ultrasonic effects on the geometry of the bores. An ideal cylindrical through hole has identical diameters at the entrance and exit. With the machinery available, the trough holes tend to have a bigger diameter on the entrance, see Fig. 6 and Fig. 7.

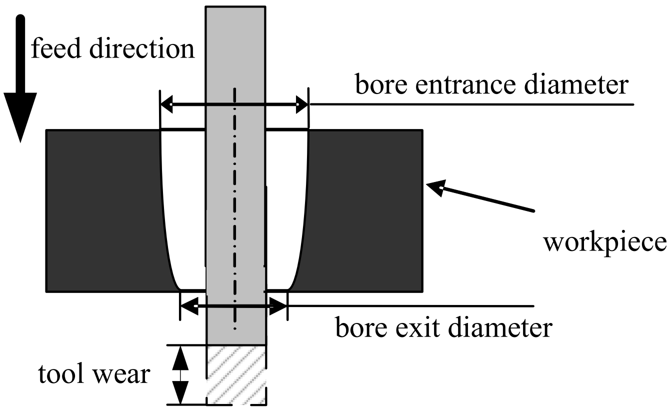


Fig. 6 schematic of the bore diameter change and tool wear compensation of the through hole boring

This can be explained by the flushing regime. Until the breakthrough the bore is a blind hole and all the ablated material must be flushed out through the entrance of the hole, resulting in bad flushing conditions and therefore a decreased dielectric strength. This leads to an increase of the lateral working gap and therefore a bigger diameter of the hole entrance. When the breakthrough is reached, the material can be flushed out through the bottom of the hole resulting in enhanced flushing conditions. Better flushing conditions result in a decrease of the working gap and therefore the diameter of the hole exit is normally smaller then the diameter of the entrance.

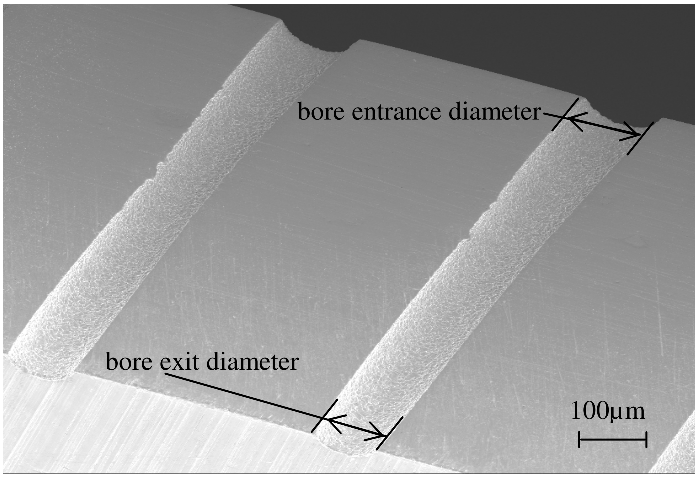


Fig. 7: example cutaway view of tapered microbores

The change of the diameter between entrance and exit, also called taper, is needed for some applications, e.g. nozzles, but because it can not be altered easily it is a major setback of the process if there is a demand for a strictly cylindrical structure without taper. Due to the fact that the taper is a result of inhomogeneities of the dielectric and bad flushing conditions, which are enhanced by the ultrasonic superposition, the change of diameters of the bores is investigated. This allows revealing the effects of the ultrasonic superposition on the dielectric homogeneity and the flushing conditions. The first experiment carried out is intended to find the ideal angle between the sonotrode and the direction of the process feed, see Fig. 8. Due to the geometrical restrictions, the lowest angle that can be examined with the current setup is 60°, while for future studies a different setup that allows for higher angles is planned.

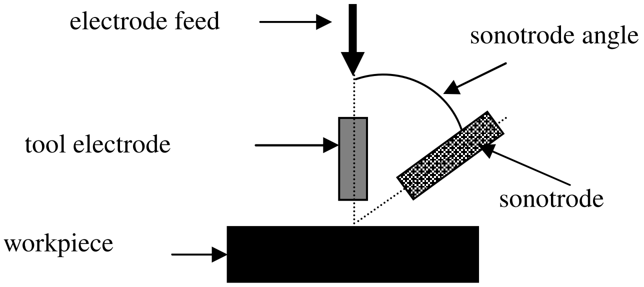


Fig. 8: angle between tool electrode and sonotrode

Fig. 9 shows that with decreasing angle the processing time is reduced. Compared to the conventional process, a reduction of machining time can only be reached when the angle is at 60°. Therefore the minimal possible angle is used for all following experiments.

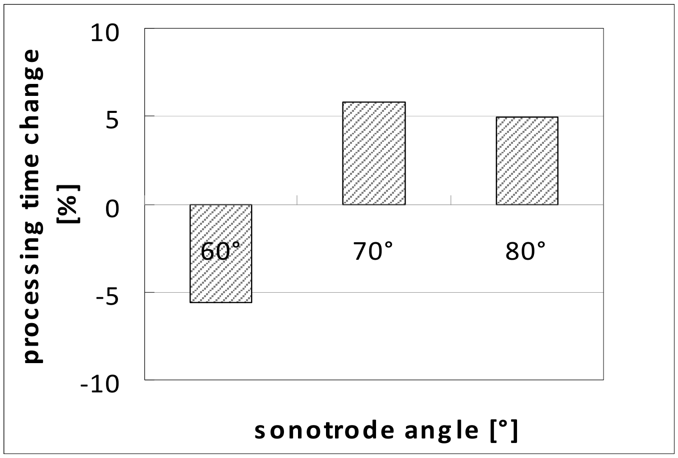


Fig. 9: processing time dependency on sonotrode angle compared to conventional machining

All machining parameters except of target working gap width and the control sensitivity are kept stable during the experiments. For each setup, 9 bores were machined. The working gap width is adjusted by the mean value of the voltage in the frontal working gap. The machine adjusts the size of the frontal gap by advancing the tool to the workpiece or drawing it back until the measured mean voltage equals the target value the user set. Since short circuits lower the average voltage and open circuits raise it, the mean voltage represents the state of the process and indirectly the width of the working gap. By reducing the target voltage value, the size of the frontal working gap is reduced. As a result, more discharges occur and the process speed is increased, although the process becomes unstable and tends to short-circuiting when the target value is too low. Two settings are chosen leading to a larger or smaller working gap size.

The control sensitivity is the second machining parameter that is altered during the experiments. It controls the speed of the adjustment of the working gap size. A higher control sensitivity leads to a faster but also more instable process due to overshooting. Four different values for the control sensitivity are under investigation, (a) to (d). When the control sensitivity is adjusted to (a), the regulation of the working gap size will be slow. The speed of regulation of the working gap rises, when its value is changed until it reaches its maximum at (d). The target value for the gap voltage and the sensitivity of regulation are both known to influence the process speed and stability. Because the ultrasonic superposition is known to enhance process speed and stability too, those parameters are varied to investigate the consequences on the process.

RESULTS AND DISCUSSION

Processing time

The process time of each bore is monitored. Mean value and standard deviation are shown for each examined parameter variant.

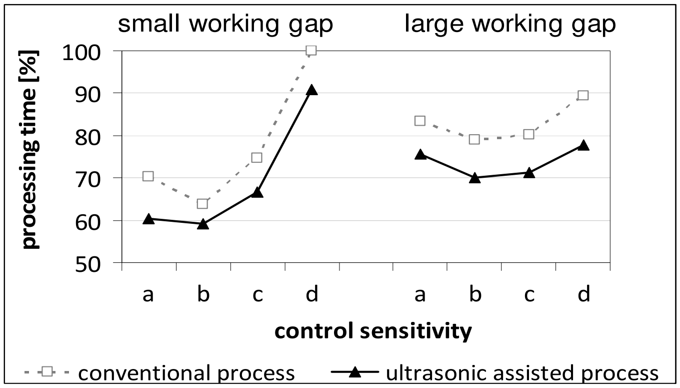


Fig. 10: influence of varied machining parameters on the processing time

All mean values of the working time are normalized to the slowest value at 100%. The processing time is reduced due to ultrasonic vibration in every case compared to the conventional process, see Fig. 10. The mean value of the reduction is 9%. The effects on the standard deviation of the processing time are not that consistent. When the working gap size is large, the ultrasonic vibration seems to stabilize the process. When the size of the working gap is reduced, which makes the process itself more instable, the standard deviation of the machining time carried out with ultrasonic superposition rises in some cases above the level of the conventional process, see Fig. 11.

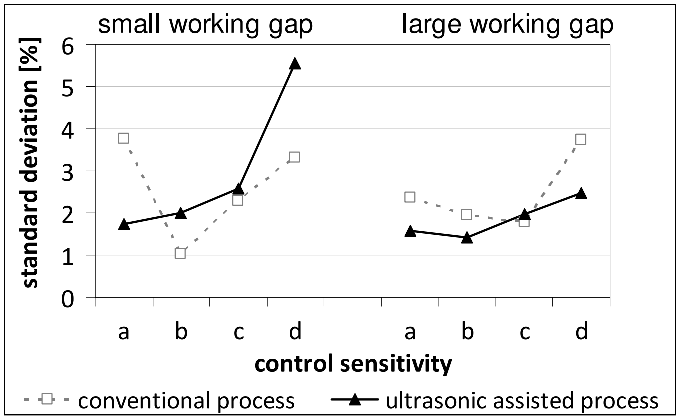


Fig. 11: influence of varied machining parameters on the standard deviation of processing time

Machined geometry

Comparing the diameters of the bores drilled by the conventional process with those drilled by the ultrasonic assisted process allows the evaluation of the influence of the ultrasonic vibration on the machined geometries and checking for a significant vibration of the tool. The mean value of both measured diameters, entrance and exit, of all bores is 181µm for those machined by the conventional process and 182µm for those that are machined by the ultrasonic assisted process. The difference between the diameters of the bores that are machined conventionally and those that are machined with ultrasonic superposition indicates that no significant electrode vibration occurred. The change of the mean diameters of entrance and exit together and therefore the amount of ablated material is insignificant. Due to the ultrasonic superposition the mean diameters of the bore entrances change from 188µm to 186 and the exit diameters from 174µm to 177µm. Especially the narrowing of the entrance diameter shows that the effect of the tool vibration can be neglected in the experiments that are carried out.

The diameters of the drilled bores as well as their standard deviations become much more independent from the variation of the machining parameters. The difference between the diameters machined by different machining parameters can be seen in Fig. 12 and Fig. 13.

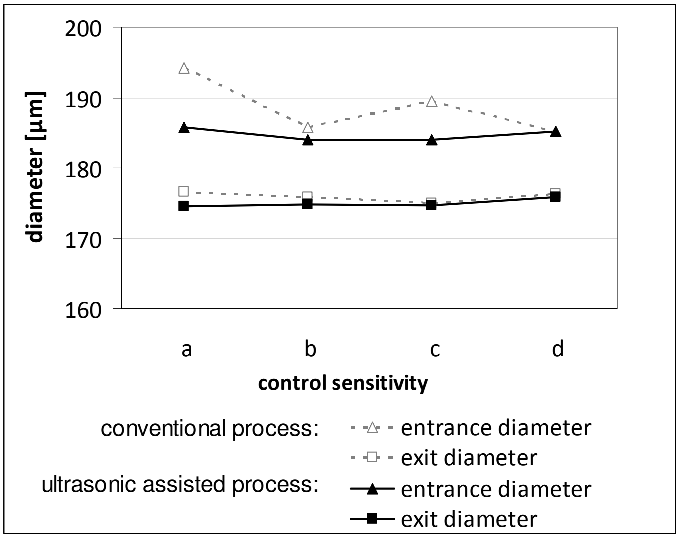


Fig. 12: bore diameters under small working gap conditions

With ultrasonic superposition, the influence of working gap size and control sensitivity on the diameters becomes almost negligible.

When working with a small working gap, especially the entrance diameters of the bores benefit from the ultrasonic superposition. Although the bores are still narrowing from entrance to the exit, this taper is reduced or unchanged and almost no influence of the control sensitivity can be noticed. The exit diameter of the bores is almost independent of control sensitivity and ultrasonic superposition.

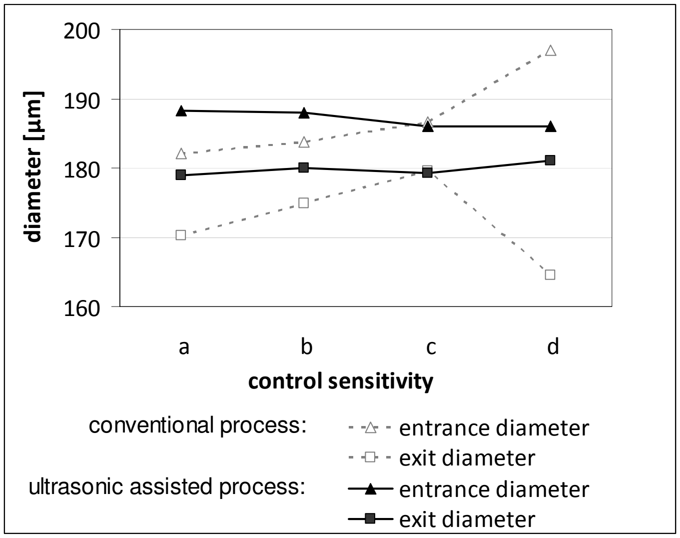


Fig. 13: bore diameters under large working gap conditions

When working with a large working gap, the entrance and the exit diameters are stabilized and again almost independent of the control sensitivity. With the larger working gap, the exit diameters of the conventionally machined bores have a dependency on the control sensitivity as well. This dependency is decisively reduced by the ultrasonic superposition. The differences between entrance and exit diameters are again reduced or unchanged, see Fig. 13.

Both varied parameters, working gap and control sensitivity, are affecting the standard deviation of the machined diameters. When the working gap is small, the standard deviation of both, entrance and exit diameters, is reduced for the process with a low control sensitivity (a and b) due to ultrasonic superposition. A higher level of the control sensitivity leads to a rise of the standard deviation of the diameters machined by the ultrasonic process, which reaches levels above the conventional process in some cases, see Fig. 14.

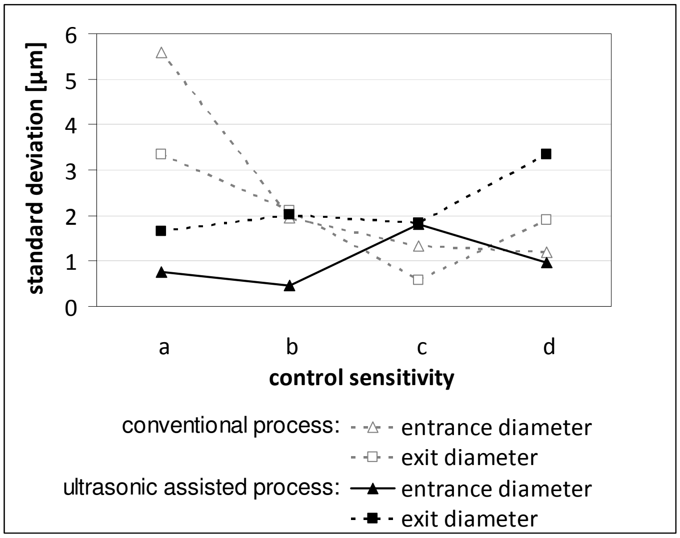


Fig. 14: standard deviation of the bore under small working gap conditions

A larger working gap leads to a rise of the diameter standard deviation of the conventional process in most cases, see Fig. 15. The change of the standard deviation of the bores machined by the ultrasonic assisted process is not that significant. With a large working gap the ultrasonic assisted process lowers the diameter standard deviation compared to the conventional process in any examined case.

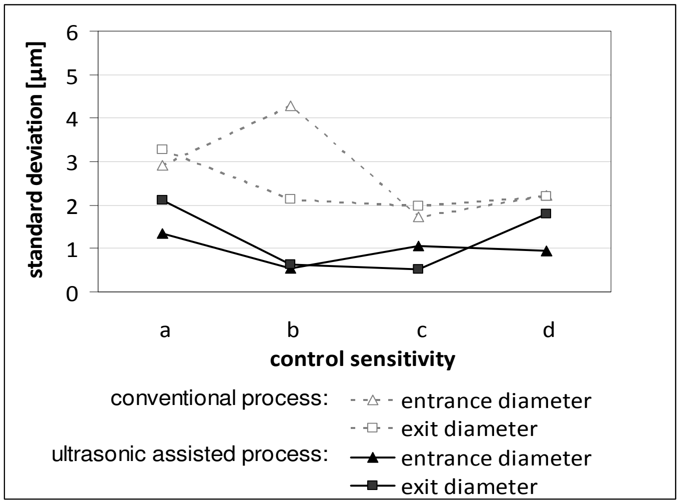


Fig. 15: standard deviation of the bore under large working gap conditions

To illustrate the effect on the hole taper, the relation between exit diameters to entrance diameters of all 144 measured bores is shown in Fig. 16. The introduction of the ultrasonic vibration reduces the discrepancy between entrance and exit diameters as well as the mean value of the standard deviation of the diameters. The approaching of the entrance and exit diameter suggests that the ablation process becomes more symmetrical due to the ultrasonic homogenization of the dielectric.

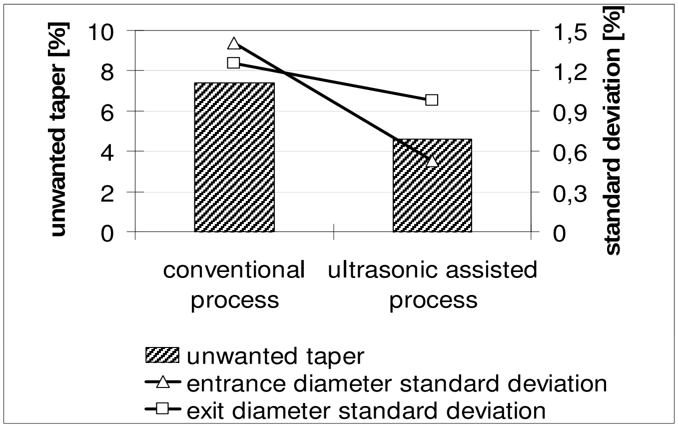


Fig. 16: reduction of unwanted taper by ultrasonic superposition

CONCLUSIONS

The work has shown the possibility of enhancing the micro EDM by indirect ultrasonic vibration. An enhancement of the process speed is achieved. The effects on the geometry of the microbores are very promising. The decrease in differences of the diameter and their variance will help to enhance the reliability of the process. Especially the fact that the achieved diameters are much more independent of the investigated process parameters reduces the need for experiments that determine the influence of parameters under different working situations dramatically. The decrease of the conicity of the bore suggests that a homogenization and cleaning of the dielectric is achieved by the indirect ultrasonic superposition, which enhances the accuracy of the machined structures as well as the process speed.

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