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Dry grinding of soft steel with use of ultrasonic vibrations

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Abstract

Compared to other machining processes, grinding involves high specific energy. A major part of this energy is transformed in to heat which have a detrimental effect on surface integrity and grinding wheel wear. In conventional dry grinding, as there are no cutting fluids to transfer the heat from the contact zone, minimizing the grinding energy and grinding forces are the matters of importance. To make a step forward to pure dry grinding a new technique, called ultrasonic assisted grinding has been used. The advantages of ultrasonic assisted grinding were proved mostly for the brittle material. Our investigations show the improvement on the surface roughness, considerable reduction of the grinding forces and thermal damage in case of using ultrasonic assisted dry grinding (UADG) comparing to conventional dry grinding (CDG) for a soft material of 42CrMo4. A decrease of up to 60-70% of normal grinding forces and up to 30-50% of tangential grinding forces has been achieved.

Keywords: Dry grinding, Ultrasonic assisted dry grinding, Grinding forces, Surface Roughness, Cutting fluids

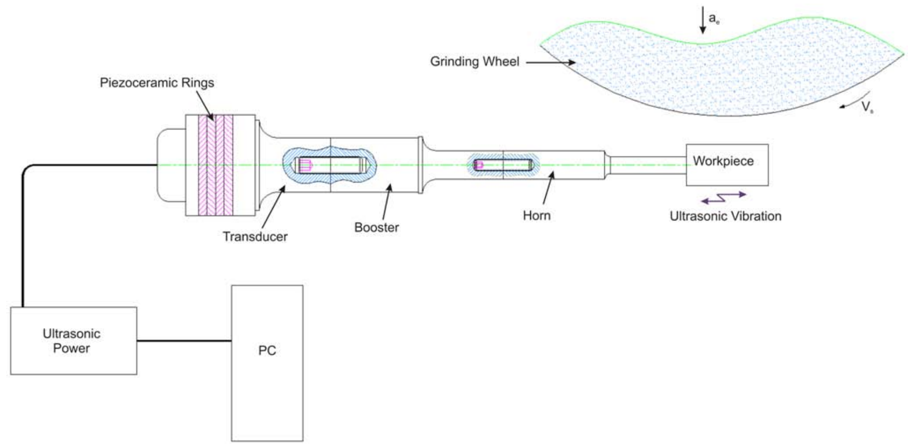
1.0 Introduction

The cutting fluids are mainly used in metal removal processes due to their effect on transmitting generated heat in the contact zone, reduction of friction in the tool-workpiece contact zone and chip transportation from the cutting area. On the other hand cutting fluids have serious disadvantages, such as health hazards and the explosiveness of oil vapor, environmental pollution, wear of the elements of the machine tool and increasing manufacturing cost. In order to decrease the negative environmental impact of the cutting fluids and reducing manufacturing costs, new machining techniques such as dry machining [1][2] are used. During grinding many of the super abrasive grits which are in contact with the workpiece do not perform real cutting, but instead generate heat by rubbing and plowing the workpiece surface in the contact zone. The high heat generation associated with a high negative rake angle and with a great contact length in grinding processes, can greatly increase the temperature in the contact zone. Without sufficient cooling and lubrication, this can cause thermal damage on the workpiece surface [3]. That is why cutting fluid is necessary in most grinding applications, and the methods of minimum grinding fluid or dry grinding have not yet been fully successful in industrial applications [4][5]. Generally in conventional dry grinding (CDG), as there is no cutting fluid to transfer the heat from the contact zone, problems frequently occur in terms of thermal damage on the workpiece surface, increasing the grinding energy and grinding forces, wear of grinding wheel, low material removal rate (regarding relatively low depth of cuts) as well as poor surface integrity compared to conventional grinding with cutting fluids. A recent and promising technique to overcome these technological constraints is known as ultrasonic assisted dry grinding (UADG). The principle of this technique is to superimpose high frequency (16–40 kHz) and low peak-to-peak (pk-pk) vibration amplitude (2–30 µm) in the feed or crossfeed direction to the tool or the workpiece. UADG is a hybrid process of CDG and ultrasonic oscillation. It is applicable to both ductile and brittle materials. By using ultrasonic assisted machining significant improvements in thrust force, burr size, material removal rate, tool wear, heat generation, noise reduction and surface finish have been reported. Zhang et al. [6] have both theoretically and experimentally concluded that there exists an optimal vibration condition such that the thrust force and torque are minimized. Takeyama and Kato [7] found that the mean thrust force in drilling can be greatly reduced under ultrasonic vibrations. Drilling chips are thinner and can be removed more easily from the drilled hole. Burr formation at the entrance and the exit sides is greatly reduced with the low cutting forces. Thus, the overall drilling quality is improved with the employment of UAD. Azarhoushang and Akbari [8] have achieved significant improvements in the circularity, cylindricity, surface roughness and hole oversize by applying ultrasonic vibration to the tool with out using any cutting fluids. Prabhakar [9] has experimentally demonstrated that the material removal rate obtained from ultrasonic assisted grinding is nearly 6-10 times higher than that from a conventional grinding process under similar conditions. Uhlmann [10] found that for ceramic materials, ultrasonic assisted grinding can be applied as an efficient production technology and the ultrasonic assisted creep feed grinding provides enormously reduced normal forces at slightly increased wheel wear and surface roughness. Tawakoli et al [11] demonstrated that in ultrasonic assisted dressing of CBN grinding wheels, considerable reduction in grinding forces and dresser wear is achievable.

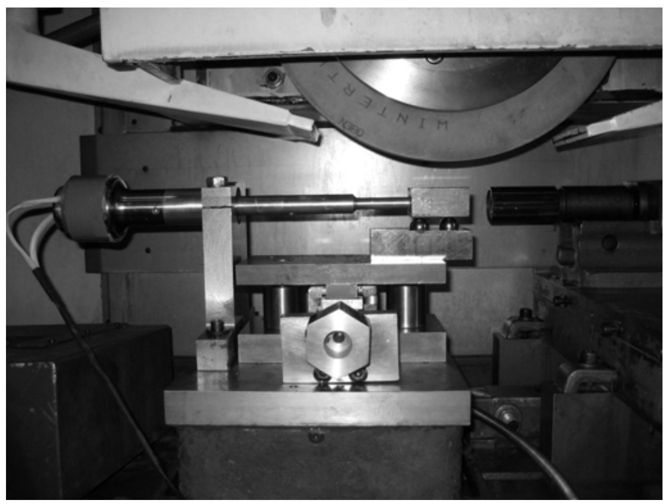
In this investigation, a UADG system has been designed, fabricated and tested. Improvements in the R_z and R_a (parameters of surface roughness) of the ground surfaces, reduction of the grinding forces and thermal damages on the ground surface due to superimposing of ultrasonic vibration in the dry grinding of 42CrMo4 have been achieved. The effect of vibration amplitude, feed speed and depth of cut on surface roughness and the grinding forces have been investigated.

2.0 Experimental setup and procedures

Fig. 1a illustrates schematically the experimental set-up. The workpiece holder consists of a piezoelectric transducer, a booster, a horn and a special fixture. The ultrasonic power supply converts 50 Hz electrical supply to high-frequency electrical impulses. These high frequency electrical impulses are fed to a piezoelectric transducer and transformed into mechanical vibrations of ultrasonic frequency (23 kHz), due to the piezoelectric effect. The vibration amplitude is then amplified by the booster and the horn and transmitted to the workpiece attached to the horn. The resultant vibration of the workpiece fixed in the tool holder reaches 10 µm (i.e. 20 µm peak to peak) at a frequency of about 23 kHz. Vibration is applied to the workpiece in the feed direction of the grinding wheel. The amplitude of the ultrasonic vibration can be adjusted by changing the setting on the power supply. The experimental set-up used to study UADG is shown in Fig. 1b.



(a)



(b)

Fig. 1. (a) Scheme of the experimental set-up. (b) Experimental set-up for ultrasonic assisted dry grinding.

3.0 Experiments

The experimental equipment consists of the following:

- Machine tool: Elb Micro-Cut AC8 CNC universal surface grinding machine
- Ultrasonic Vibration Generator: Mastersonic MMM generator-MSG.1200.IX
- Eddy current displacement measurement system: Micro epsilon eddyNCDT 3300, to measure the amplitude of vibration.
- Surface roughness tester: Hommel-Werke, model T-8000
- Dynamometer: Kistler piezoelectric dynamometer model 9255B

The settings of main machining parameters for the present study are summarized in Table 1.

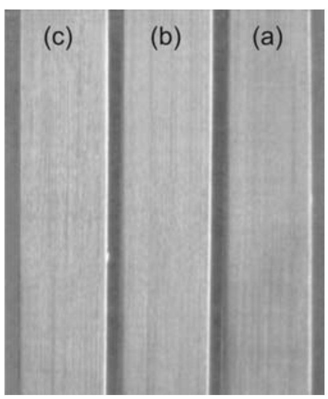
Table 1. Major machining parameters

Grinding wheel	Vitrified bond Al_2O_3 grinding wheel, Grain Size 120
Workpiece	42CrMo4, 85 HRB, (60*55*30 mm*mm*mm)
Grinding conditions	Feed speed vft= 500-1000-1500-2000 mm/min; Cutting speed v_c= 60 m/s; Depth of cut a_e= 0.010- 0.030 mm; No Coolant (Dry grinding)
Grinding process	Dry surface grinding
Dressing conditions	Wheel speed v_{cd}= 60m/s, Depth of dressing a_{ed}= 50 µm, Overlapping ratio Ud = 2, Total depth of dressing a_{ed}-total= 100 µm
Dressing tool	Diamond single point dresser width b_d =2 mm
Direction of ultrasonic vibration	Feed direction
Ultrasonic vibration conditions	Frequency f=23 KHz, Amplitude A=10µm

The tests were carried out for both UADG and CDG with the same instrument. However, during the CDG the ultrasonic generator was switched off. Every workpiece was divided into three different sections (Fig2).

4.0 Experimental results and discussion

Almost all of CDGs were unsuccessful due to the thermal damage on the ground workpiece surface. As there were no cutting fluids to transfer the high heat from the contact zone this result had been expected. Fig. 2 shows photographs of the ground surfaces. It is apparent that ultrasonically assisted ground surfaces have experienced much less thermal damage compared to conventional ground surfaces.



(UADG A=10 µm F=23 KHz)

(CDG)

Fig2. The ground surfaces, v_c=60 m/s a_e=20µm a) v_{ft}=1000 mm/min b) v_{ft}=1500 mm/min c) v_{ft}=2000 mm/min.

The effect of vibration amplitude, feed speed and depth of cut on surface roughness and grinding forces were studied. In order to achieve reliable data each test was repeated 3 times. In all the figures, lines were formed by calculating the least-squares fit through the data points for a second-order polynomial equation. Fig. 3

shows the relationship between vibration amplitude and normal grinding force. The amplitude zero in this figure represents results of conventional dry grinding. The experimental results show significant improvement for UADG compared to CDG in different vibration amplitudes. Apparently, the reason for these improvements is the change of the nature of the cutting process, which is transformed into a process with a multiple-impact interaction between the abrasive grits and the formed chip.

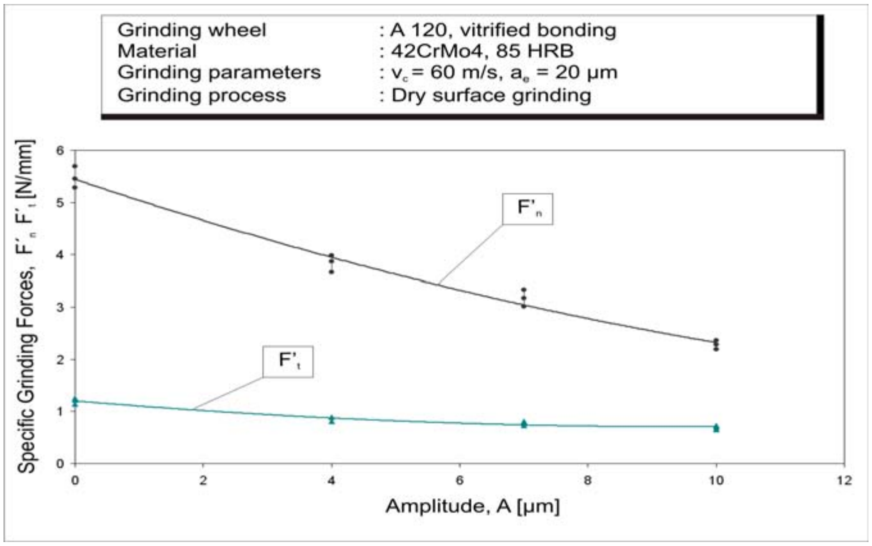


Fig. 3. Specific Grinding forces vs. Vibration Amplitude (a_e=20µm, f=23 kHz).

Figs. 4–7 compare the grinding forces and surface roughness produced by UADG with CDG under different depth of cuts and feed speeds. Experiments were carried out at v_c=60 m/s , f=23 kHz, A=10 µm. Based on the results from previous stages, it is believed that UADG performs enhanced under these conditions. These conditions are not essentially the optimal ones. For depths of cuts more than 10 µm in CDG thermal damages of the ground surfaces were observed. This phenomenon is shown with a fire symbol in the figures 4 and 5. It should be noted that the scatter in the measured surface roughness and grinding forces obtained through UADG is much less compared to CDG. It means that using UADG increases the repeatability of the process.

The maximum oscillating velocities (up to 87 m/min) and accelerations (up to 208,840 m/s^2) are generated at the amplitude of 10 µm and a frequency value of 23 kHz. The larger the vibration amplitude, the greater the material removal rate per active grain and the higher the kinetic energy with which the grits strike the work surface. Due to the high frequency interaction of active grains on the workpiece, the cutting process in UADG becomes discontinuous and ultrasonic impact action occurs, thus causing the material to begin to rollover more easily as well as more micro cracking propagation in the cutting zone which both make an effective interaction between grits and workpiece surface. Therefore the grinding forces and frictional effects are decreased, so that less plastic deformation occurs.

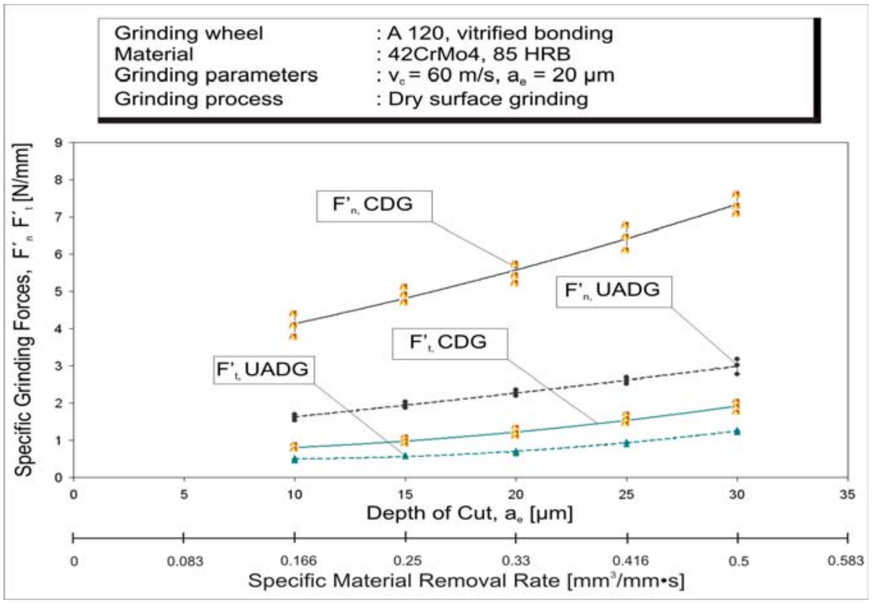


Fig4. Specific Grinding forces vs. Depth of Cut, v_{ft}=1000 mm/min (UADG: A=10µm, f=23 kHz).

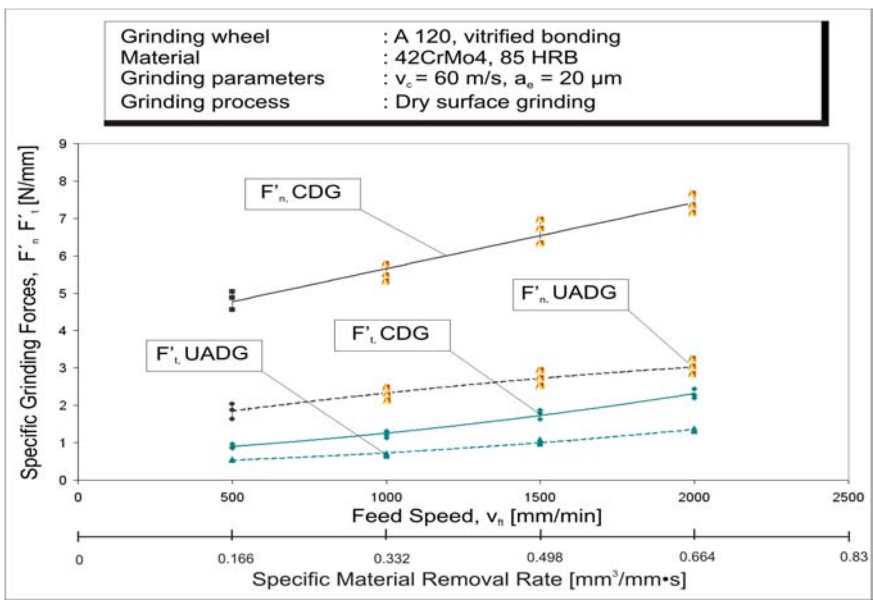


Fig5. Grinding normal force vs. Feed Speed, a_e=20 µm (UADG: A=10µm, f=23 kHz).

It has already been proven that deformation processes for ultrasonic assisted machining are restricted in the vicinity of the cutting edge along the surface of the workpiece and are not observed underneath the cutter, in contrast to the conventional machining process [12]. Plastic deformation of the machined surface in case of using ultrasonic oscillation is less than that in conventional machining. In addition the coefficient of friction in grinding decreases with an increase in sliding speed between the grit and the material. As the sliding speed in UADG due to ultrasonic vibration is higher than sliding speed in CDG, the coefficient of friction reduces. This suggests that in UADG a fewer number of strong bonds between the grit and the material are formed. Authors assume that by oscillation of the workpiece in feed direction, the rubbing and plowing regimes which cause the major part of plastic deformation are reduced so that the grinding specific energy is also reduced and the thermal damage on the ground surface is significantly decreased.

SUMMARY PREPARATION FOR PAPERS

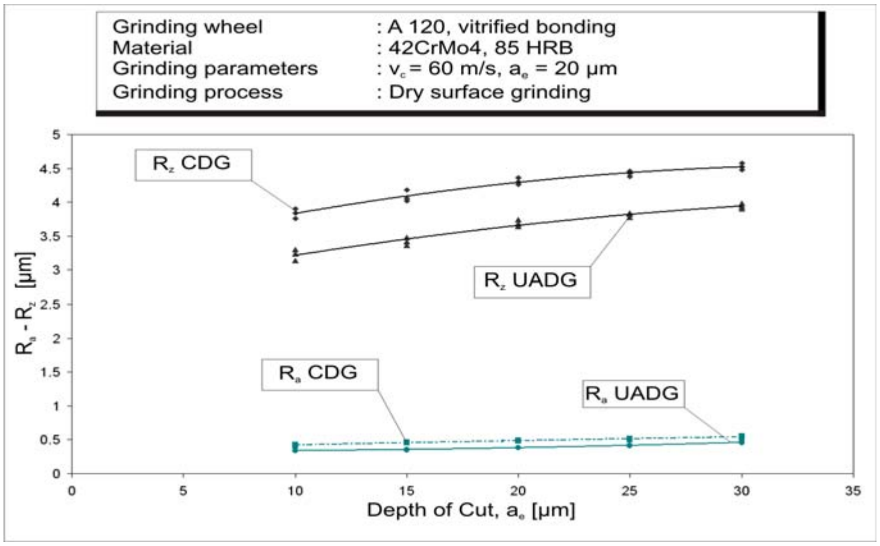


Fig6. R_a and R_z vs. Depth of Cut, v_{ft}=1000 mm/min (UADG: A=10µm, f=23 kHz).

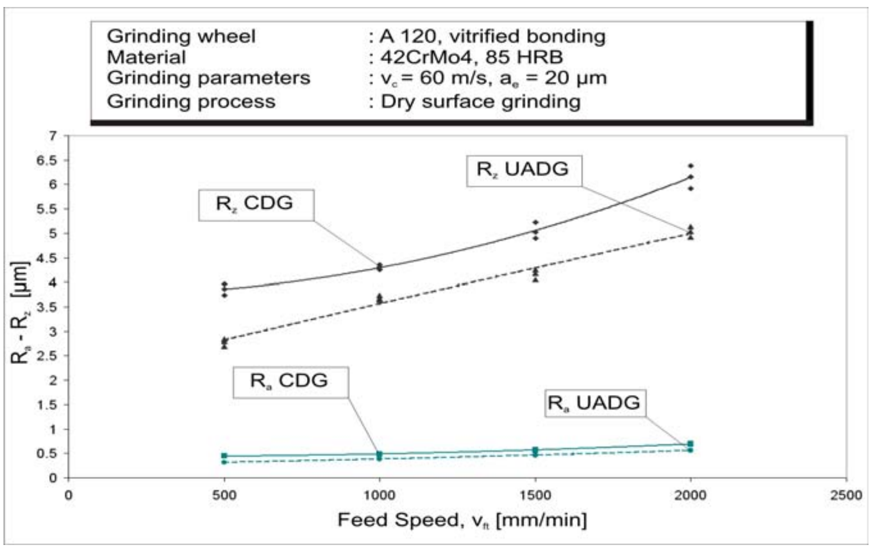


Fig7. R_a and R_z vs. Feed Speed, a_e=20 µm (UADG: A=10µm, f=23 kHz).

Reduction in plowing and rubbing regimes is also lead to reduction of the distance between peaks and valleys and consequently decreasing R_z. Due to feed ultrasonic oscillation (sinusoidal movement of the workpiece in feed direction) the possibility of the interaction between the grit and the workpiece surface in each contact length will be increased. It is thought that the grit will have more chance to cut the peak of the surface and therefore the R_z parameter of the surface roughness will be improved.

5.0 Conclusion

- Comparative experiments of the grinding forces demonstrated up to 70% reduction in normal grinding force and up to 50% in tangential grinding forces for the workpieces machined with superimposed ultrasonic vibration. Most of CDGs were unsuccessful due to the thermal damage on the ground workpiece surface. The reason for this phenomenon was due to the absence of cutting fluids in the process and consequently the generation of high heat in the contact zone. These improvements are subjected to the change of the nature of the cutting process in UAD, which is transformed into a process with a multiple-impact interaction between the tool and the formed chip resulting in interrupted cutting and reducing the grinding forces, frictional effect and plastic deformation zone.

- It was also found that using UADG leads to significant improvements on the R_z and R_a parameter. It is assumed that the improvement in these parameters is due to the fact that the grit in UADG has a higher chance to cut the peak of the surface due to the feed ultrasonic oscillation and increasing the possibility of the interaction of the grit and the workpiece surface in each contact length.

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SUMMARY PREPARATION FOR PAPERS

Ultrasonic assisted dry grinding of soft steel

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Abstract

Dry machining has been increasingly investigated in order to decrease the negative environmental impact of the cutting fluids, diminishing problems concerning waste disposal demand and also due to interest in decreasing manufacturing costs. However generally in dry grinding, as there are no cutting fluids to transfer the heat from the contact zone, problems frequently occur in terms of high heat generation on grinding wheel surface and workpiece surface, increasing the grinding energy (grinding forces), wear of grinding wheel, low material removal rate (regarding relatively low depth of cuts) as well as poor surface roughness compared to conventional grinding. A recent and promising method to overcome these technological constraints is the use of ultrasonic assistance, where high-frequency and low amplitude vibrations are superimposed on the movement of the workpiece. The design of an ultrasonically vibrated workpiece holder and the experimental investigation of ultrasonically assisted dry grinding of 100Cr6 are presented. The surface roughness and normal grinding force of the ultrasonically and conventionally ground workpieces were measured and compared. The obtained results show that the application of ultrasonic vibration can eliminate the thermal damage on the workpiece and decrease the normal grinding force considerably. A decrease of up to 60% of normal grinding forces has been achieved.

Keywords: Dry grinding, Ultrasonic machining, Ultrasonic assisted dry grinding, Cutting fluids, Surface Roughness

1. Introduction

he cutting fluids are mainly used in metal removal processes due to their effect on transmitting generated heat in the contact zone (cooling), reduction of friction in the tool-workpiece contact zone (lubricating), chip transportation from the cutting area, cleaning and minimizing corrosion. On the other hand cutting fluids have serious disadvantages, such as health hazards and the explosiveness of oil vapor, environmental pollution and wear of the elements of the machine tool. Metallic particles generated during cutting by cutting fluids (splash, evaporation and bacterial pollution) cause most of these problems [1]. In addition cutting fluids increase manufacturing cost (e.g. high disposal costs), and require space for filtering and circulation systems.

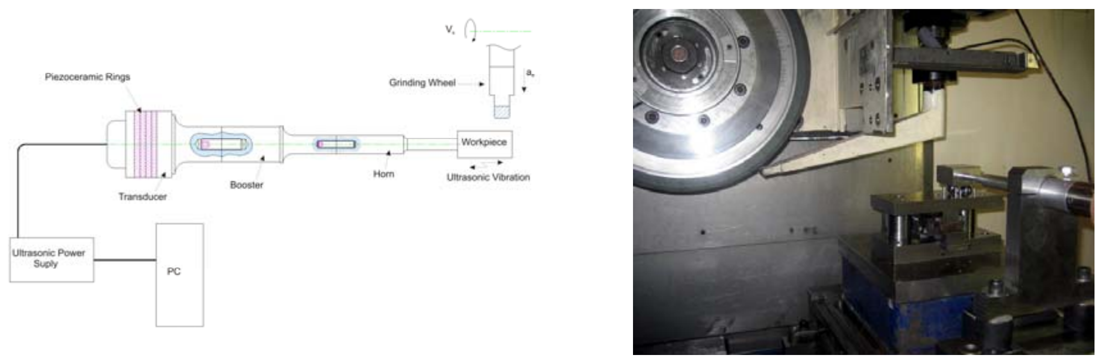
In order to decrease the negative environmental impact of the cutting fluids and reducing manufacturing costs, new machining techniques such as dry machining [2–5] are used. Many machining processes have decreased and even eliminated the use of cutting fluids in the last decades, but dry grinding is one of the most difficult processes in this regard. During grinding many of the super abrasive grits which are in contact with the workpiece do not perform real cutting, but instead generate heat by rubbing and plowing the workpiece surface in the contact zone. The high heat generation associated with a high negative rake angle and with a great contact length in grinding processes, can greatly increase the temperature in the contact zone. Without sufficient cooling and lubrication, this can cause thermal damage on the workpiece surface [6-8]. That is why cutting fluid is necessary in most grinding applications, and the methods of minimum grinding fluid or dry grinding have not yet been fully successful in industrial applications [9,10]. Generally in conventional dry grinding (CDG), as there are no cutting fluids to transfer the heat from the contact zone, problems frequently occur in terms of high heat generation on grinding wheel surface and workpiece surface (thermal damage on the workpiece surface), increasing the grinding energy (grinding forces), wear of grinding wheel, low material removal rate (regarding relatively low depth of cuts) as well as poor surface roughness compared to conventional grinding with cutting fluids. A recent and promising technique to overcome these technological constraints is known as ultrasonic assisted dry grinding (UADG). The principle of this technique is to superimpose high frequency (16–40 kHz) and low peak-to-peak (pk-pk) vibration amplitude (2–30 μm) in the feed or crossfeed direction to the tool or the workpiece. This cutting process is different from ultrasonic machining. In ultrasonic machining, metal removal is effected with the help of abrasive grains suspended in a slurry, which are made to strike repeatedly upon the workpiece surface by a tool oscillating ultrasonically [11-13]. Ultrasonic machining is only applicable to brittle materials. On the other hand, UADG is a hybrid process of CDG and ultrasonic oscillation. It is applicable to both ductile and brittle materials. By using ultrasonic assisted machining significant improvements in thrust force, burr size, material removal rate, tool wear, heat generation, noise reduction and surface finish have been reported. Chang and Bone [14] have shown that burr size reduction in drilling aluminium is possible with ultrasonic assisted drilling (UAD). Neugebauer and Stoll [15] have experimentally demonstrated that in UAD of aluminium alloys, force and moment reductions of 30–50% are possible and the reduced load of the tool's cutting edge enabled an up to 20-fold increase in tool life over conventional cutting. Zhang et al. [16] have both theoretically and experimentally concluded that there exists an optimal vibration condition such that the thrust force and torque are minimized. Onikura et al. [17,18] utilized a piezoactuator to generate 40 kHz of ultrasonic vibration in the drilling spindle. They found that the use of ultrasonic vibration reduces the friction between chip and rake face, resulting in chips which are thinner and can therefore lead to the reduction of cutting forces. Jin and Murakawa [19] found that the chipping of the cutting tool can effectively be prevented by applying ultrasonic vibration and tool life can be prolonged accordingly. Takeyama and Kato [20] found that the mean thrust force in drilling can be greatly reduced under ultrasonic vibrations. Drilling chips are thinner and can be removed more easily from the drilled hole. Burr formation at the entrance and the exit sides is greatly reduced with the low cutting forces. Thus, the overall drilling quality is improved with the employment of UAD. Azarhoushang and Akbari [21] have achieved significant improvements in the circularity, cylindricity, surface roughness and hole oversize by applying ultrasonic vibration to the tool with out using any cutting fluids. Prabhakar [22] has experimentally demonstrated that the material removal rate obtained from ultrasonic assisted grinding is nearly 6-10 times higher than that from a conventional grinding process under similar conditions. Mult et al. [23] investigated ultrasonic assisted creep feed grinding of sintered silicon nitride and alumina. They found that for ceramic materials, ultrasonic assisted grinding can be applied as an efficient production technology and the ultrasonic assisted creep feed grinding provides enormously reduced normal forces at slightly increased wheel wear and surface roughness.

In this investigation, a UADG system has been designed, fabricated and tested. Improvements in the R_z (parameter of surface roughness) of the ground surfaces and reduction of the normal grinding force due to superimposing of ultrasonic vibration in the dry grinding of 100Cr6 have been achieved. The effect of vibration amplitude, feed speed and depth of cut on surface roughness and the normal grinding force have been investigated.

2. Design and fabrication of UADG system

In order to study UADG, an actuated workpiece holder has been designed and built. Fig. 1a illustrates schematically the experimental set-up. The workpiece holder consists of a piezoelectric transducer, a booster, a horn and a special fixture. The ultrasonic power supply converts 50 Hz electrical supply to high-frequency (21 kHz) electrical impulses. These high frequency electrical impulses are fed to a piezoelectric transducer and transformed into mechanical vibrations of ultrasonic frequency (21 kHz), due to the piezoelectric effect. The vibration amplitude is then amplified by the booster and the horn and transmitted to the workpiece attached to the horn. The resultant vibration of the workpiece fixed in the tool holder reaches 10 μm (i.e. 20 μm peak to peak) at a frequency of about 21 kHz. Vibration is applied to the workpiece in the crossfeed direction of the grinding wheel. The amplitude of the ultrasonic vibration can be adjusted by changing the setting on the power supply. The experimental set-up used to study UADG is shown in Fig. 1b.

In the design of the UADG acoustic head, it is considered that the whole structure must possess enough stiffness to withstand the dynamic loads during the grinding operation. The acoustic head parts should have high fatigue resistance and low acoustic losses (meaning that they should not absorb too much energy from the vibrations). Each part of the acoustic head is made of aluminum 7075-T6 with high strength, high fatigue resistance and very good acoustic properties to provide enough stiffness and low acoustic losses. The fixture which clamps the acoustic head is made of steel.



(a) (b)

Fig. 1. (a) Scheme of the experimental set-up. (b) Experimental set-up for ultrasonic assisted dry grinding.

3. Experiments

The experimental equipment consists of the following:

- Machine tool: Elb Micro-Cut AC8 CNC universal surface grinding machine
- Ultrasonic Vibration Generator (Mastersonic MMM generator-MSG.1200.IX): to convert 50 Hz electrical supply to high-frequency electrical impulses. The frequency range of the generator is 17.000 to 46.728 kHz and the frequency step is 1 Hz. The power of the generator is 1200W and the maximum output current is 3A
- Eddy current displacement meter (Micro epsilon: eddyNCDT 3300): to measure the amplitude of vibration. Measuring ranges 0 – 0.5 mm, Linearity 0.2 %, Resolution 0.005 %, Measuring rate 100 kHz
- Surface roughness tester (Hommel-Werke: T-8000)
- Digital toolmakers microscope (Keyence: VHX): to observe the ground surface, which possesses a maximum magnification of 1000 times.

Dynamometer: (Kistler piezoelectric dynamometer model 9255B)

The settings of main machining parameters for the present study are summarized in Table 1.

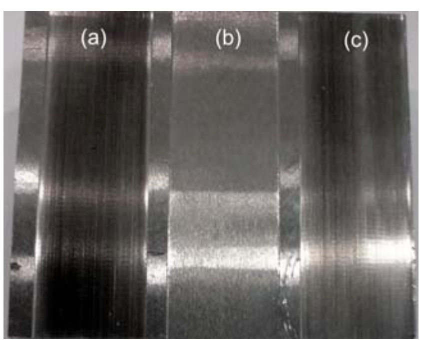
Grinding wheel	Vitrified bond CBN grinding wheel, B126 C125; Ø400 mm * 16 mm
Workpiece	100Cr6, 82 HRB, (60*47*29)
Grinding conditions	Feed speed v_{ft}= 1000- 2000 mm/min; Cutting speed v_c= 60 m/s; Depth of cut a_e= 0.010- 0.030 mm; No Coolant (Dry grinding)
Grinding process	Surface grinding
Dressing conditions	Dressing ratio q=0.8, Wheel speed v_c= 60, Overlapping ratio U_d =0.4, Depth of dressing a_{ed}= 5 µm, Total depth of dressing $a_{ed\text{-}total}$= 10 µm
Dressing tool	Diamond disc dresser width R_{sp} = 0.2 mm
Direction of ultrasonic vibration	Cross feed direction (perpendicular to feed)
Ultrasonic vibration conditions	Frequency f=21 KHz, Amplitude A=10µm

Table 1. Major machining parameters

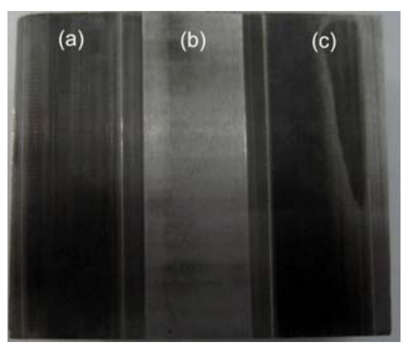
In this experiment, the tests were carried out for both UADG and CDG with the same instrument. However, during the CDG the ultrasonic generator was switched off. Every workpiece was divided into three different sections and UADG experiments were applied on the center section. (Fig2)

4. Experimental results and discussion

Most of CDGs were unsuccessful due to the thermal damage on the ground workpiece surface. As there were no cutting fluids to transfer the high heat from the contact zone this result had been expected. Fig. 2 shows photographs of the ground surfaces. It is apparent that in both samples the middle section (ultrasonically assisted ground surface) has experienced much less thermal damage compared to other sections (conventional ground surfaces).



(I)



(II)

Fig2. (I) v_{ft}=1000 mm/min v_c=60 m/s; a) a_e=15 µm (CDG); b) a_e=15 µm A=10 µm (UADG); c) a_e=10 µm (CDG)

(II) v_{ft}=2000 mm/min v_c=60 m/s; a) a_e=25 µm (CDG); b) a_e=30 µm A=10 µm (UADG); c) a_e=30 µm (CDG)

The effect of vibration amplitude, feed speed and depth of cut on surface roughness and normal grinding force were studied. In order to achieve reliable data each test was repeated 3 times. In all the figures, lines were formed by calculating the least-squares fit through the data points for a second-order polynomial equation. Fig. 3 shows that the relationship between vibration amplitude and normal grinding force is not linear. Please note that amplitude zero in this figure represents results of conventional dry grinding. Results show significant improvement for UADG compared to CDG in different vibration amplitudes. Apparently, the reason for these improvements is the change of the nature of the cutting process, which is transformed into a process with a multiple-impact interaction between the abrasive grits and the formed chip.

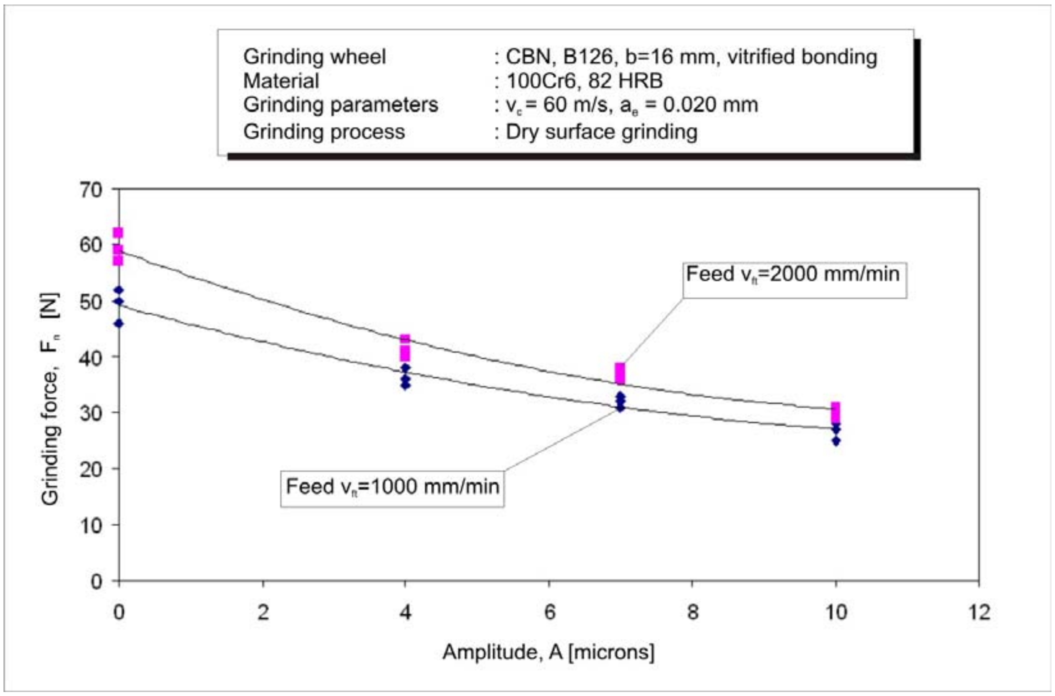


Fig. 3. Normal Grinding force vs. Vibration Amplitude (a_e=20µm, f=21 kHz).

Figs. 4–7 compare the normal grinding force and surface roughness produced by UADG with CDG under different depth of cuts. Experiments were carried out at v_c=60 m/s , f=21 kHz, A=10 µm. Based on the results from previous stages, it is believed that UADG performs enhanced under these conditions. These conditions are not essentially the optimal ones. For depths of cuts more than 10 µm in CDG thermal damages of the ground surfaces, which change the material properties of the workpiece, were observed. This phenomenon is shown with a fire symbol in the figures 4 and 5. It should be noted that the scatter in the measured surface roughness and grinding forces obtained through UADG is much less compared to CDG. It means that using UADG increases the repeatability of the process.

The maximum oscillating velocities (up to 80 m/min) and accelerations (up to 174,100 m/s^2) are generated at the amplitude of 10 µm and a frequency value of 21 kHz. The larger the vibration amplitude, the greater the material removal rate per active grain and the higher the kinetic energy with which the grits strike the work surface. Due to the high frequency interaction of active grains on the workpiece, the cutting process in UADG becomes discontinuous and ultrasonic impact action (UIA) occurs, thus causing the material to begin to rollover more easily, it also helps to develop micro cracking in the cutting zone, makes the process of chip formation more regular and the contact between the grit and the workpiece become more effective. This causes grinding forces and frictional effects to decrease, resulting in less plastic deformation and smaller contact zone.

It has already been proven by some researchers [24,25] that deformation processes for ultrasonic assisted machining are restricted in the vicinity of the cutting edge along the surface of the workpiece and are not observed underneath the cutter, in contrast to the conventional machining process. Plastic deformation of the machined surface in case of using ultrasonic oscillation is less than that in conventional machining. Authors assume that by oscillation of the workpiece in crossfeed direction, the rubbing and plowing regimes which cause the major part of plastic deformation are reduced so that the grinding specific energy is also reduced and the thermal damage on the ground surface is significantly decreased.

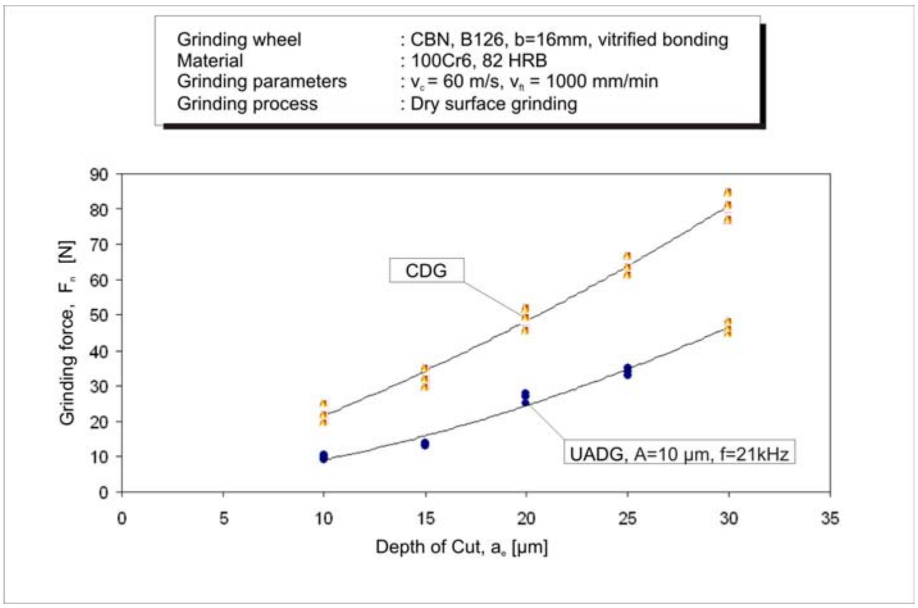


Fig4. Grinding normal force vs. Depth of Cut, v_{ft}=1000 mm/min.

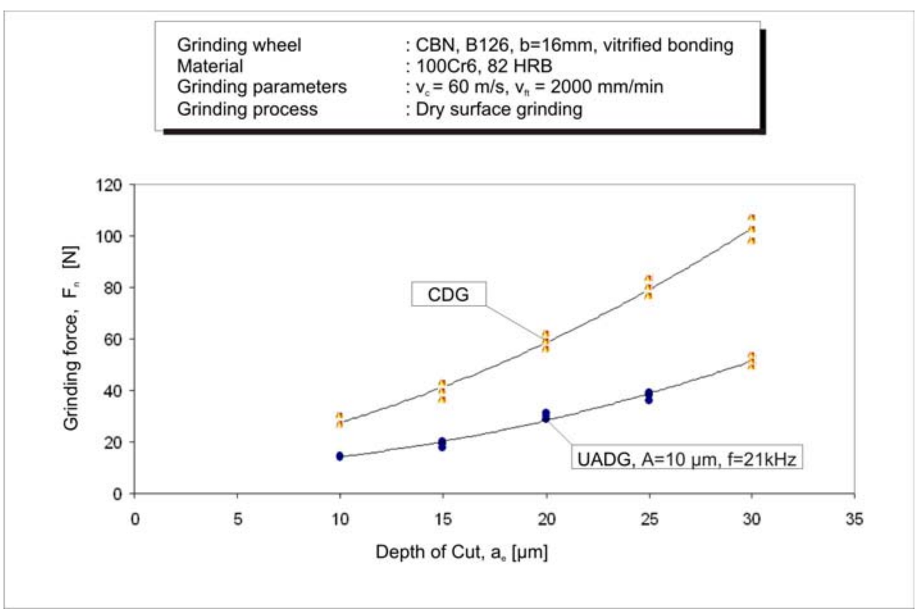


Fig5. Grinding normal force vs. Depth of Cut, v_{ft}=2000 mm/min.

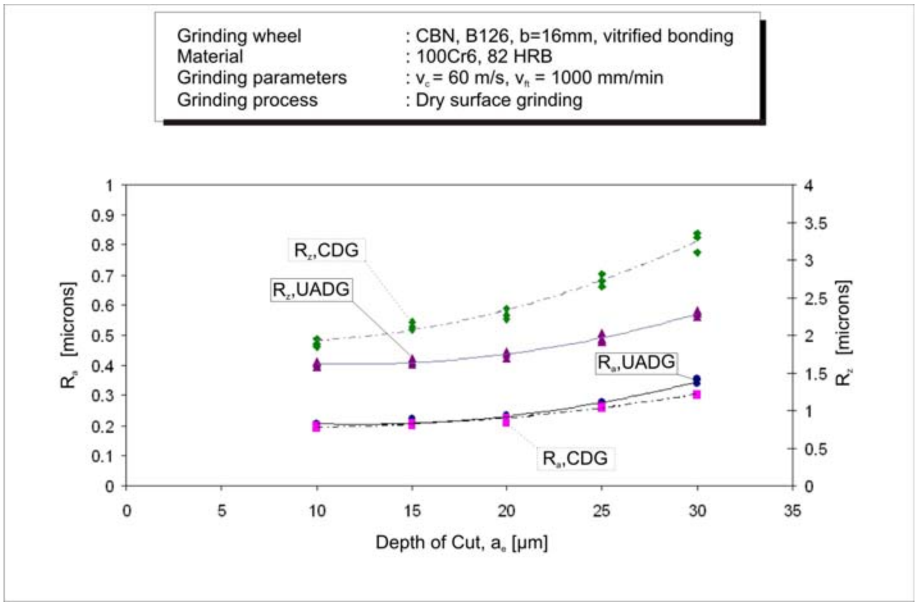


Fig6. R_a and R_z vs. Depth of Cut, v_{ft}=1000 mm/min (UADG: A=10µm, f=21 kHz).

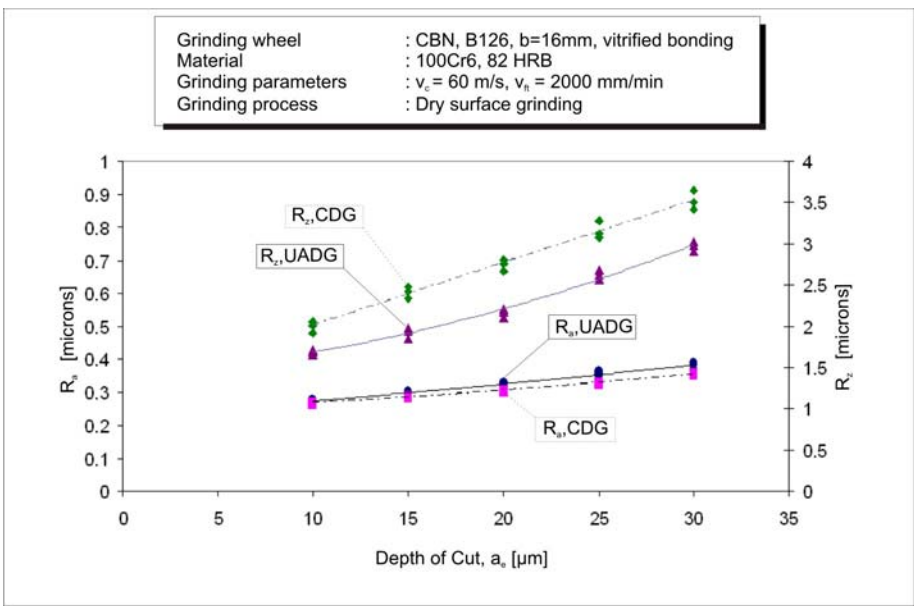


Fig7. R_a and R_z vs. Depth of Cut, v_{ft}=2000 mm/min (UADG: A=10µm, f=21 kHz).

Due to equation (1), as the total material removal rate and V_C for both cases are almost the same and because of lateral movement (sinusoidal movement of the workpiece) the A_{cu} for the UADG due to vibration amplitude is higher than that in CDG (fig 8). Thus the number of the active cutting edge in UADG will be decreased. Base of this analogy reduction in grinding forces (Tangential and Normal) can be explained due to the reduction of number of active cutting edge.

$$\dot{Q} = v_c \cdot A_{cu} \cdot N_{active} \quad (1)$$

$$F_{Ng} = K \cdot A_{wg} \quad (2)$$

$$F_{N-total} = F_{Ng} \cdot N_{active} \quad (3)$$

$\dot{Q}$: Material removal rate

v_c: Cutting Speed

A_{cu}: Average uncut chip area

N_{active}: Number of the active grains

F_{Ng}: Normal Force of an active grain

A_{wg}: Cross section area of an uncut chip for an active grain

K: Constant which depends on the material property (especially hardness)

$F_{N\text{-}total}$: Total normal grinding force

Due to equations (2) and (3) when the number of active cutting edges in UADG decrease, the normal grinding force also decreases. The reduction of plastic deformation in UADG means that plowing and rubbing regimes in the grinding process happen less frequently and therefore the distance between peaks and valleys is reduced and consequently R_z is also reduced. Due to crossfeed ultrasonic oscillation (sinusoidal movement of the workpiece in crossfeed direction) the possibility of the interaction between the grit and the workpiece surface in each contact length will be increased. It is thought that the grit will have more chance to cut the peak of the surface and therefore the R_z parameter of the surface roughness will be improved. However as the number of the active grits in general for UADG is less than CDG and the grain projection in UADG compare to CDG is enhanced the distance between each interaction of the grit and workpiece is increased (fig9) so that the R_a parameter of surface roughness will be slightly increased.

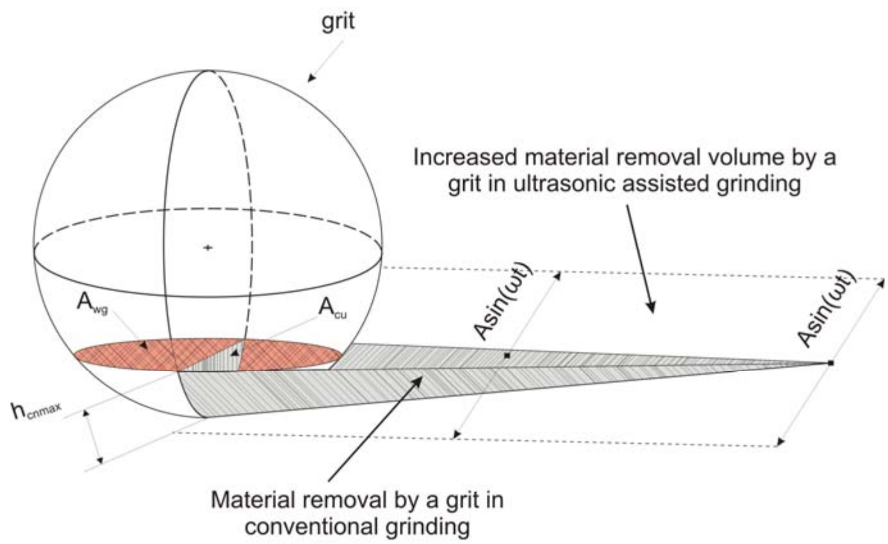


Fig8. Material removal volume in conventional and ultrasonic assisted grinding

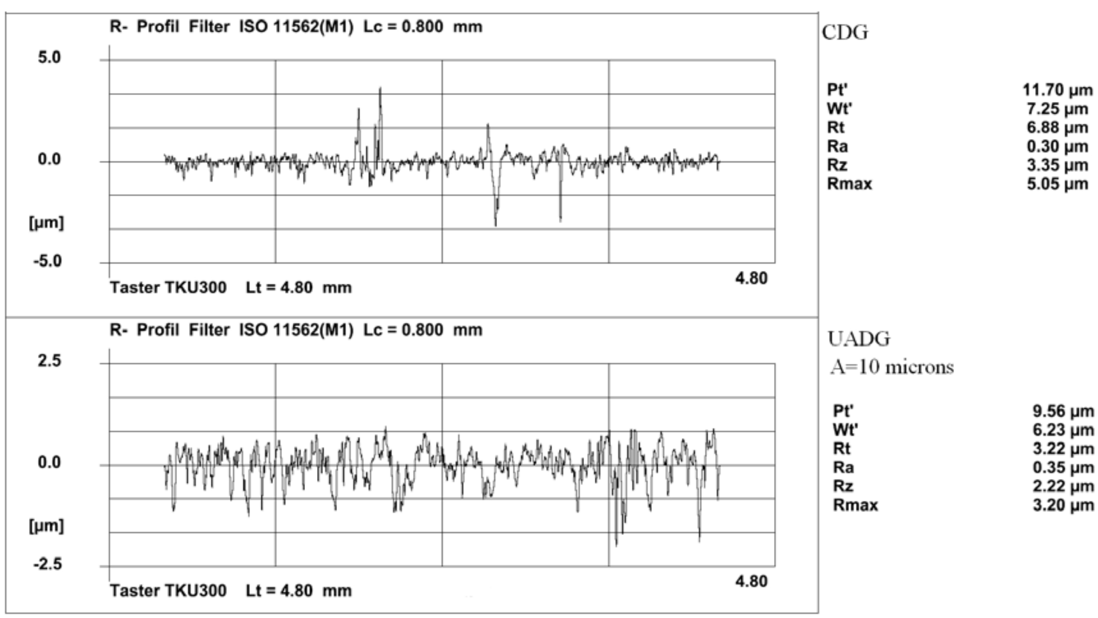


Fig9. Surface roughness profile (v_c=60 m/s, v_{ft}=1000 mm/s, a_e=30 µm)

5. Conclusion

Experimental studies of UADG and CDG demonstrate considerable advantages of the former technology for dry grinding 100Cr6.

- Comparative experiments of the grinding forces demonstrated up to 60% reduction in normal grinding force for the workpieces machined with superimposed ultrasonic vibration. Most of CDGs were unsuccessful due to the thermal damage on the ground workpiece surface. The reason for this phenomenon was due to the absence of cutting fluids in the process and consequently the generation of high heat in the contact zone. These improvements are subjected to the change of the nature of the cutting process in UAD, which is transformed into a process with a multiple-impact interaction between the tool and the formed chip resulting in interrupted cutting and reducing the grinding forces, frictional effect and plastic deformation zone.

- It was also found that using UADG leads to significant improvements on the R_z parameter and a slight increase in the R_a parameter. It is assumed that the improvement in the R_z parameter is due to the fact that the grit in UADG has a higher chance to cut the peak of the surface due to the crossfeed ultrasonic oscillation (sinusoidal movement of the workpiece in crossfeed direction) and increasing the possibility of the interaction of the grit and the workpiece surface in each contact length. However as the number of the active grits in general for UADG is less than CDG and the grain projection in UADG compared to CDG is enhanced the distance between each interaction of the grit and workpiece increases so that the R_a parameter will be slightly increased.

Future studies will include the use of ultrasonic oscillation in the feed direction and the comparison of the corresponding process parameters.

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The authors would like to acknowledge the help of Mr. Nima Jandaghi and Mr. Rolf Rinderknecht in conducting experiments.

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Grinding of Soft Steel with Assistance of Ultrasonic Vibrations

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Keywords: Grinding, Ultrasonic assisted grinding, Grinding force, Surface Roughness

Abstract. Compared to other machining processes, conventional grinding has a low material removal rate and involves high specific energy. A major part of the specific energy in grinding is changed to heat which makes harmful effect on surface quality. A recent and promising method is the use of ultrasonic assistance to increase the material removal rate along with decreasing the thermal damage on the workpiece and reducing cutting forces. The advantages of Ultrasonic Assisted Grinding (UAG) were proved mostly for the brittle material. Our investigations show the improvement on the surface roughness, reduction of the grinding forces and thermal damage in case of using UAG comparing to Conventional Grinding (CG) for a soft material of 100Cr6. The designed and developed ultrasonically vibrated workpiece holder and the experimental investigation show a decrease of up to 40% of normal grinding forces.

1. Introduction

Among the different machining processes, grinding is one of the most complex one because of the undefined cutting edge and statistical nature of the process. Due to the low material removal rate and high specific energy in conventional grinding, this production process is mostly considered only as a secondary finishing operation. A recent and promising technique to increase the material removal rate but simultaneously decrease the thermal damage on the workpiece and reduce cutting forces is known as ultrasonic assisted grinding (UAG). The principle of this technique is adding high frequency (16–40 kHz) and low peak-to-peak (pk-pk) vibration amplitude (2–30 μm) in the feed or crossfeed direction to the tool or the workpiece. UAG is a hybrid process of conventional grinding (CG) and ultrasonic oscillation. By using ultrasonic assisted machining, significant improvements in thrust force, burr size, material removal rate, tool wear, heat generation, noise reduction and surface finish have been reported. Zhang et al. [1] have both theoretically and experimentally concluded that there exists an optimal vibration condition such that the thrust force and torque are minimized. Onikura et al. [2, 3] found that the use of ultrasonic vibration reduces the friction between chip and rake face, resulting thinner chips which lead to the reduction of cutting forces. Jin and Murakawa [4] have showed that Tool life can be prolonged by applying ultrasonic vibration. Azarhoushang and Akbari [5] achieved significant improvements in the circularity, cylindricity, surface roughness and hole oversize by applying ultrasonic vibration to the tool without using any cutting fluids. Mult et al. [6] and Uhlmann [7] found that for ceramic materials, ultrasonic assisted grinding can be applied as an efficient production technology and the ultrasonic assisted creep feed grinding provides enormously reduced normal forces at slightly increased wheel wear and surface roughness. Tawakoli et al [8,9] demonstrated that in ultrasonic assisted dressing of CBN grinding wheels, considerable reduction in grinding forces and dresser wear is achievable.

In this investigation, an UAG system has been designed, fabricated and tested. Improvements in the Rz (parameter of surface roughness) of the ground surfaces and reduction of the normal grinding force due to superimposing of ultrasonic vibration in the grinding of 100Cr6 have been achieved. Besides, the effect of vibration amplitude, feed speed and depth of cut on surface roughness and the normal grinding force have been presented.

2. Design and fabrication of UAG system

In order to study UAG, an actuated workpiece holder was developed. The workpiece holder consists of a piezoelectric transducer, a booster, a horn and a special fixture. The ultrasonic power supply converts 50 Hz electrical supply to high-frequency (21 kHz) electrical impulses. These high frequency electrical impulses are fed to a piezoelectric transducer and transformed into mechanical vibrations of ultrasonic frequency (21 kHz), due to the piezoelectric effect. The vibration amplitude is then amplified by the booster and the horn and transmitted to the workpiece attached to the horn. The resultant vibration of the workpiece fixed in the tool holder reaches 10 µm (i.e. 20 µm peak to peak) at a frequency of about 21 kHz. Vibration is applied to the workpiece in the crossfeed direction of the grinding wheel. The amplitude of the ultrasonic vibration can be adjusted by changing the setting on the power supply.

3. Experiments

The experimental equipments consist of the following:

- Machine tool: Elb Micro-Cut AC8 CNC universal surface grinding machine
- Ultrasonic Vibration Generator: Mastersonic MMM generator-MSG.1200.IX, Power of 12000 W, Frequency ranges of 17.000 to 46.728 kHz.
- Eddy current displacement measurement system: Micro epsilon eddyNCDT 3300, to measure the amplitude of vibration. Measuring ranges 0 – 0.5 mm, Linearity 0.2 %, Resolution 0.005 %, Measuring rate 100 kHz
- Surface roughness tester: Hommel-Werke: T-8000
- Dynamometer: Kistler piezoelectric dynamometer model 9255B

The settings of main machining parameters for the present study are summarized in Table 1.

Table 1, Major machining parameters

Grinding wheel	Vitrified bond CBN grinding wheel, B126 C125; Ø400 mm * 16 mm
Workpiece	100Cr6, 82 HRB, (60*47*29 mm*mm*mm)
Grinding conditions	Feed speed v_{ft}= 1000- 2000 mm/min; Cutting speed v_c= 60 m/s; Depth of cut a_e= 0.050- 0.300 mm
Grinding process	Surface grinding
Coolant	120 l/min, Emulsion (Castrol Syntilo 2000)
Dressing conditions	Dressing ratio q_d=0.8, Wheel speed v_{cd}= 60, Depth of dressing a_{ed}= 5 µm, Overlapping ratio U_d =4, Total depth of dressing $a_{ed\text{-}total}$= 10 µm
Dressing tool	Diamond disc dresser radius R_{sp} = 0.2 mm
Direction of ultrasonic vibration	Cross feed direction (perpendicular to feed)
Ultrasonic vibration conditions	Frequency f=21 KHz, Amplitude A=10µm

In this experiment, the tests were carried out for both UAG and CG with the same instrument. However, during the CG the ultrasonic generator was switched off.

4. Experimental results and discussion

The experimental set-up used in this study for CG as well as UAG is shown in Fig. 1. In CGs, thermal damages on the ground surface were found whenever the depth of cut increased to more than 100 µm. This is due to high grinding forces and resulted high specific energy and corresponding heat generation in the contact zone. In case of UAG there was found no damages on the ground surface up to depth of cut of 200 µm with the same grinding parameters. Fig. 2 shows photograph of the ground surfaces and comparison of two cases of CG and UAG. It is apparent that the right section (ultrasonically assisted ground surface) has experienced much less thermal damage compared to the left section (conventional ground surfaces).

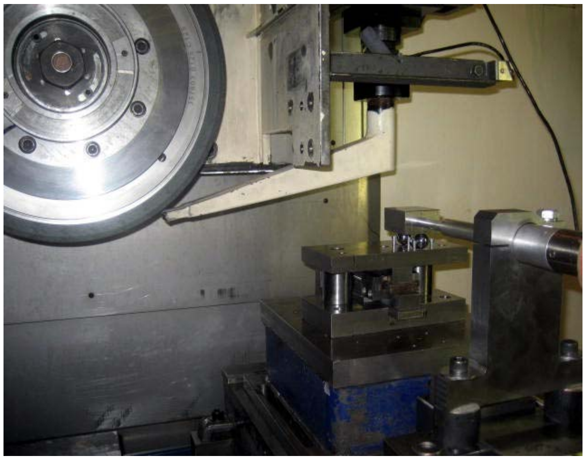

Fig. 1. Experimental set-up for ultrasonic assisted grinding.

a) A=0 µm (CG)
b) A=10 µm (UAG)

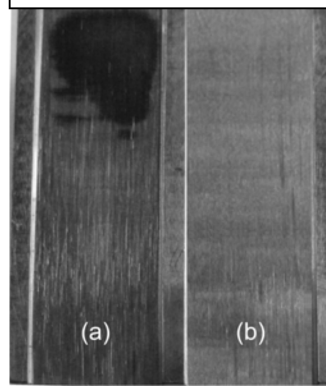

Fig. 2 Ground surface v_c=60 m/s v_{ft}=1000 mm/min a_e=200 µm

In order to achieve reliable data each test was repeated 4 times. Fig. 3-7 show the effect of vibration amplitude, feed speed and depth of cut on surface roughness and normal grinding force for both CG and UAG. In all the figures, lines were formed by calculating the least-squares fit through the data points for a second-order polynomial equation. Fig. 3 shows the relationship between vibration amplitude and normal grinding force. Amplitude zero in this figure represents results of conventional grinding. The experimental Results show significant improvement for UAG compared to CG in different vibration amplitudes. Apparently, the reason for these improvements is the change of the nature of the cutting process, which is transformed into a process with a multiple-impact interaction between the abrasive grits and the formed chip.

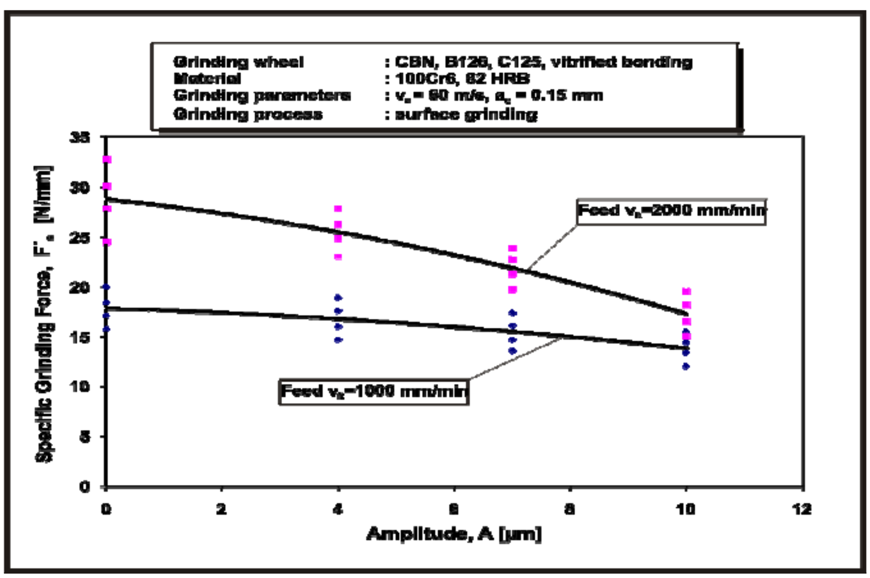

Fig. 3. Grinding force vs. Vibration Amplitude

Figs. 4–7 compare the normal grinding force and surface roughness produced by UAG with CG under different depth of cuts. Experiments were carried out at v_c=60 m/s, f=21 kHz, A=10 µm. The fire symbol shows the burning and thermal damages of the ground surface.

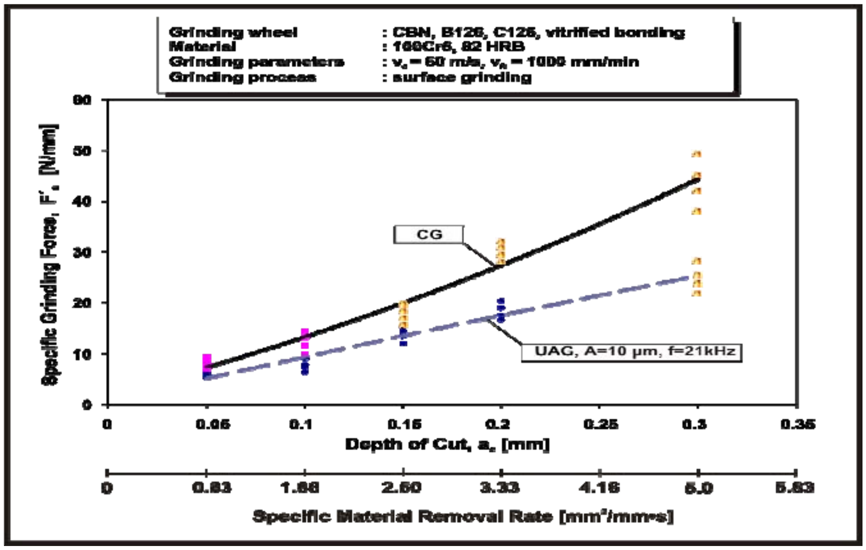

Fig. 4. Grinding force vs. Depth of cut v_{ft}=1000 mm/min (UAG: A=10µm, f=21 kHz).

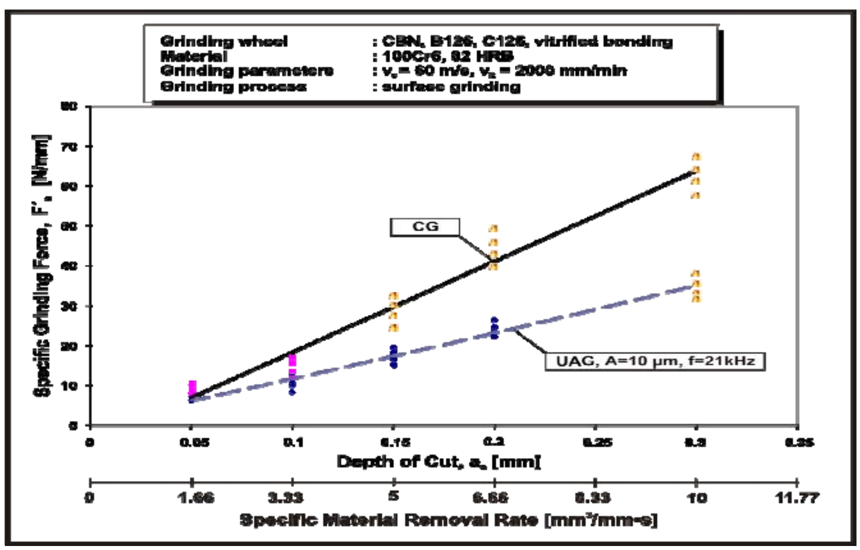

Fig. 5. Grinding force vs. Depth of cut v_{ft}=2000 mm/min (UAG: A=10µm, f=21 kHz).

The maximum oscillating accelerations (up to 174,100 m/s^2) are generated at the amplitude of 10 µm and a frequency value of 21 kHz. Due to the high frequency interaction of active grains on the workpiece, ultrasonic impact action occurs, causes the material to begin to rollover more easily as well as more micro cracking propagation in the cutting zone which both make an effective interaction between grits and workpiece surface. Therefore the grinding forces and frictional effects are decreased, so that less plastic deformation occurs.

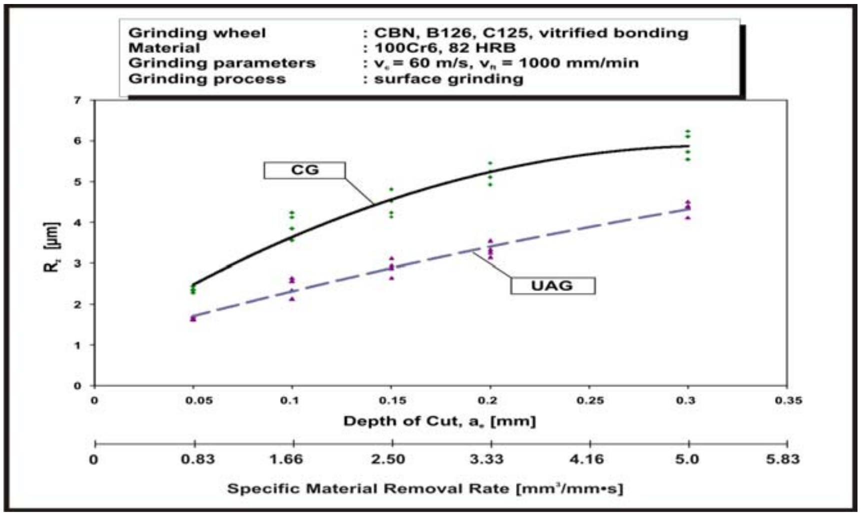

Fig. 6. R_z vs. Depth of Cut, v_{ft}=1000 mm/min (UAG: A=10µm, f=21 kHz).

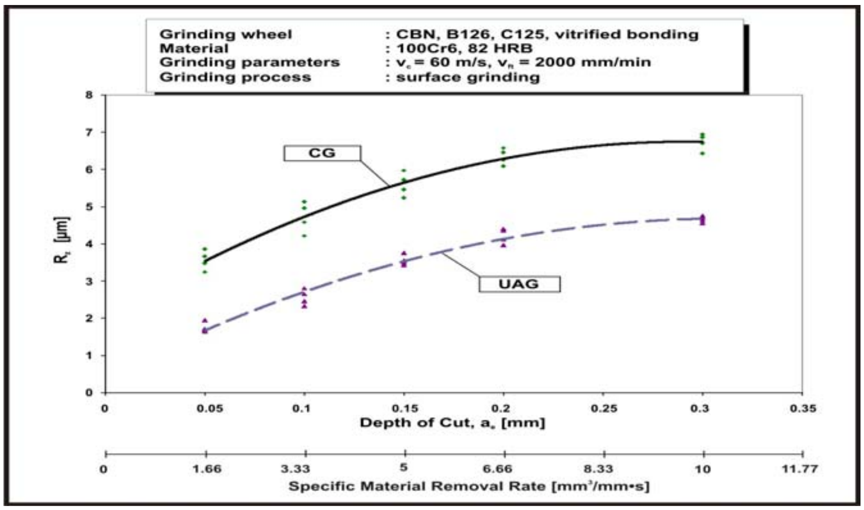

Fig. 7. R_z vs. Depth of Cut, v_{ft}=2000 mm/min (UAG: A=10µm, f=21 kHz).

Authors assume that by oscillation of the workpiece in crossfeed direction, the rubbing and plowing regimes which cause the major part of heat generation are reduced so that the grinding specific energy is also reduced and the thermal damage on the ground surface is significantly decreased.

6. Conclusion

Experimental studies of UAG and CG demonstrate considerable advantages of the former technology for grinding 100Cr6.

- Comparative experiments of the grinding forces demonstrated up to 40% reduction in normal grinding force for the workpieces machined with superimposed ultrasonic vibration. Most of CGs were unsuccessful due to the thermal damage on the ground workpiece surface. The reason for this phenomenon was due to the high grinding forces resulting to the considerable heat generation in the contact zone. These improvements are subjected to the changing in the nature of the cutting process in UAD, which is transformed into a process with a multiple-impact interaction between the tool and the formed chip resulting in interrupted cutting and reducing the grinding forces, frictional effect and plastic deformation zone.
- It was also found that UAG leads to significant improvements on the R_z parameter. It is assumed that the improvement in the R_z parameter is due to the fact that the grit in UAG has

a higher chance to cut the peak of the surface due to the crossfeed ultrasonic oscillation (sinusoidal movement of the workpiece in crossfeed direction) and increasing the possibility of the interaction of the grit and the workpiece surface in each contact length.

Our universe was structured based on the harmonic waves which their interaction makes our world so wonderful. Nature always uses the best and the simplest way, for example sound and electromagnetic waves move in a sinusoidal way. From this point of view the ultrasonic assisted grinding is a step forward to close the process to the harmony of the universe.

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Abrichten von CBN-Schleifscheiben mit Ultraschallunterstützung

Abstract:

Dressing of CBN Wheels using with ultrasonic assistance

Due to the many advantageous as well as high efficiency of Cubic boron nitride (CBN) comparing to conventional abrasives, the traditional grinding wheels have been substituted by CBN Wheels in most modern manufacturing environments. However it should also be mentioned that the full utilization of vitrified CBN grinding tools, especially in automated machinery, is only possible with appropriate preparation of CBN grinding tools. Although ultrasonic assistance has been successfully used for a long time in different machining processes, the use of its positive effects in dressing of superabrasives grinding tools is rather new so that could draw the researchers' attention to this method of conditioning in the last decade. In ultrasonic assisted dressing high-frequency and low-amplitude vibrations are superimposed on the movement of dressing tool or grinding tool. The experimental investigation carried out at the KSF Institute showed that applying ultrasonic vibration to a stationary diamond dressing tool in discontinuous mode reduces the grinding forces and increases the dressing ratio. The use of ultrasonic assistance in point crushing also reduces the grinding forces, causing a reduction of the heat generated at the grinding zone. These results demonstrate the great potential of the use of the ultrasonic assistance in dressing process.

1 Einleitung

Sowohl beim Spanen mit geometrisch bestimmten als auch beim Spanen mit geometrisch unbestimmten Schneiden können durch die Überlagerung der Kinematik des konventionellen Bearbeitungsprozesses mit einer zusätzlichen Schwingung im Mikrometerbereich bei Frequenzen im Ultraschallbereich erhebliche Prozessverbesserungen erzielt werden.

Die folgenden Punkte zählen zu den wichtigsten Vorteilen des Einsatzes der Ultraschallunterstützung bei der Materialbearbeitung [Daus04, Kapp 99, Kloc03, Sham99, Schm02, Thoe98]:

- Reduzierung der wirkenden Bearbeitungskräfte
- Verbesserung der Kühlschmierstoffzuführung in die Prozesszone
- Reduzierung der Reibung zwischen Werkzeug und Span
- Reduzierung des Werkzeugverschleißes
- Reduzierung der Materialschädigung im mikroskopischen und makroskopischen Bereich und damit Erzeugung wesentlich feinerer Strukturelemente
- Erhöhung der Formgenauigkeit der Werkstückprofile

Die Ultraschallunterstützung wird auf verschiedene Weise in der Schleiftechnik eingesetzt. Durch Einbringung von Ultraschallschwingungen in die Schleifwirkzone können wesentliche Optimierungen insbesondere beim Schleifen von Hochleistungswerkstoffen erzielt werden. Das ist vor allem auf die Änderung des Abtrennvorganges zurückzuführen [Kloc03, Uhlm01]. Es wurden bereits vielfach ultraschallunterstützte Schleifverfahren entwickelt und erprobt. Beispiele dafür zeigt das **Bild 1**.

Eine weitere Möglichkeit zur Optimierung des Schleifprozesses durch die Ultraschallschwingungen bietet der Einsatz eines schwingenden, in geringerem Abstand gegenüber der Schleifscheibe installierten Gegenstandes, der durch die Lenkung und Beschleunigung des Kühlschmierstoffs in Richtung der Schleifscheibe die Reinigungswirkung und die Abkühlungsraten an der Schleifscheibe erhöht [Maly90, Peac61]. Bei einem anderen Forschungsprojekt haben Wu u.a. [Wu04] beim spitzenlosen Außenrundschleifen die Regelscheibe durch einen elliptisch ultraschallangeregten Gegenstand ersetzt. Hierdurch konnten sie die Rundheitsgenauigkeit der Werkstücke erhöhen.

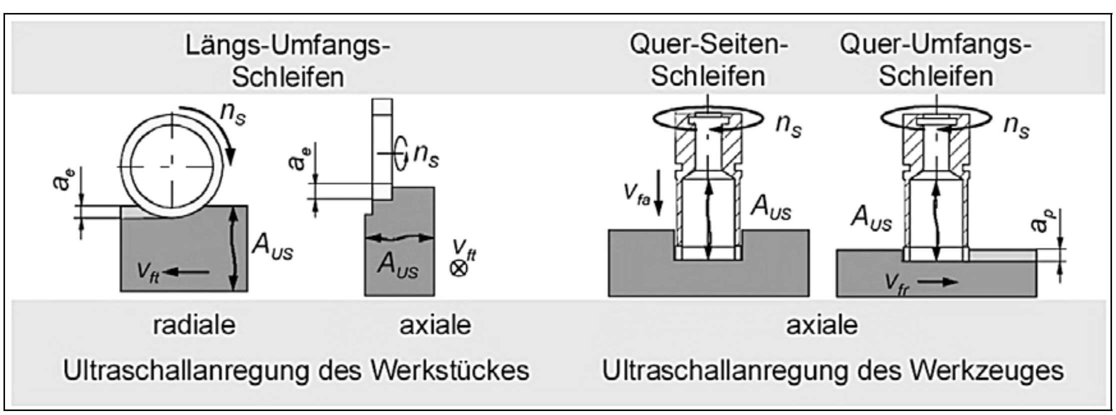


Bild 1: Beispiele für ultraschallunterstützte Schleifenverfahren [Uhlm01]

Obwohl die Ultraschallunterstützung schon längst in den unterschiedlichen Bearbeitungsprozessen verwendet wird, ist deren Einsatz beim Abrichten von hochharten Schleifwerkzeugen ein neues Verfahren, das in der letzten Dekade die Aufmerksamkeit der Forscher auf sich gezogen hat.

Über die ersten Untersuchungen zum ultraschallunterstützten Abrichten von CBN-Schleifscheiben wurde von Ikuse u.a. im Jahr 1996 berichtet, wobei stehende Diamantwerkzeuge mit einer Frequenz von etwa 33 kHz und einer im lastfreien Zustand maximalen US-Amplitude von 2,5 µm beaufschlagt wurden. Durch den Einsatz der Ultraschallunterstützung beim Abrichten konnte eine Senkung der Schleifkräfte und eine Verbesserung der Werkstückrauheit, sowie eine des Abricht-Verschleißverhältnisses nachgewiesen werden [Ikus96].

Durch den Einsatz von longitudinalen Ultraschallschwingungen beim Profilieren von einer keramisch gebunden bzw. kunstharzgebunden Diamantschleifscheibe mit einem Diamant-Abrichttopf konnte Liebe höhere Abrichtbeträge gegenüber dem konventionellen Abrichten erreichen, wobei der Winkel zwischen den Rotationsachsen der Schleifscheibe und des Abrichttopfes 75° betrug. Beim ultraschallunterstützten Abrichten von der keramischen Schleifscheibe wurden jedoch durch die Schwingungen Risse in der Bindung induziert, die bei nachfolgenden Schleifversuchen zu einer Reduzierung des Schleifverhältnisses führten. In anschließenden Schleifversuchen mit Kunstharzschleifscheiben zeigte sich bei annähernd gleichem Kraftniveau über den Prozessverlauf ein größerer Gradient bei der ultraschalunterstützt abgerichteten Schleifscheibe, was auf ein vergleichsweise schnelleres Abstumpfen der scharfen Schneidkanten zurückzuführen ist [Lieb96].

Ebenfalls hat Sroka Untersuchungen bei der Profilierung von kunstharzgebunden Diamantschleifscheibe mit einem rotierenden Diamant-Abrichttopf, der mit Schwingungen im Ultraschallbereich beaufschlagt wurde, durchgeführt. Durch die Ultraschallunterstützung konnte er das Abrichtverhältnis auf 10fache steigern und die Profilkosten um 59% reduzieren [Srok05].

Nomura et al. untersuchten den Effekt der Ultraschallschwingung auf das Abrichten und Touchieren von kleinen CBN-Schleifscheiben zum Innenrundschleifen. Bei den Untersuchungen wurde der Schleifstift mit einer longitudinalen Ultraschallschwingung beaufschlagt, womit eine Reduzierung der beim Touchieren auftretenden Kräfte um über 22% und eine Verbesserung der Schleifscheiben-Rundheit um etwa 30% nachgewiesen werden konnte [Nomu05].

Aufgrund der großen Bedeutung des Abrichtprozesses beim Einsatz von CBN-Schleifscheiben und dessen derzeit vorhandenen Schwierigkeiten und Probleme, wie z. B. der schnelle Verschleiß von Abrichtwerkzeugen, befasst sich *„Kompetenzzentrum für Schleiftechnologie und Feinstbearbeitung“* der Hochschule Furtwangen intensiv mit Fragestellungen auf dem Gebiet der Abrichttechnologie [Tawa05, Tawa06, Tawa08]. Hier werden einige der Resultate der durchgeführten Untersuchungen zur Ermittlung des Einflusses der Ultraschallunterstützung beim Abrichten mit einem stehenden bzw. einer freilaufenden Diamantcrushierrolle dargestellt.

2 Ultraschallunterstütztes Abrichten

Beim ultraschallunterstützten Abrichten wird der konventionellen Wirkbewegung des Prozesses eine Ultraschallbewegung überlagert, wobei die Ultraschallunterstützung durch eine Schwinganregung des Abrichtwerkzeugs in die Kontaktzone eingebracht wird. Das ultraschallunterstützte Abrichten lässt sich sowohl mit stehenden als auch mit rotierenden Abrichtwerkzeugen realisieren (**Bild 2**).

Beim ultraschallunterstützten Abrichten können in Abhängigkeit von der Ultraschallamplitude A_{US} und der Abrichtzustellung a_{ed} zwei unterschiedliche Kontaktarten auftreten: der kontinuierliche Eingriffsmodus und der unterbrochene Eingriffsmodus (**Tabelle 1**).

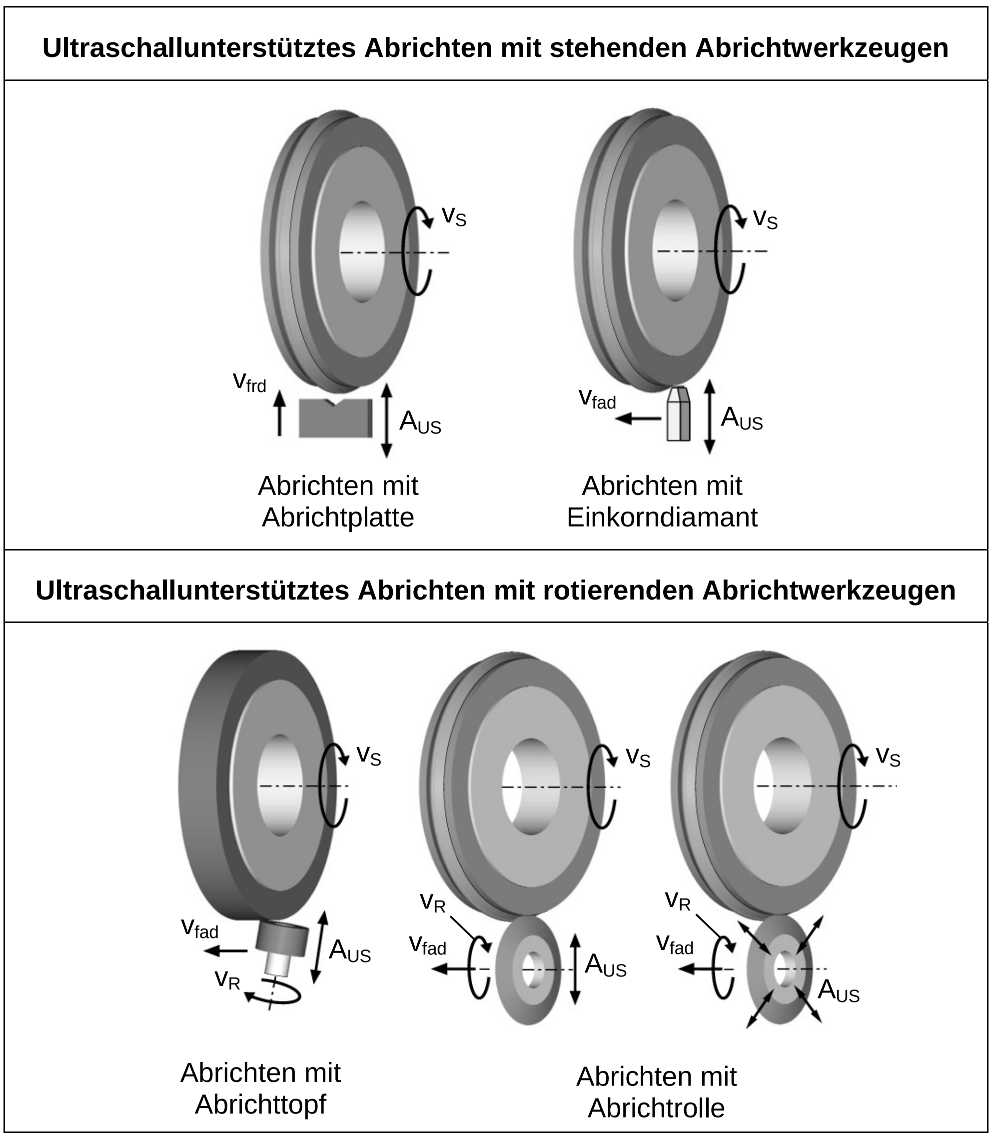


Bild 2: Verfahren des ultraschallunterstützten Abrichtens

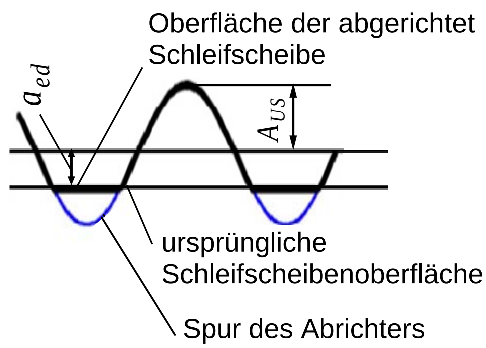
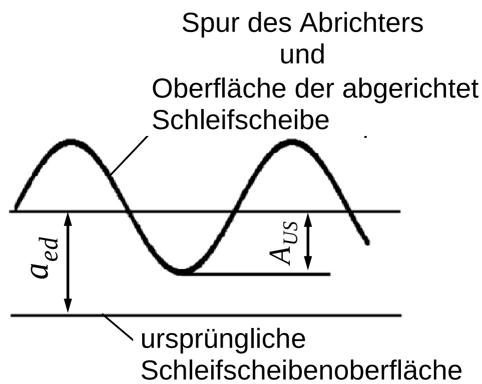
Abrichtmodus	Bedingung	Darstellung	Beschreibung
unterbrochener Modus	$a_{ed} < A_{US}$		Der Abrichter stößt diskontinuierlich an die Schleifscheibe; Es gibt Zonen auf der Oberfläche der Schleifscheibe, die vom Abrichter nicht berührt werden.
kontinuierlicher Modus	$a_{ed} \geq A_{US}$		Der Abrichter stößt diskontinuierlich an die Schleifscheibe; Die Ortskurve der Schleifscheibe ist sinusförmig

Tabelle 1: Zwei unterschiedliche Kontaktarten beim ultraschallunterstützten Abrichten mit einem stehenden Diamantwerkzeug [Jiao06]

Beim ultraschallunterstützten Abrichten mit rotierenden Abrichtwerkzeugen bezeichnet der unterbrochene Modus diejenigen Kontaktart, in dem es aufgrund der Ultraschallschwingung zu einem Freischneiden und erneutem Einschneiden des Abrichtkornes während eines Korneingriffes kommt. Beim unterbrochenen Eingriffsmodus mit stehenden Abrichtwerkzeugen sind die Abrichtkräfte durchschnittlich kleiner und gleichmäßiger. Das führt zu einer gleichmäßigeren Höhe der während des Abrichtens erzeugten Mikroschneiden [Jiao06].

Zur Erzeugung der Ultraschallschwingungen wird vorwiegend ein piezoelektrischer Schallwandler eingesetzt, der anhand vom piezoelektrischen Effekt die elektrische Energie in eine elastomechanische Schwingung umwandelt. Die Bereitstellung der hochfrequenten elektrischen Wechselspannung erfolgt durch die Umwandlung von niederfrequenter Netzspannung in einem Spannungsgenerator. Die longitudinal stehenden Ultraschallwellen wurden mit einem Amplitudentransformator vom Schallwandler auf das Abrichtwerkzeug übertragen. **Bild 3** zeigt eine schematische Darstellung der Versuchsanordnung beim Abrichten mit stehenden Abrichtwerkzeugen.

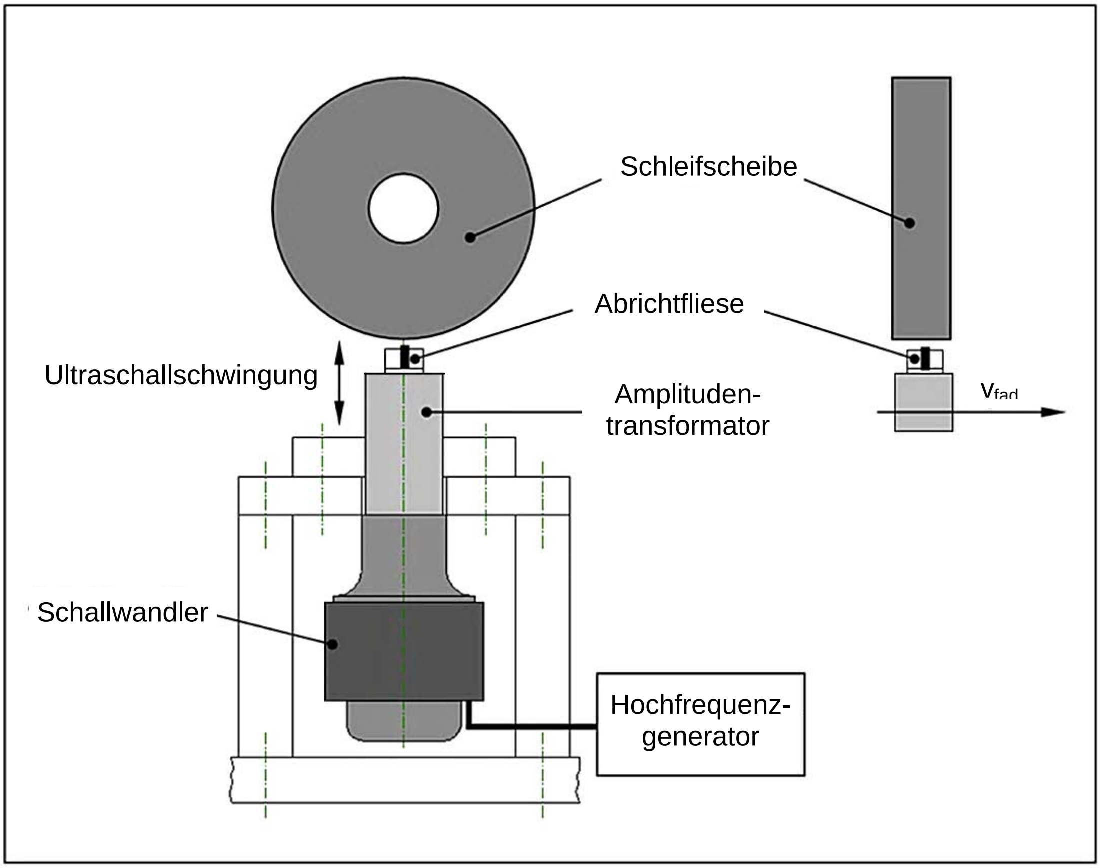


Bild 3: Schematische Darstellung der Versuchsanordnung beim Abrichten mit einem stehenden Abrichtwerkzeug

3 Versuchsbedingungen und -resultate

3.1 Ultraschallunterstütztes Abrichten mit dem stehenden Abrichtwerkzeug

Die Ermittlung des Einflusses der Ultraschallunterstützung beim Abrichten mit stehenden Diamantwerkzeuge auf die Schleifergebnisse erfolgte unter Verwendung einer keramisch gebundenen CBN-Schleifscheibe mit der Korngröße B126. Die Versuchsbedingungen sind in **Tabelle 2** angegeben. Die Abrichtversuche wurden im unterbrochenen Modus durchgeführt.

In **Bild 4** sind die bezogenen Schleifkräfte F'_n und F'_t in Abhängigkeit von der tangentialen Vorschubgeschwindigkeit v_{ft} und des bezogenen Zeitspanungsvolumens Q'_w dargestellt, wobei das Auftreten von Schleifbrand mit einem Feuer-Symbol markiert ist. Es zeigt sich, dass der Einsatz der Ultraschallunterstützung beim Abrichten von keramisch gebundenen CBN-Schleifscheiben zur Reduzierung der Schleifkräfte und der Schleifbrandgefahr führt. Der Hauptgrund dafür ist eine optimierte Erzeugung von Mikroschneiden und Spanräume im CBN-Belag durch die Ultraschallunterstützung, welche die Reibung reduziert und den Spanbildungsprozess begünstigt [Lieb96].

Werkzeugmaschine	CNC-Flachschleifmaschine vom Typ „MICRO-CUT AC 8 CNC“ der Firma ELB-Schliff
Schleifscheibe	keramisch gebundene CB-Schleifscheibe, B126 C125; Ø300 mm x Ø127 mm x 20 mm
Schleifbedingungen	Werkstück: 100Cr6, 60 HRC; v_{ft}= 400-1200 mm/min, v_c= 50 m/s, a_e= 0,02 mm; Kühlschmierstoff: Schleiföl, 100 l/min
Abrichtwerkzeug	CVD-Abrichtfliese
Bedingungen des konventionelln Abrichten	v_{cd} = 50 m/s, a_{ed} = 3 µm, v_{fad}= 200 mm/min; Kühlschmierstoff: Schleiföl, 100 l/min
Bedingungen des ultraschallunterstützten Abrichten	Ultraschallamplitude: A_{US} = 3 µm; Ultraschallfrequenz: f_{US} = 18,750 kHz; v_{cd} = 50 m/s, a_{ed} = 0 µm, v_{fad}= 200 mm/min; Kühlschmierstoff: Schleiföl, 100 l/min

Tabelle 2: Versuchsbedingungen – Abrichtfliese

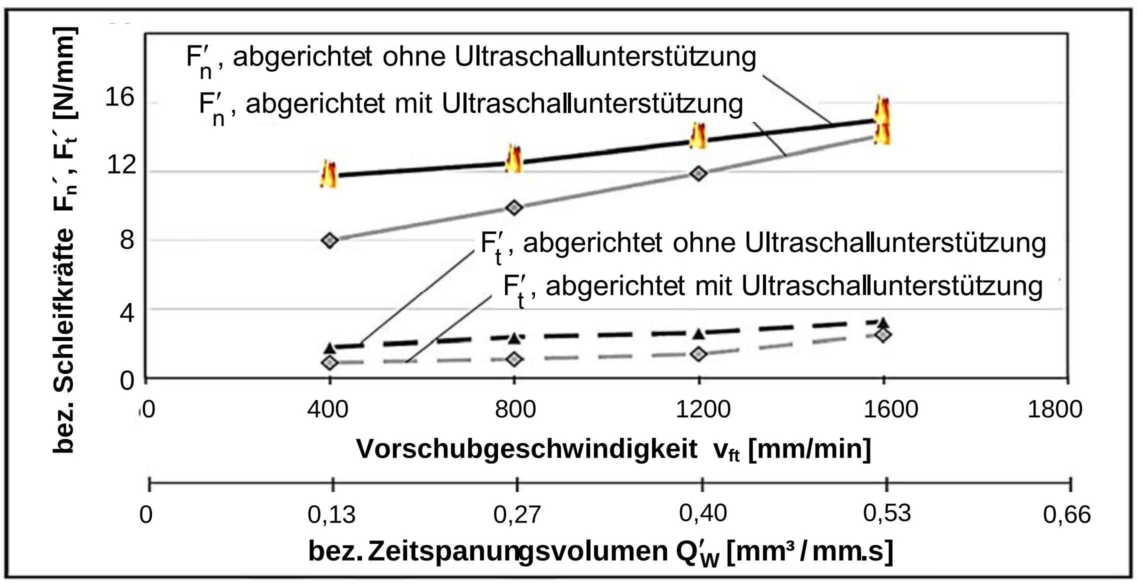


Bild 4: Reduzierung der Schleifkräfte durch den Einsatz der Ultraschallunterstützung beim Abrichten mit CVD-Abrichtfliese

Bild 5 zeigt, dass der Einsatz der Ultraschallunterstützung beim Abrichten mit stehenden Abrichtwerkzeugen zu einem raueren CBN-Belag.

In **Bild 6** sind die Profile zweier verschiedener Oberflächen, die mit unter unterschiedlichen Bedingungen abgerichteten Schleifscheiben geschliffen wurden, einander gegenübergestellt. Dabei wird eine Verbesserung der Profilgenauigkeit durch die Ultraschallunterstützung beim Abrichten deutlich. Der Grund dafür kann an der Reduzierung der Abrichtkräfte liegen.

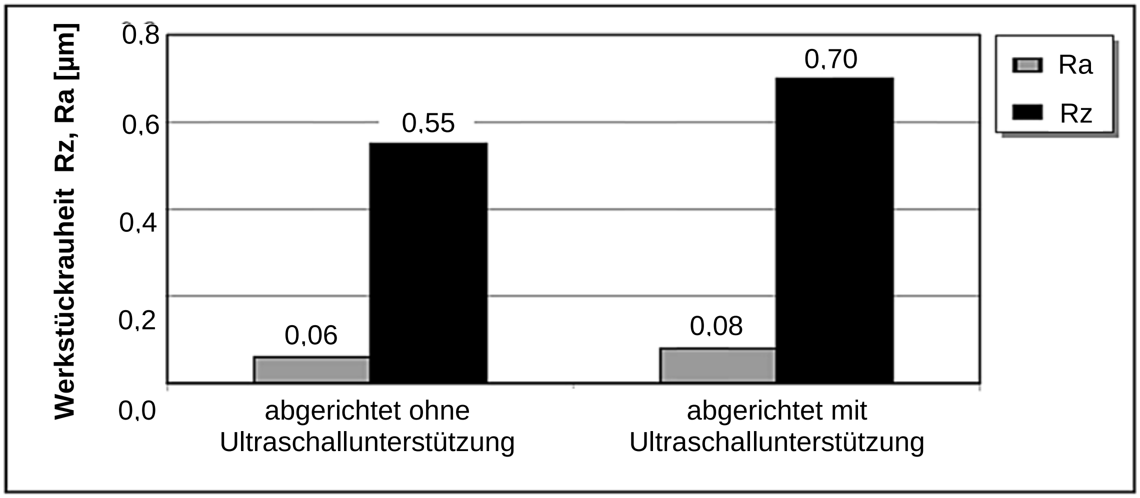


Bild 5: Einfluss der Ultraschallunterstützung beim Abrichten auf die Rauheit des geschliffenen Werkstück beim Abrichten mit CVD-Abrichtfliese

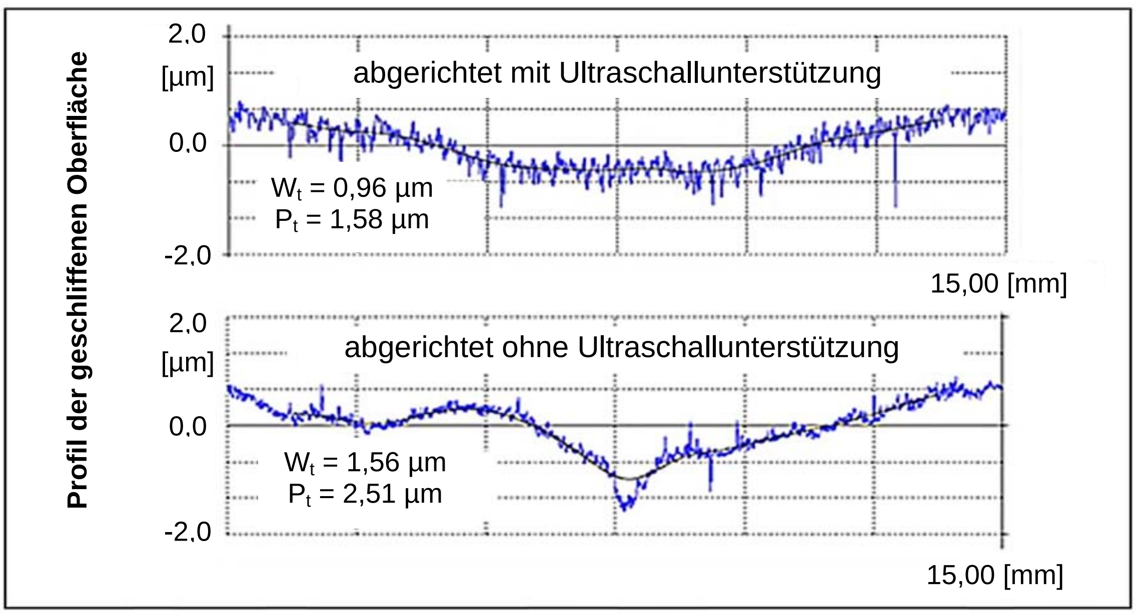


Bild 6: Verbesserung der Profilgenauigkeit durch die Ultraschallunterstützung beim Abrichten mit CVD-Abrichtfliese

Bild 7 stellt die Abricht-Verschleißquotienten D für konventionelles und ultraschallunterstütztes Abrichten dar, wobei das Verhältnis D das abgerichtete Kornvolumen der CBN-Schleifscheibe V_{CBN} auf das Verschleißvolumen des Abrichtwerkzeuges V_D bezieht. Der Abricht-Verschleißquotient steigt dabei von 906,5 beim konventionellen auf 2323,4 beim ultraschallunterstützten Abrichten an. Die Verschleißreduzierung ist im Wesentlichen auf die Reduzierung des Reibungskoeffizienten und damit der Wärmeentwicklung durch die Ultraschallschwingungen zurückzuführen. Dadurch wird die Gefahr einer Graphitisierung des Abrichtdiamanten, welche in direktem Zusammenhang mit der Verschleißausbildung am Abrichtdiamanten und den Abtragsmechanismen an der Schleifscheibe steht, reduziert.

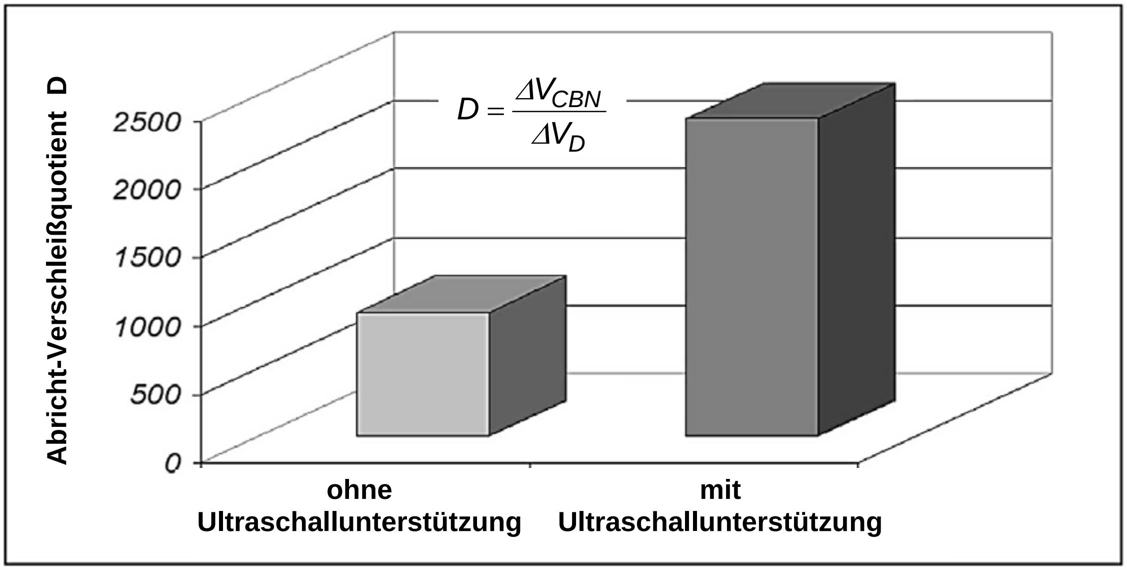


Bild 7: Abricht-Verschleißquotient D

In **Bild 8** sind die REM-Aufnahmen der Diamantstäbchen nach dem Abrichtprozess dargestellt. Im Vergleich zum konventionellen Abrichtprozess zeigt die Oberfläche des Diamanten beim ultraschallunterstützten Abrichten einen wesentlich gleichmäßigeren Verschleiß mit geringen abrasiven Spuren und kaum Kornabsplitterungen in der Randzone des Diamanten. Darüber hinaus weist das Trägergefüge hier nur geringe Beschädigungen auf, welche auf die Reduzierung der Wärmeentwicklung zurückzuführen ist.

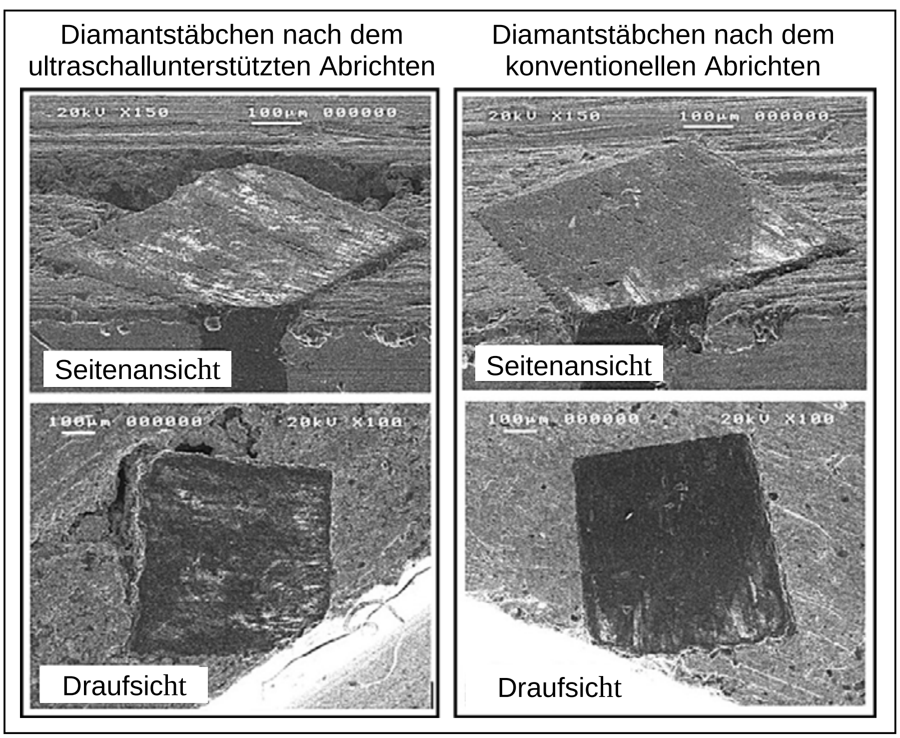


Bild 8: REM-Aufnahmen der Diamntstäbchen

3.2 Ultraschallunterstütztes Crushieren

Das Crushierverfahren ist ein Sonderverfahren des Konditionierens der Schleifwerkzeugen mit rotierenden Abrichtwerkzeugen, bei dem das Verhältnis der Umfangsgeschwindigkeit der Abrichtrolle v_r zu der Umfangsgeschwindigkeit der Schleifscheibe v_s, das als das Abrichtgeschwindigkeitsverhältnis q_d bezeichnet wird, gleich eins ist. In Abwesenheit der Relativgeschwindigkeit zwischen Schleifscheibe und Abrichtrolle beruht das Wirkprinzip des Crushierens auf dem Zerbrechen von Bindungsbrücken durch die Normalkraft. Daher ist das Crushieren nur bei Schleifscheiben mit spröden Bindungssystemen wie Keramik oder Sprödbronze einsetzbar. Beim Eintritt eines Punktes der Crushierrolle in die Schleifscheibentopographie wirkt eine Normalkraft zwischen den Wirkpartner, die bei Überschreiten eines bestimmten Kraftniveaus zum Zerbrechen von Bindungsbrücken im Schleifbelag führt, so dass das Schleifscheibenprofil generiert wird. Dabei wird zwischen Vollcruschieren und Punktcrushieren unterschieden. Beim Vollcrushieren wird eine Profilrolle und beim Punktcrushieren wird eine Diamantformrolle als Abrichtwerkzeug eingesetzt [Hess03].

Zur Ermittlung des Einflusses der Ultraschallunterstützung beim Punktcrushieren wurde eine freilaufende Crushierrolle mit einem PKD-Belag mit Schwingungen im Ultraschallbereich in Richtung der Schleifscheibe beaufschlagt (**Bild 9**). Die Versuchsbedingungen sind in **Tabelle 3** angegeben. Die Abrichtversuche wurden hier ebenfalls im unterbrochenen Modus durchgeführt.

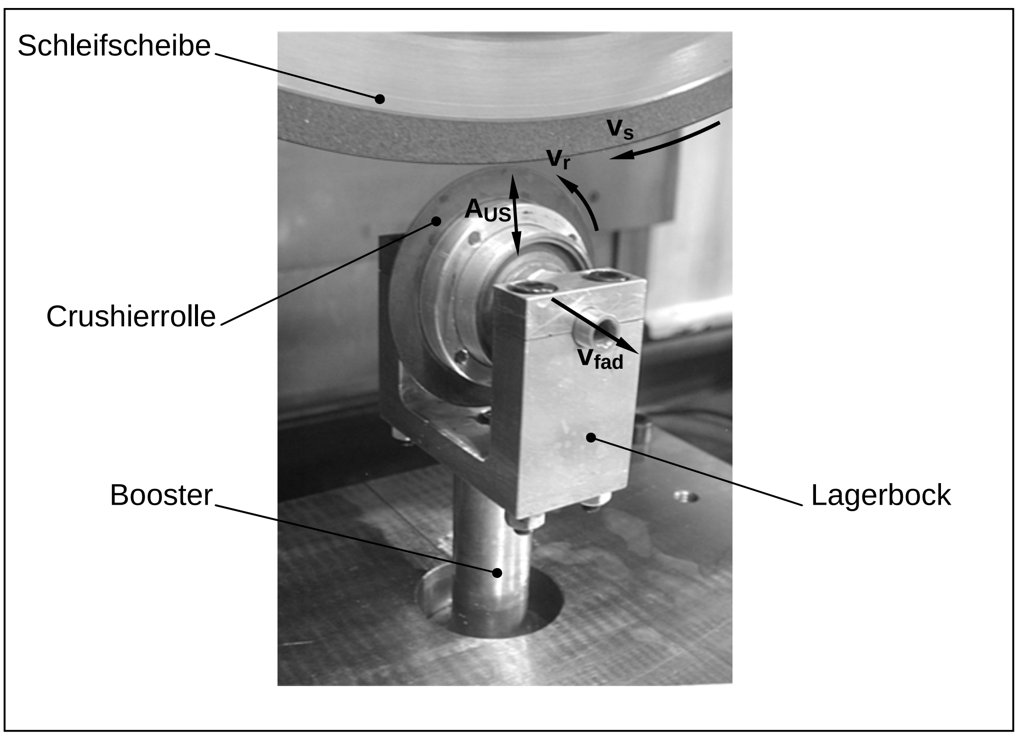


Bild 9: Versuchsaufbau beim ultraschallunterstützten Crushieren

Werkzeugmaschine	CNC-Flachschleifmaschine vom Typ „MICRO-CUT AC 8 CNC“ der Firma ELB-Schliff
Schleifscheibe	keramisch gebundene CB-Schleifscheibe, B126 C125; Ø400 mm x Ø203,2 mm x 15 mm
Schleifbedingungen	Werkstück: 100Cr6, 60 HRC; v_{ft}= 500-2000 mm/min, v_c= 25 m/s, a_e= 0,05-1,25 mm; Kühlschmierstoff: Lösung, 120 l/min
Abrichtwerkzeug	Crushierrolle mit PKD-Belag
Bedingungen des konventionelln Abrichten	v_{cd} = 25 m/s, a_{ed} = 3 µm, v_{fad}= 120 mm/min; Kühlschmierstoff: Lösung, 120 l/min
Bedingungen des ultraschallunterstützten Abrichten	Ultraschallamplitude: A_{US} = 3 µm; Ultraschallfrequenz: f_{US} = 20kHz; v_{cd} = 25 m/s, a_{ed} = 0 µm, v_{fad}= 120 mm/min; Kühlschmierstoff: Lösung, 120 l/min

Tabelle 3: Versuchsbedingungen – Crushierrolle

In **Bilder 10 und 11** sind die bezogenen Schleifkräfte F'_n und F'_t in Abhängigkeit von der Schleifzustellung bzw. der Vorschubgeschwindigkeit v_{ft} dargestellt. Deutlich ist zu erkennen, dass der Einsatz der Ultraschallunterstützung beim Crushieren zur Reduzierung der Schleifkräfte führt, welche auf die Erzeugung einer raueren Schleifscheibentopographie durch die Ultraschallunterstützung zurückzuführen ist. Dies ist dadurch zu erklären, dass durch die Ultraschallschwingung sowohl Rissbildung an den Bindingbrücken sowohl Kornsplitterung an den Schleifkorn intensiver wird.

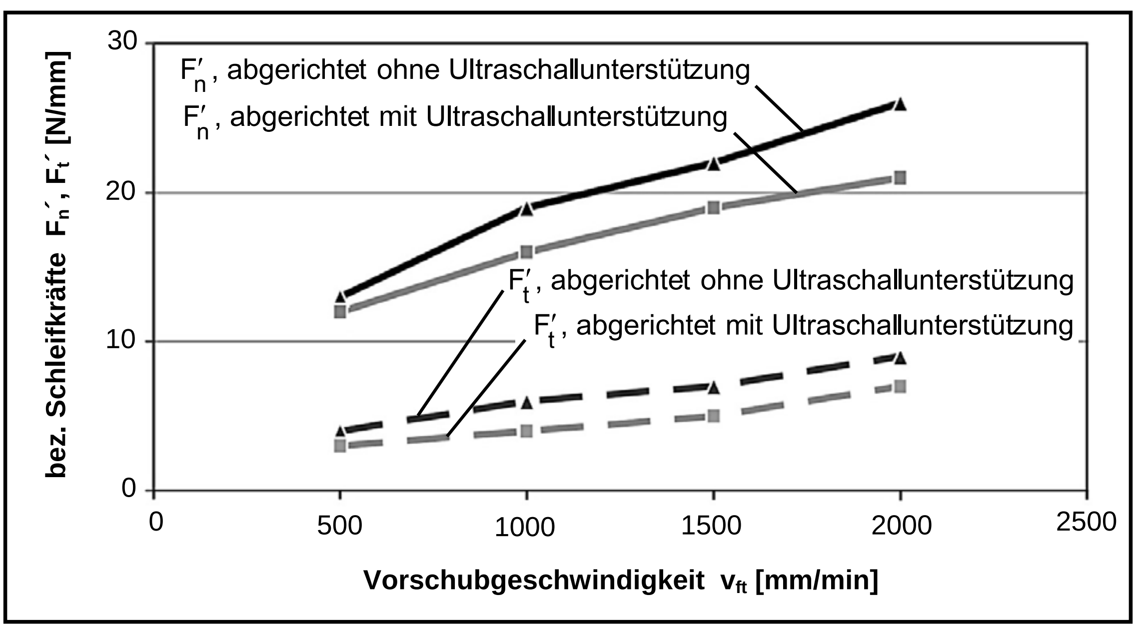


Bild 10: Einfluss des Einsatz der Ultraschallunterstützung beim Crushieren auf die Schleifkräfte bei einer Schleifzustellung von 0,05 mm

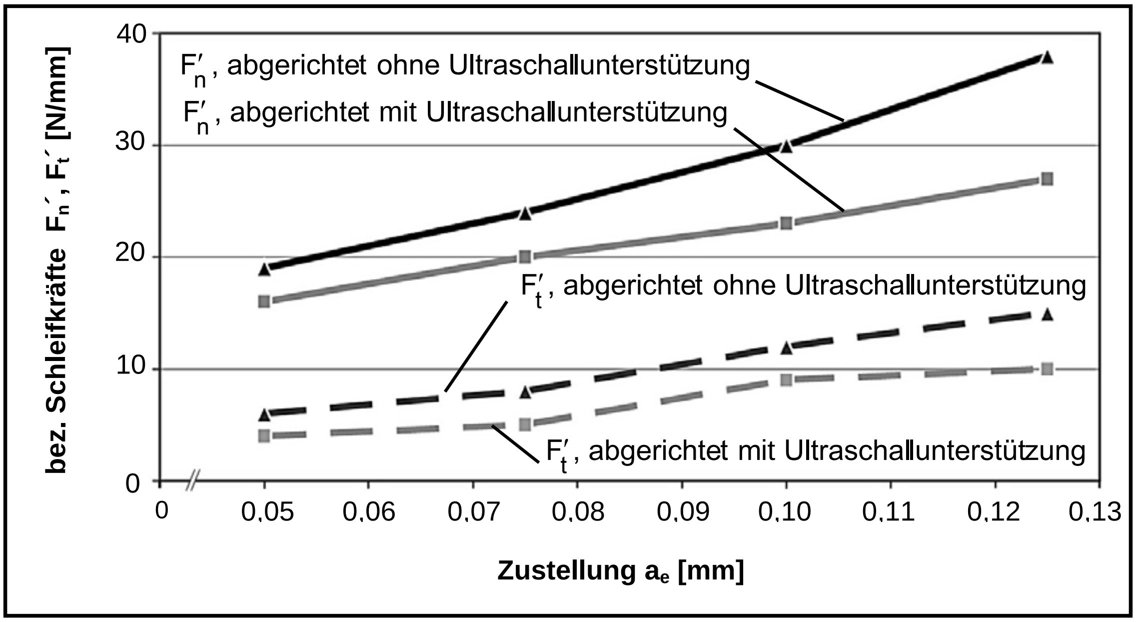


Bild 11: Einfluss des Einsatz der Ultraschallunterstützung beim Crushieren auf die Schleifkräfte bei einer Vorschubgeschwindigkeit von 1000 mm/min

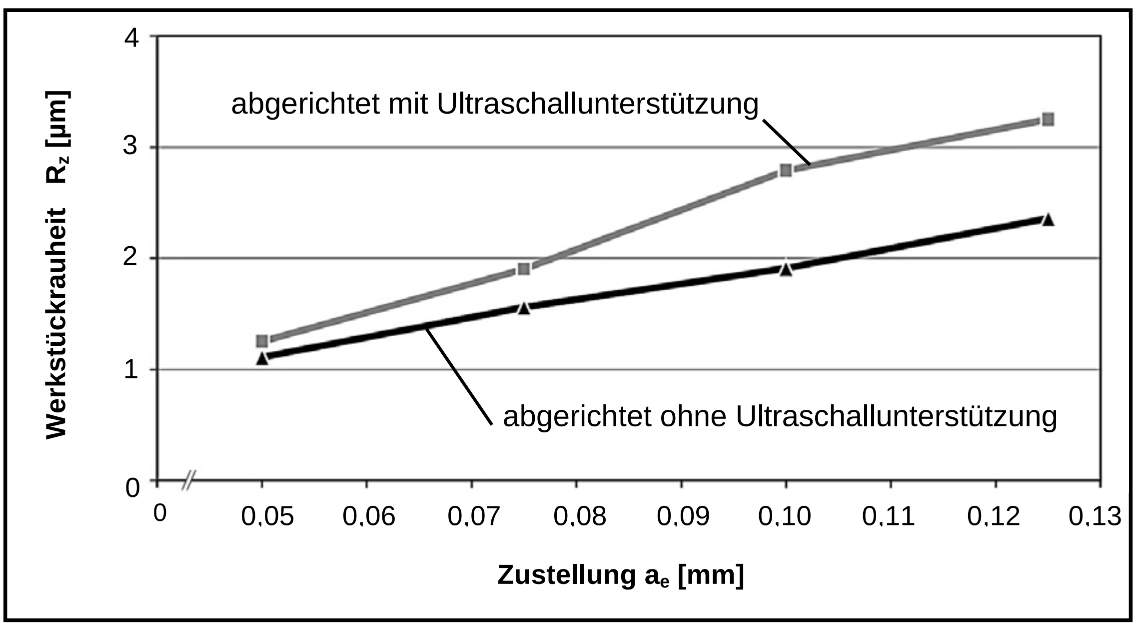


Bild 12: Einfluss des Einsatz der Ultraschallunterstützung beim Crushieren auf die Werkstückrauheit bei einer Vorschubgeschwindigkeit von 1000 mm/min

Bild 12 zeigt den Einfluss der Ultraschallunterstützung beim Crushieren auf die Werkstückrauheit. Das weist wiederum auf eine rauere Schleifscheibentopographie hin.

4 Zusammenfassung

Der Einsatz der Ultarschallunterstützung beim Abrichten von keramisch gebundenen CBN-Schleifscheiben mit einem stehenden Abrichtwerkzeug im unterbrochenen Modus führt zu einer Reduzierung des Abrichtdiamantenverschleißes und einer Erhöhung der Schleifscheibenprofilgenauigkeit. Die Reduzierung der Schleifkräfte und damit die Verminderung der Wärmeentwicklung in der Schleifkontaktzone aufgrund einer optimierten Schleifscheibentopographie sind weitere positive Einflusse des ultarschallunterstützten Abrichtens im Verglleich zum konventionellen Abrichten. Der Einsatz der Ultarschallunterstützung beim Crushieren führt ebenfalls zur Reduzierung der Schleifkräfte.

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Ultrasonic-assisted drilling of Inconel 738-LC

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Abstract

Generally in the drilling of modern aviation materials such as nickel and titanium base super alloys, problems frequently occur in terms of burr formation at the cutter exit, tool stress, high heat generation on tool surface as well as low process reliability. A recent and promising method to overcome these technological constraints is the use of ultrasonic assistance, where high-frequency and low-amplitude vibrations are superimposed on the movement of cutting tools. This paper presents the design of an ultrasonically vibrated tool holder and the experimental investigation of ultrasonically assisted drilling of Inconel 738-LC. The circularity, cylindricity, surface roughness and hole oversize of the ultrasonically and conventionally drilled workpieces were measured and compared. The obtained results show that the application of ultrasonic vibration can improve the hole quality considerably. Improvements of up to 60% have been achieved.

Keywords: Drilling; Rotary ultrasonic machining; Ultrasonic-assisted drilling; Nickel-based super alloys; Hole quality

1. Introduction

A range of new alloys and composite materials are being developed every day for various engineering applications. Many of these new materials are difficult to drill with the existent conventional drilling (CD) technology. CD of modern nickel- and titanium-based super alloys used in aerospace applications and in gas turbine blades causes high tool temperatures and subsequently rapid wear of cutting edges due to their high strength and abrasivity even at relatively low cutting speeds. A growing demand for machining these intractable materials requires new advanced drilling technology. A recent and promising technique to overcome these technological constraints is known as ultrasonic-assisted drilling (UAD). The principle of this technique is adding high frequency (16–40 kHz) and low peak-to-peak (pk-pk) vibration amplitude (2–30 μm) in the feed direction to the tool or workpiece. This cutting process is distinct from ultrasonic drilling. Ultrasonic drilling, also known as rotary ultrasonic machining, is a specific class of ultrasonic machining. In ultrasonic machining, metal removal is effected with the help of abrasive grains suspended in a slurry, which are made to strike repeatedly upon the workpiece surface by a tool oscillating ultrasonically. Ultrasonic drilling is an ultrasonic machining process with a rotating cylindrical tool. The rotation of the tool enhances the abrasive process and causes higher accuracy when generating cylindrical shape elements. Ultrasonic drilling is only applicable to brittle materials. On the other hand, UAD is a hybrid process of CD and ultrasonic oscillation. It is applicable to both ductile and brittle materials. Different researchers have reported significant improvements in thrust force, burr size, tool wear and noise reduction and surface finish. Chang and Bone [1] have shown that burr size reduction in drilling aluminium is possible with UAD. Neugebauer and Stoll [2] have experimentally demonstrated that in UAD of aluminium alloys, force and moment reductions of 30–50% are possible and the reduced load of the tool's cutting edge enabled an up to 20-fold increase in tool life over conventional cutting. Zhang et al. [3] have both theoretically and experimentally concluded that there exists an optimal vibration condition such that the thrust force and torque are minimized. Onikura et al. [4,5] utilized a piezoactuator to generate 40 kHz of ultrasonic vibration in

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the drilling spindle. They found that the use of ultrasonic vibration reduces the friction between chip and rake face, resulting in chips which are thinner and can therefore lead to the reduction of cutting forces. Jin and Murakawa [6] found that the chipping of the cutting tool can effectively be prevented by applying ultrasonic vibration and tool life can be prolonged accordingly. Takeyama and Kato [7] found that the mean thrust force in drilling can be greatly reduced under ultrasonic vibrations. Drilling chips are thinner and can be removed more easily from the drilled hole. Burr formation at the entrance and the exit sides is greatly reduced with the low cutting forces. Thus, the overall drilling quality is improved with the employment of UAD.

Using ultrasonic vibrations in machining processes causes considerable advantages for machining intractable materials. It has been shown that the use of ultrasonic vibration in turning procedures improves the surface quality significantly and reduces the width of the hardened surface layer, a result of the extensive deformation and high-temperature processes during the turning procedures. It also reduces the average cutting forces up to several times in the process [8,9].

In this investigation, a UAD system has been designed, fabricated and tested. Improvements of cylindricity, circularity, hole oversize, drill skidding and inner surface roughness of the drilled hole due to superimposing of ultrasonic vibration in the drilling of Inconel 738-LC have been obtained. The effect of vibration amplitude, spindle speed, feed rate on cylindricity, circularity and surface roughness has been investigated. The use of two different coated drills for tool wear reduction has also been studied.

2. Design and fabrication of UAD system

In order to study UAD, an actuated tool holder has been designed and built. Fig. 1a illustrates schematically the experimental set-up. The tool holder consists of a piezoelectric transducer, a horn and a special fixture. The ultrasonic power supply converts 50 Hz electrical supply to high-frequency (21 kHz) electrical impulses. These high-frequency electrical impulses are fed to a piezoelectric transducer and transformed into mechanical vibrations of ultrasonic frequency (21 kHz), due to the piezoelectric effect. The vibration amplitude is then amplified by the horn and transmitted to the drill attached to the horn. The resultant vibration of the drill fixed in the tool holder reaches 10 μm (i.e. 20 μm peak to peak) at a frequency of about 21 kHz. Vibration is applied to the drill in the feed direction of the workpiece. The amplitude of the ultrasonic vibration can be adjusted by changing the setting on the power supply. The workpiece is clamped in the chuck of a universal lathe and rotates at a constant speed. The experimental set-up used to study UAD is shown in Fig. 1b.

The design for the UAD acoustic head is based on the following considerations:

1. Effective vibration of the drill is achieved when it is used as a wave guide (another tune length) for amplification of vibration amplitude. So modal analysis was used to

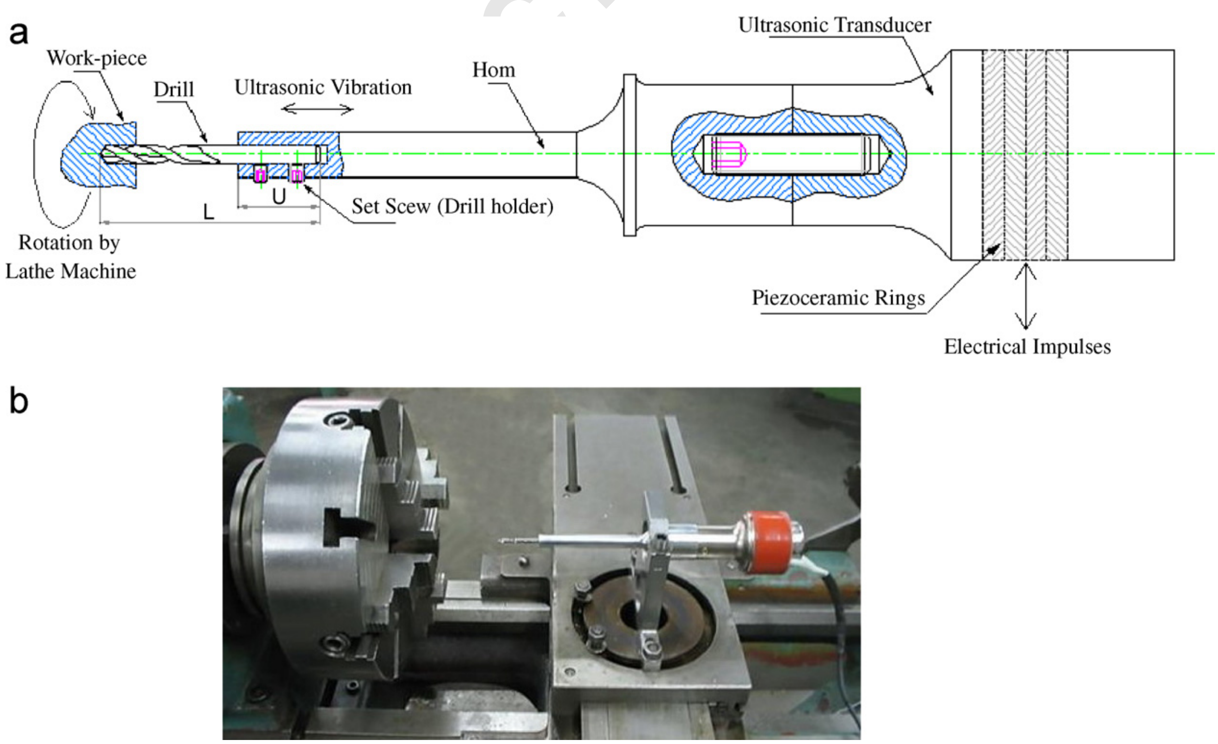

Fig. 1. (a) Scheme of the experimental set-up. (b) Experimental set-up for ultrasonic assisted drilling.

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find the optimum total length of the drill (L) and the optimum length of the drill part which is inside the horn (U) (see Fig. 1a), so that the acoustic head may reach a resonance frequency of about 21 kHz (the desired vibration condition).

2. The whole structure must possess enough stiffness to withstand the dynamic loads during the drilling operation. The acoustic head parts should have high fatigue resistance and low acoustic losses (meaning that they should not absorb too much energy from the vibrations). Each part of the acoustic head is made of aluminium 7075-T6 with high strength, high fatigue resistance and very good acoustic properties to provide enough stiffness and low acoustic losses. The fixture which clamps the acoustic head is made of steel.

3. Experiments

The experimental equipment consists of the following:

- Universal lathe machine (Tabriz-TN40A): to perform drilling experiments.
- Column drilling machine (Tabriz-MR2): to perform drilling experiments.
- Generator (Mastersonic MMM generator-MSG.1200.IX): to convert 50 Hz electrical supply to high-frequency electrical impulses. The frequency range of the generator is 19.020 to 46.728 kHz and the frequency step is 1 Hz. The power of the generator is 1200 W and the maximum output current is 3 A.
- Laser displacement metre (Keyence LC-2430): to measure the amplitude of vibration. The sampling rate of this sensor is 50 kHz. The resolution is 0.01 mm and the laser beam spot is 12 mm.
- CNC three axial CMM machine (Cincinnati-DISK LK G80): to measure the hole cylindricity, hole circularity and hole oversize.
- Hand held surface roughness tester (Time group, TR200): to measure the surface roughness of the drilled holes.
- Toolmakers microscope (Olympus-STM): to observe the burrs at the cutter exit, which possesses a maximum magnification of 200 times with a resolution of 0.5 mm.
- Drill: Diameter of 5 mm, TiAlN-coated carbide drills (Dormer-R522) and TiN-coated carbide drills (Dormer-R550).
- Workpiece material: Inconel 738-LC ($45 \times 35 \times 8\,\text{mm}^3$).
- UAD performed without coolant (i.e. dry cutting).

Inconel 738-LC is a high-grade heat-resistant Ni-based super alloy widely used in the gas turbine blades and aerospace industry. The excellent material toughness results in difficulty in chip breaking during the process. In addition, precipitate hardening of γ'' secondary phase (Ni_3Nb) together with work-hardening during machining makes the cutting condition even worse. All these difficulties lead to serious tool wear and less material removal rate (MRR). This material is very abrasive and causes tool blunting and high cutting temperatures when machined conventionally.

4. Experimental results and discussion

In this experiment, the tests were carried out for both UAD and CD with the same instrument. However, during the CD the ultrasonic generator was switched off. All CDs were unsuccessful and the drills broke at the cutter exit. It is thought that the reason for this phenomenon was because the drills were caught in the burrs formed during drilling at the cutter exit, resulting in the breakage of the drills. Fig. 2 shows photographs of the burrs produced at the cutter exit during the drilling tests. In order to be certain that the problems which arise in drilling Inconel 738-LC with CD is not related to the unit stiffness, several drilling experiments was performed with a column drilling machine which is much more stable. Again, at the cutter exit, the drill was caught in the burrs resulting in the levitation of both workpiece and fixture. In this stage, the fixture was not fixed to the machine table (see Fig. 2e). Once the fixture was fixed to the machine table the drill broke at the cutter exit.

The effect of vibration amplitude, spindle speed and feed rate on the circularity, cylindricity and surface roughness were studied. The drills used were standard TiAlN coated carbide drills. Each drill was used to drill four specimens for each test.

Figs. 3–5 show that the relationships between vibration amplitude and circularity, cylindricity and surface roughness are not linear. In all the figures, lines were formed by calculating the least-squares fit through the data points for a second-order polynomial equation.

Owing to the breakage of the drill in CD at the cutter exit it was not possible to measure the cylindricity of the hole. However, entrance circularity and inner surface roughness of the holes were measured.

Results show significant improvement for UAD compared to CD in different vibration amplitudes. Apparently, the reason for these improvements is the change of the nature of the cutting process, which is transformed into a process with a multiple-impact interaction between the tool and the formed chip. The axial oscillation causes the cutting edges to move towards the feeding direction, so that the oscillating and feeding motions are in one direction and therefore add up and both velocities are overlapping. The maximum oscillating velocities (up to 80 m/min) are generated at the amplitude of 10 μm and a frequency value of 21 kHz.

The larger the vibration amplitude, the smaller the axial feed of the tool per each vibration. Therefore, the cut becomes discontinuous and ultrasonic impact action (UIA) occurs, thus causing the material to begin to rollover more

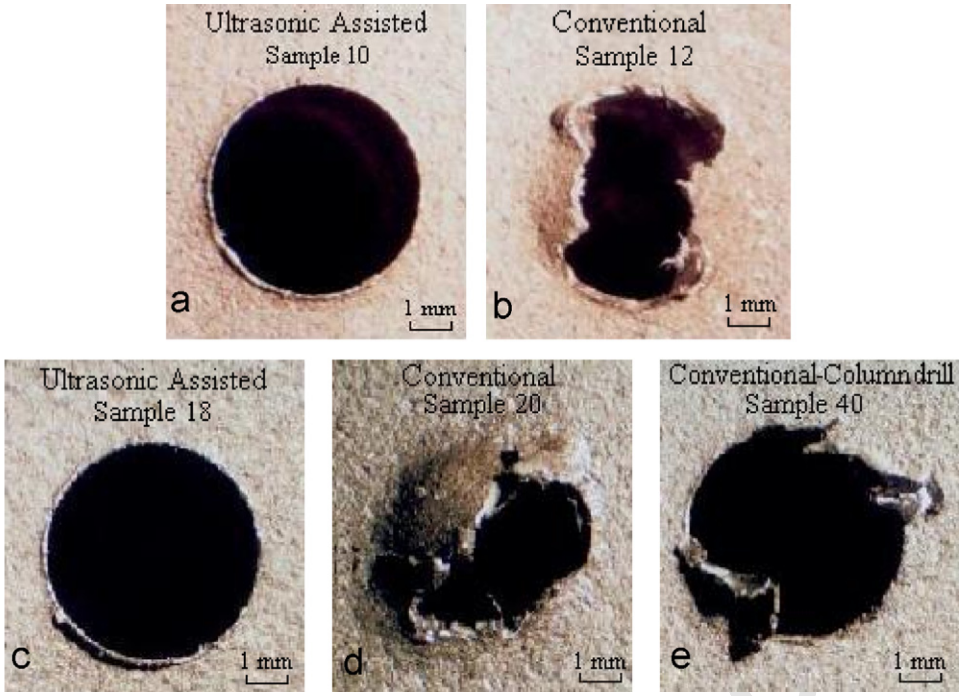

Fig. 2. Burr types samples at drill exit: (a) 250 RPM, 21 kHz, $f = 0.8$ mm/s, $A = 10\,\mu$m. (b) 250 RPM, $f = 0.8$ mm/s. (c) 350 RPM, 21 kHz, $f = 0.5$ mm/s, $A = 10\,\mu$m. (d,e) 350 RPM, $f = 0.5$ mm/s (A = amplitude, f = feed rate).

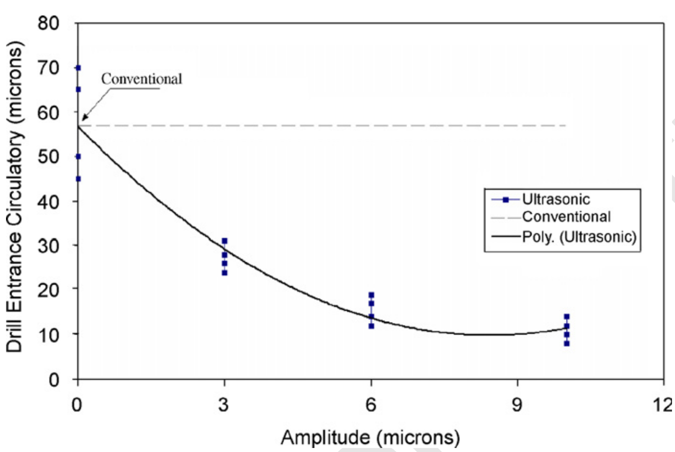

Fig. 3. Drill entrance circularity vs. vibration amplitude (5 mm diameter drill, 250 RPM, $f = 0.5$ mm/s, 21 kHz).

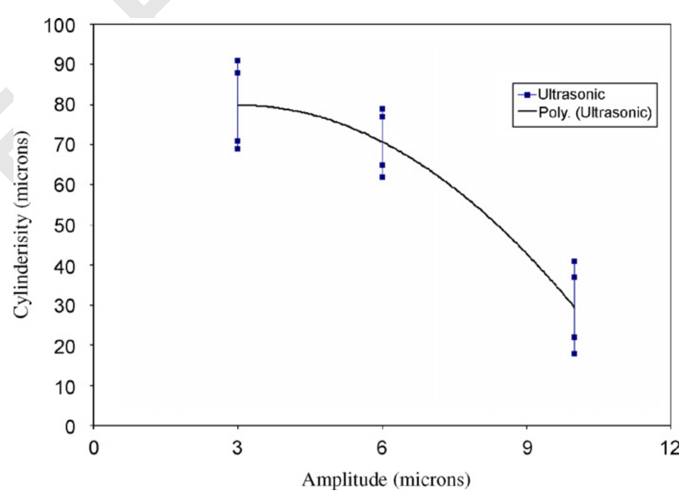

Fig. 4. Drilled hole cylindricity vs. vibration amplitude (5 mm diameter drill, 250 RPM, $f = 0.5$ mm/s, 21 kHz).

easily. This causes the thrust force to decrease, resulting in less plastic deformation and smaller chips and burrs.

Figs. 6–8 compare the circularity, cylindricity and surface roughness produced by UA drilling with CD under different spindle speeds.

In contrast to CD where the cutting speed is zero at the tool centre and cutting conditions are accordingly unsuitable; in UAD because of the oscillation speed, the working speed in the drill centre is different from zero and therefore the material is rolled over more easily and quickly into the main cutting edges by the chisel edge.

In general cases, increasing spindle speed reduces the uncut chip thickness and cutting forces, resulting in thinner and smaller chips which are easily removed from the hole and lead to better hole quality. However, the preventing parameter is temperature. Increasing spindle speed causes high cutting temperatures and tool blunting and requires high system stability. It is shown that increasing the spindle speed up to 350 rpm has no significant effect on hole quality, but when it reaches 500 rpm, cutting temperatures drastically increase and therefore the hole quality decreases dramatically.

The comparison has been made between the circularity, cylindricity and surface roughness produced by UAD with CD under different feed rates in Figs. 9–11. The relationships are again non-linear.

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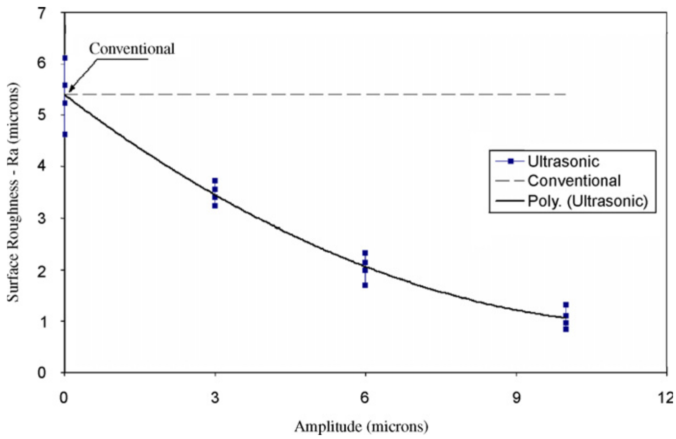

Fig. 5. Drilled hole surface roughness (Ra) vs. vibration amplitude (5 mm diameter drill, 250 RPM, $f = 0.5$ mm/s, 21 kHz).

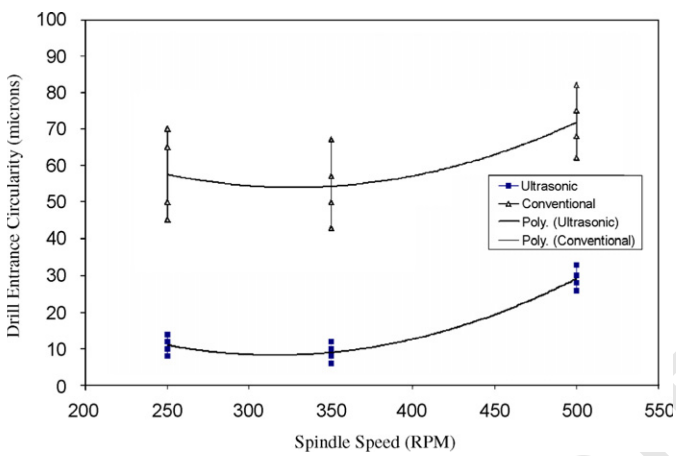

Fig. 6. Drill entrance circularity vs. spindle speed (5 mm diameter drill, $A = 10\,\mu m$, $f = 0.5$ mm/s, 21 kHz).

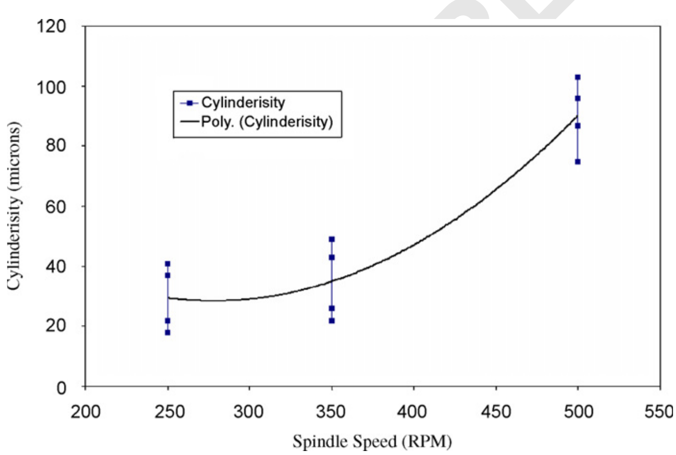

Fig. 7. Drilled hole cylindricity vs. spindle speed (5 mm diameter drill, $A = 10\,\mu m$, $f = 0.5$ mm/s, 21 kHz).

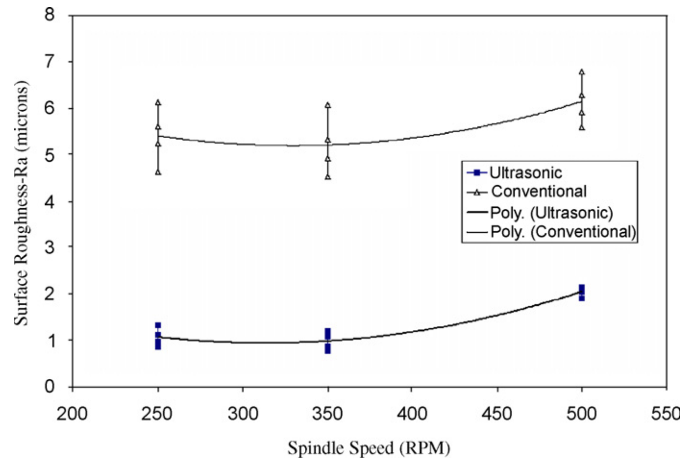

Fig. 8. Drilled hole surface roughness (Ra) vs. spindle speed (5 mm diameter drill, $A = 10\,\mu m$, $f = 0.5$ mm/s, 21 kHz).

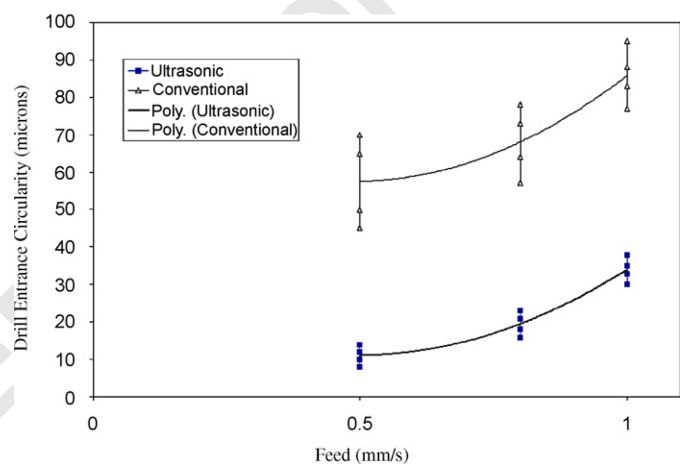

Fig. 9. Drill entrance circularity vs. feed rate (5 mm diameter drill, 250 RPM, $A = 10\,\mu m$, 21 kHz).

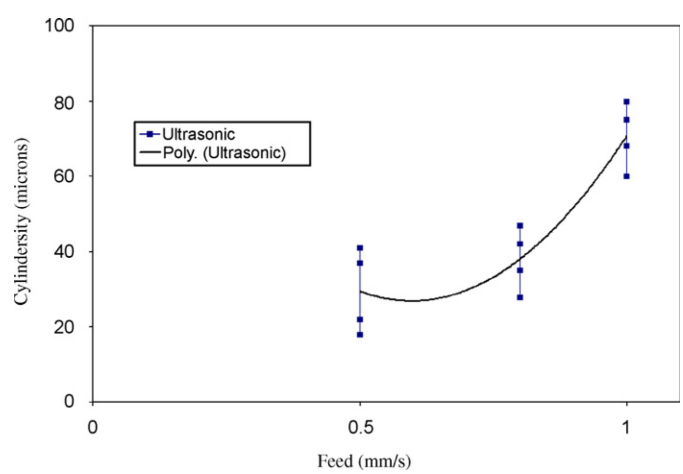

Fig. 10. Drilled hole cylindricity vs. feed rate (5 mm diameter drill, 250 RPM, $A = 10\,\mu m$, 21 kHz).

Results illustrate a substantial improvement for UAD compared to CD in different feed rates. As it is shown, hole quality degrades rapidly at higher feed rates. This is because at higher feed rates the uncut chip thickness and cutting forces increase and the chip segmentation effect of the UIA is reduced. Another important factor is the system stability; when feed rate reaches 1 mm/s, the cutting forces

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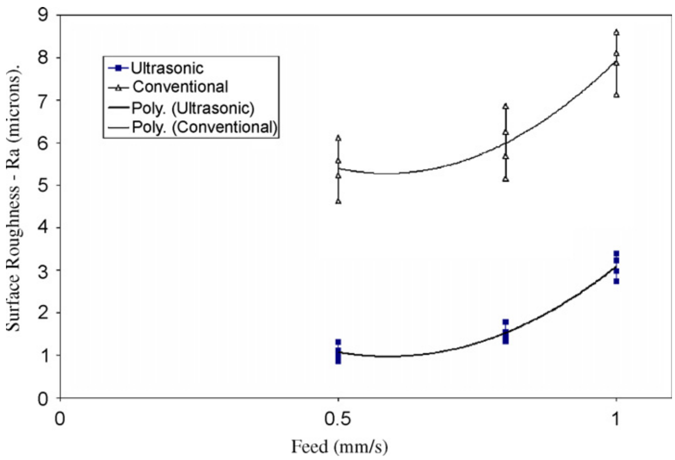

Fig. 11. Drilled hole surface roughness (Ra) vs. feed rate (5 mm diameter drill, 250 RPM, $A = 10\,\mu$m, 21 kHz).

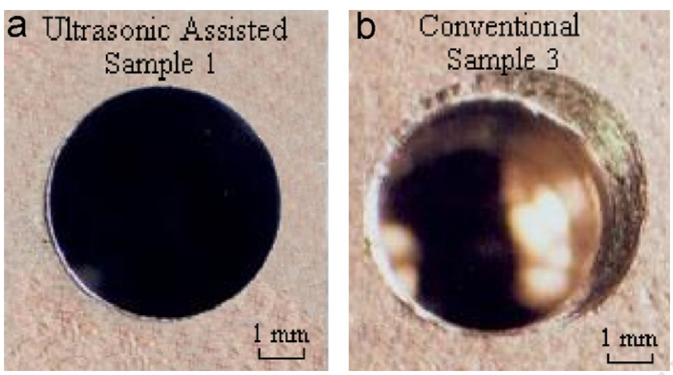

Fig. 12. Drill skidding samples at drill entrance: (a) 250 RPM, 21 kHz, $f = 0.5$ mm/s, $A = 10\,\mu$m. (b) 250 RPM, $f = 0.5$ mm/s.

rise substantially and system stability reduces considerably. These conditions reduce the hole quality significantly.

It should be noted that the scatter in the measured surface roughness and circularity values obtained through UAD is much less compared to CD. It means that using UAD increases the repeatability of the process.

It was also found that using UAD leads to significant improvements on the hole oversize and drill skidding. Fig. 12 shows that in the same conditions, between CD and UAD, the UAD technique almost eliminates drill skidding and helps the drill to penetrate downward quickly. In fact when using UAD there is no need for a centre hole (in the UAD experiments centre holes were not made prior to drilling). Because ultrasonic vibrations are axial, they improve hole alignment by decreasing the drill tip displacement on the surface of the workpiece. Hole oversize reduces significantly with the use of UAD. Average hole oversize in CD was about H11 (5.075 mm) but in UAD (in the same condition) it was reduced to H9 (5.030 mm). This improvement is related to the effects of ultrasonic vibration on reducing cutting forces and drill tip displacement/skidding.

The chip morphology was also examined. CD produced long, continuous chips. On the other hand, the chips produced by UAD are discontinuous with small serrations and the cross-sections of these chips are influenced by superimposing ultrasonic oscillations with CD (see Fig. 13).

In the next stage of investigation, two different types of coated carbide drills, solid carbide TiAlN coated drill (Dormer-R522) and solid carbide TiN-coated drill (Dormer-R550) were used in several drilling experiments without the use of a coolant. TiAlN-coated drill was used to drill four holes at 250 RPM, $f = 0.5$ mm/s, $F = 21$ kHz, $A = 10\,\mu$m. Based on the result from the previous stage, it is believed that UAD performs better under these conditions. These conditions are not essentially the optimal ones.

It was found that TiN-coated carbide drill can not withstand the high cutting temperatures which are produced in drilling Inconel 738-LC. Fig. 14a shows TiN-coated drills after drilling two holes.

The results show that UAD can effectively reduce the chipping of the cutting tool and therefore tool life can be prolonged accordingly. This was expected, because the ultrasonic action reduces cutting and friction forces and also cutting temperatures. Fig. 14b shows TiAlN-coated drills after drilling four holes. It was observed that during CD the drill always broke at the cutter exit, therefore in order to prevent the breakage of the drill the experiments (both CD and UAD) were only resumed up to the point where 2 mm was left to the other side of the workpiece (2 mm to the cutter exit). Therefore, as the thickness of the workpieces were 8 mm, the drilling hole length was approximately 6 mm.

As is shown in Fig. 14b, the tool wear for CD is more significant. Abraded-off coated layer, chipping and breakage of cutting edge can be observed as the tool wear in CD. After drilling the third hole BUE started to form at the drill edges during CD. This was due to the fact that after drilling the first two holes, abrasion of the coated layer took place causing an increase in friction force which plays a key role at the beginning stage of tool wear. The tool wear in UAD is less than CD and the coated layer is only slightly abraded and chipping with micro-cracks only occurred near the chisel edge.

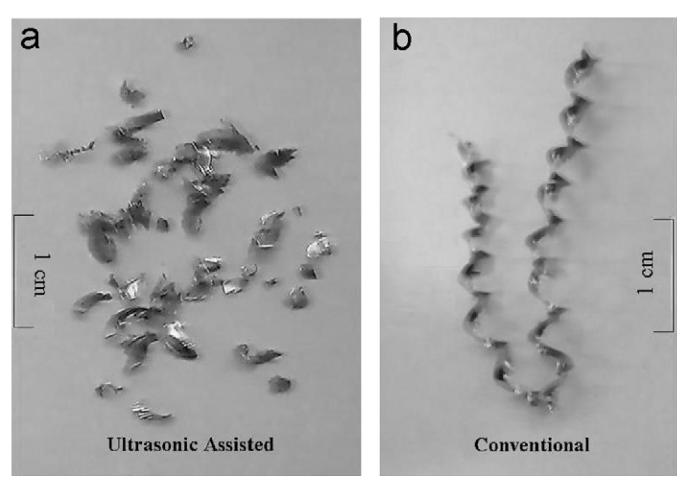

Fig. 13. Chip morphology: 250 RPM, 21 kHz, $f = 0.5$ mm/s (for UAD, $A = 10\,\mu$m).

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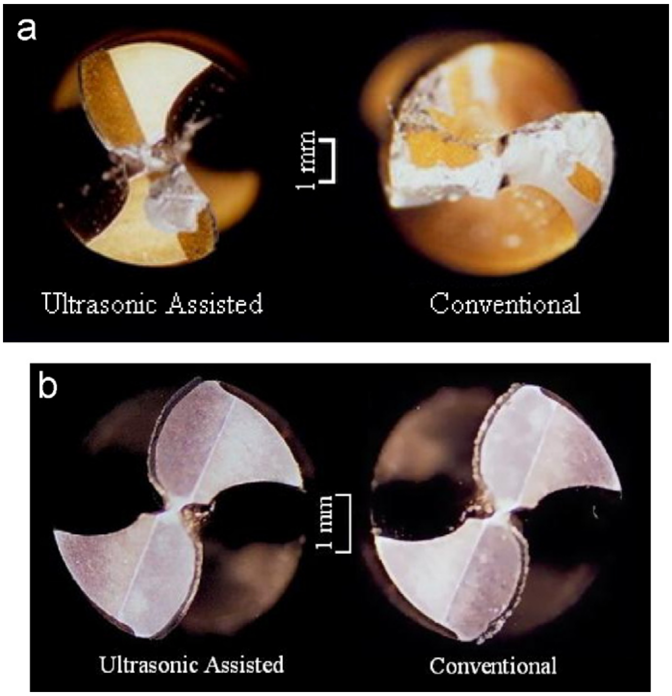

Fig. 14. (a) Worn TiN-coated drills from tests performed at 250 RPM, 21 kHz, $f = 0.5$ mm/s. (b) Worn TiAlN-coated drills from tests performed at 250 RPM, 21 kHz, $f = 0.5$ mm/s (for UAD, $A = 10\,\mu$m).

In addition to the above-mentioned explanations, another reason for hole quality improvements in UAD is that the oscillations are divided into two steps; in the first step, oscillation is positive and is added up with the feed motion, therefore the effective rake angle is significantly enlarged in comparison to the rake angle of the drill, where as the effective clearance angle hardly eliminates compared to the drill's clearance angle. In the second step, there is a reverse in ratios as a result of reversing direction. The technological parameters such as the oscillating amplitude, the oscillating frequency and the tool speed, effect the curve of the amount of angular changes.

The angular variation explained above essentially contributes to the UAD effects. Because of the large effective rake angles that are produced in the first oscillation step, the chip easily slips along the cutting edge. In the second oscillation step, the effective rake angle is significantly reduced. As a result of constant angular variation, the adhering of the chip to the drill edges is avoided, particularly to the tool face. In this way, the friction on the tool is considerably reduced. This effect also reduces the cutting moment in the process and the emerging chip can be removed from the hole easily. Therefore, it applies less pressure on the chip root, which may lead to a smaller plastic flow zone and cause less burning on the drill.

5. Conclusion

Experimental studies of UAD and CD demonstrate considerable advantages of the former technology for machining Inconel 738-LC. Comparative experiments of the hole quality demonstrated up to 60% improvement in average surface roughness and circularity for the workpieces machined with superimposed ultrasonic vibration. All CDs were unsuccessful and the drills broke at the cutter exit. It is thought that the reason for this phenomenon was because the drills were caught in the burrs formed during drilling at the cutter exit, resulting in the breakage of the drills. It was also found that using UAD leads to significant improvements on the hole oversize and drill skidding. These improvements are subjected to the change of the nature of the cutting process in UAD, which is transformed into a process with a multiple-impact interaction between the tool and the formed chip resulting in discontinuous and finer chips and reducing the thrust force acting on the workpiece. This way friction on the tool is decreased. This effect reduces the cutting moment in the process and the emerging chip can be removed from the hole easily. Therefore, it applies less pressure on the chip root, which may lead to a smaller plastic flow zone and smaller burrs and cause less burning on the drill and the tool life can be prolonged accordingly.

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