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.

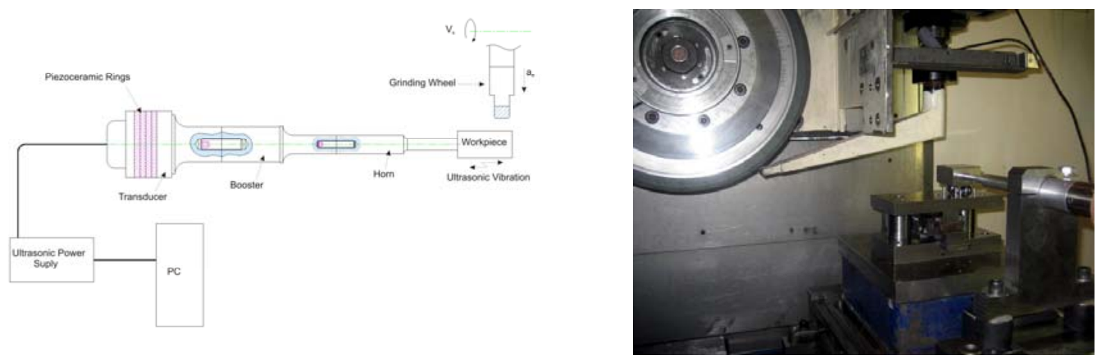
In order to decrease the negative environmental impact of the cutting fluids and reducing manufacturing costs, new machining techniques such as dry machining [2–5] are used. Many machining processes have decreased and even eliminated the use of cutting fluids in the last decades, but dry grinding is 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.

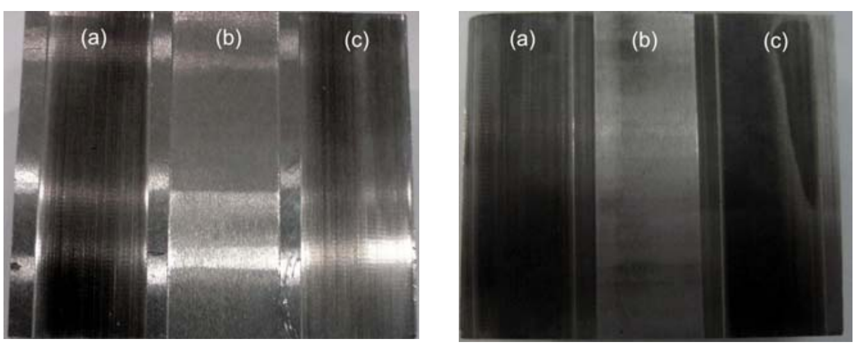
Grinding wheel	Vitrified bond CBN grinding wheel, B126 C125; Ø400 mm * 16 mm
Workpiece	100Cr6, 82 HRB, (60*47*29)
Grinding conditions	Feed speed v_{ft}= 1000- 2000 mm/min; Cutting speed v_c= 60 m/s; Depth of cut a_e= 0.010- 0.030 mm; No Coolant (Dry grinding)
Grinding process	Surface grinding
Dressing 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.

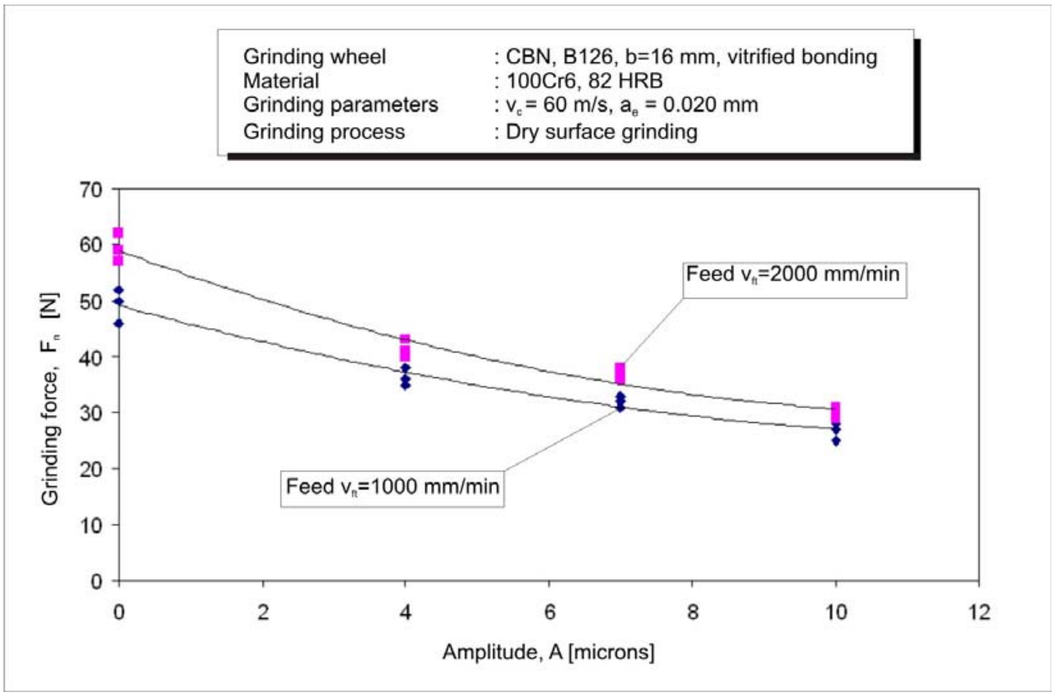


Fig. 3. Normal Grinding force vs. Vibration Amplitude (a_e=20µm, f=21 kHz).

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.

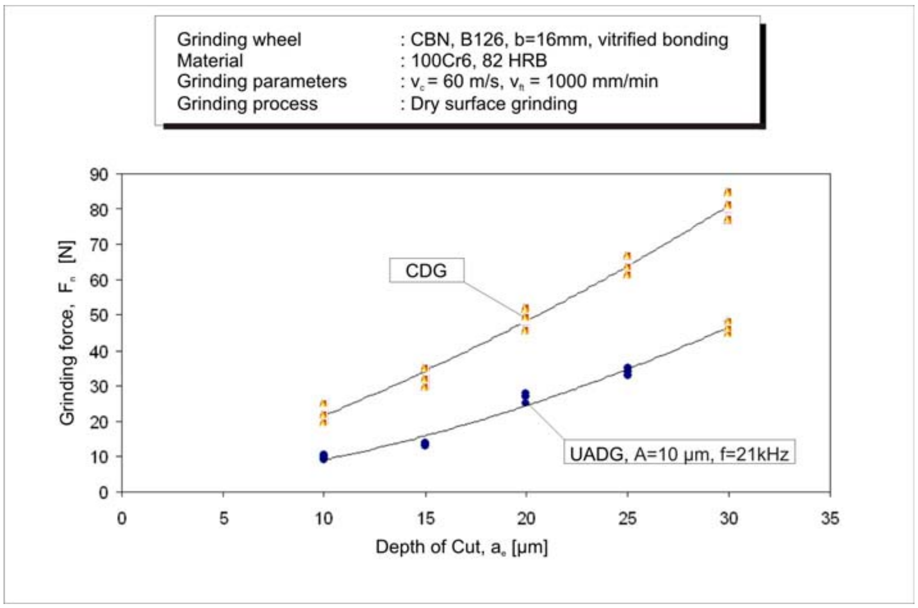


Fig4. Grinding normal force vs. Depth of Cut, v_{ft}=1000 mm/min.

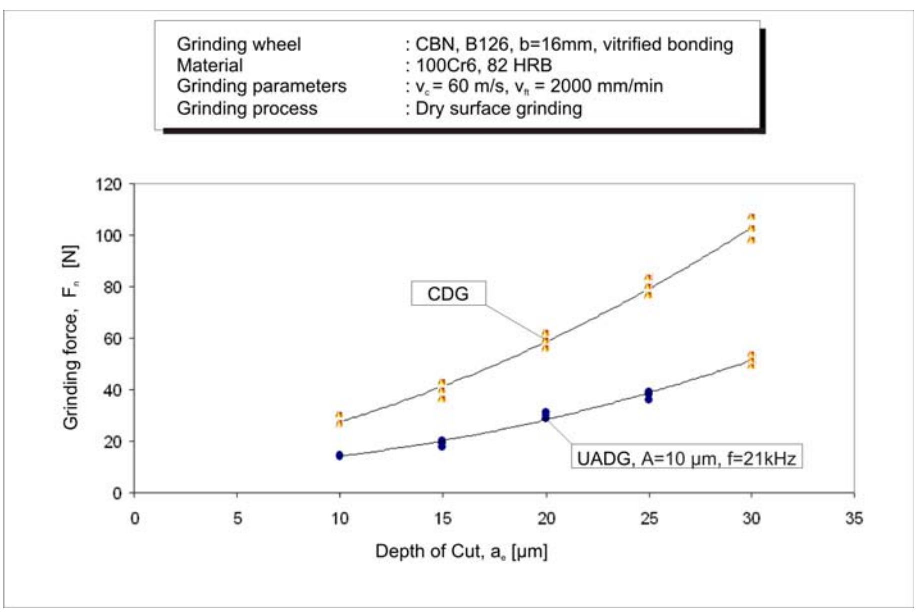


Fig5. Grinding normal force vs. Depth of Cut, v_{ft}=2000 mm/min.

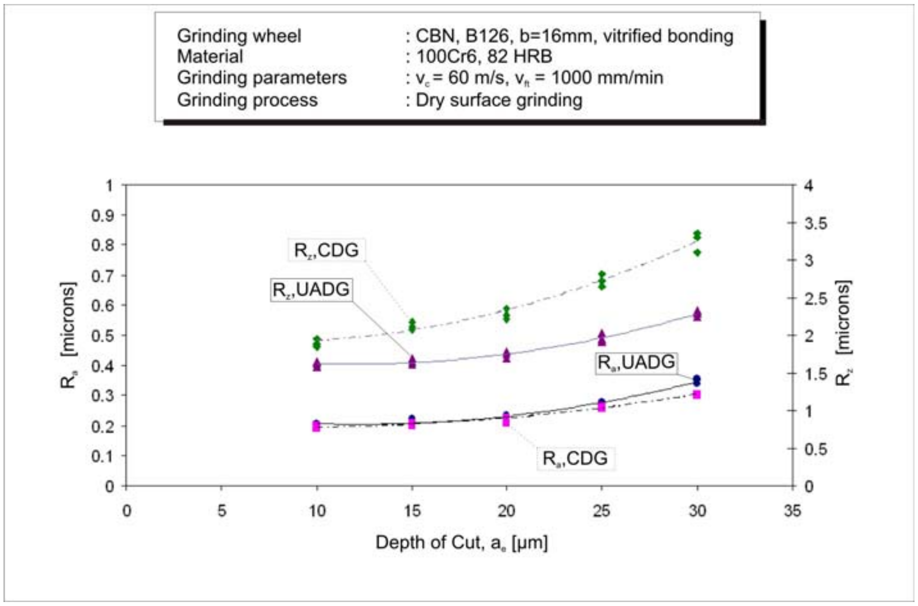


Fig6. R_a and R_z vs. Depth of Cut, v_{ft}=1000 mm/min (UADG: A=10µm, f=21 kHz).

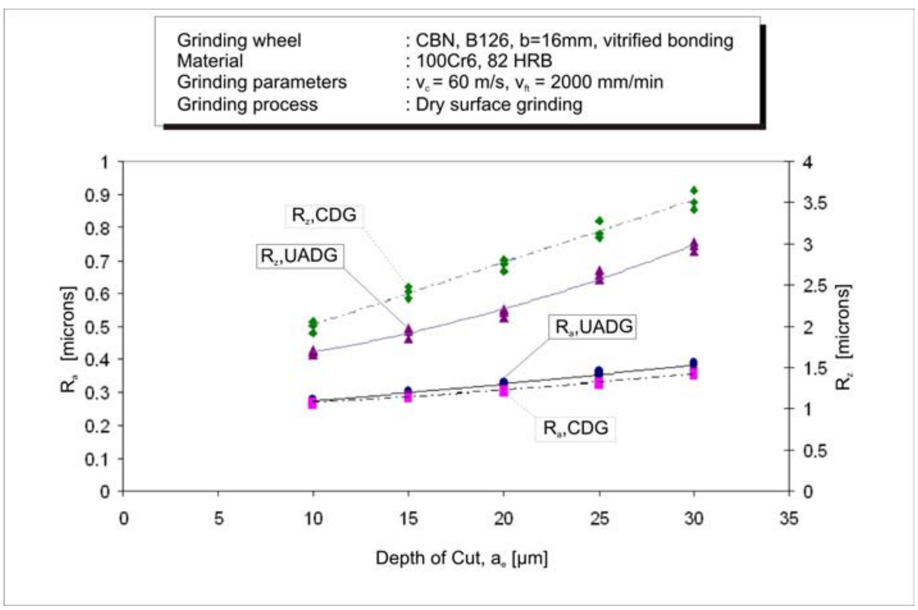


Fig7. R_a and R_z vs. Depth of Cut, v_{ft}=2000 mm/min (UADG: A=10µm, f=21 kHz).

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.

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

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

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

$\dot{Q}$: 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.

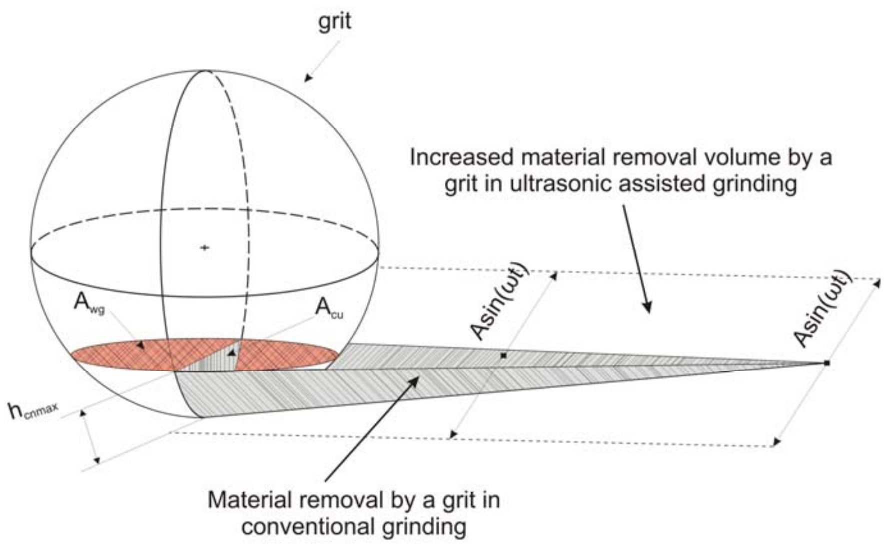


Fig8. Material removal volume in conventional and ultrasonic assisted grinding

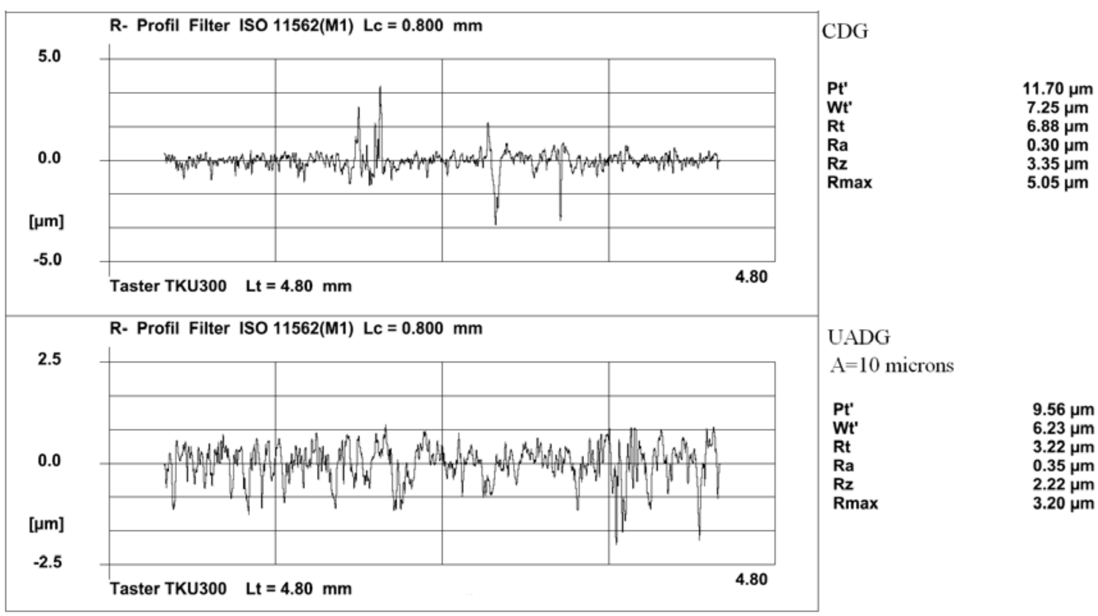


Fig9. Surface roughness profile (v_c=60 m/s, v_{ft}=1000 mm/s, a_e=30 µm)

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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