The 6th International Conference on Manufacturing Research (ICMR08)
Brunel University, UK, 9-11th September 2008

Dry grinding of soft steel with use of ultrasonic vibrations

Taghi Tawakoli(1), Bahman Azarhoushang(1)*

1. Institute of grinding and precision technology (KSF), Furtwangen University, Germany.

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

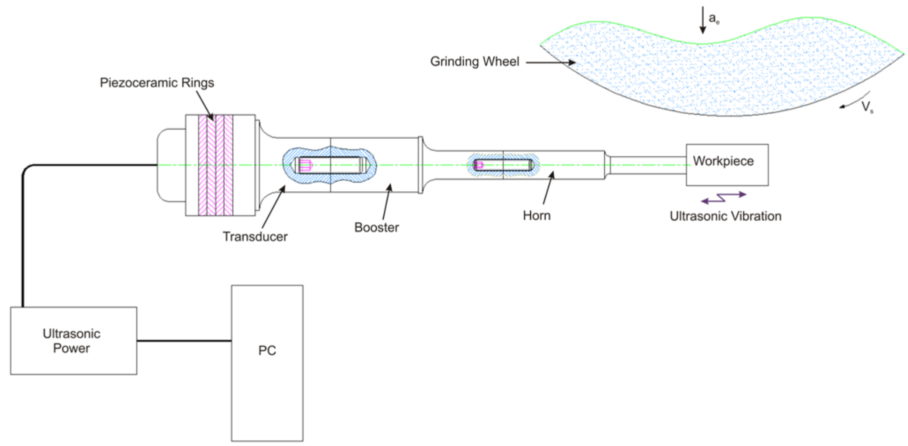
1.0 Introduction

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.

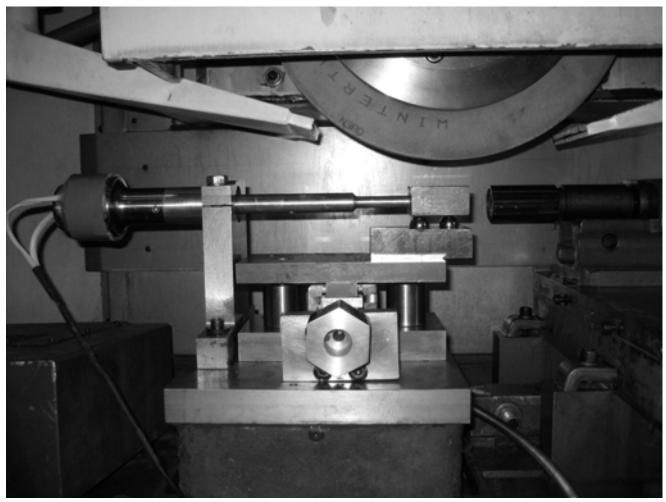
In this investigation, a UADG system has been designed, fabricated and tested. Improvements in the R_z and R_a (parameters of surface roughness) of the ground surfaces, reduction of the grinding forces and thermal damages on the ground surface due to superimposing of ultrasonic vibration in the dry grinding 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.

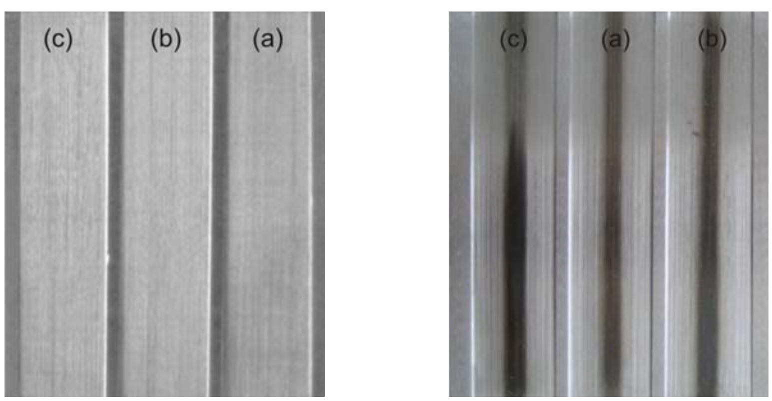
Table 1. Major machining parameters

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.

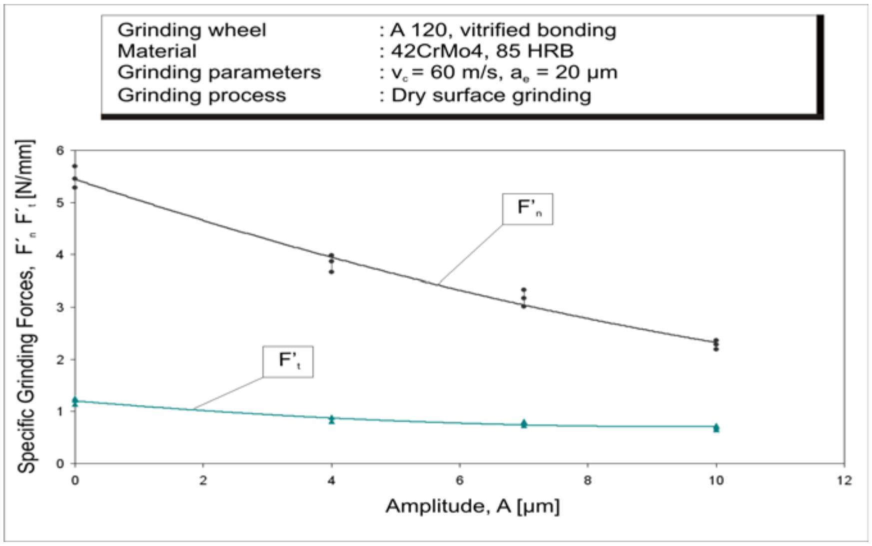


Fig. 3. Specific Grinding forces vs. Vibration Amplitude (a_e=20µm, f=23 kHz).

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.

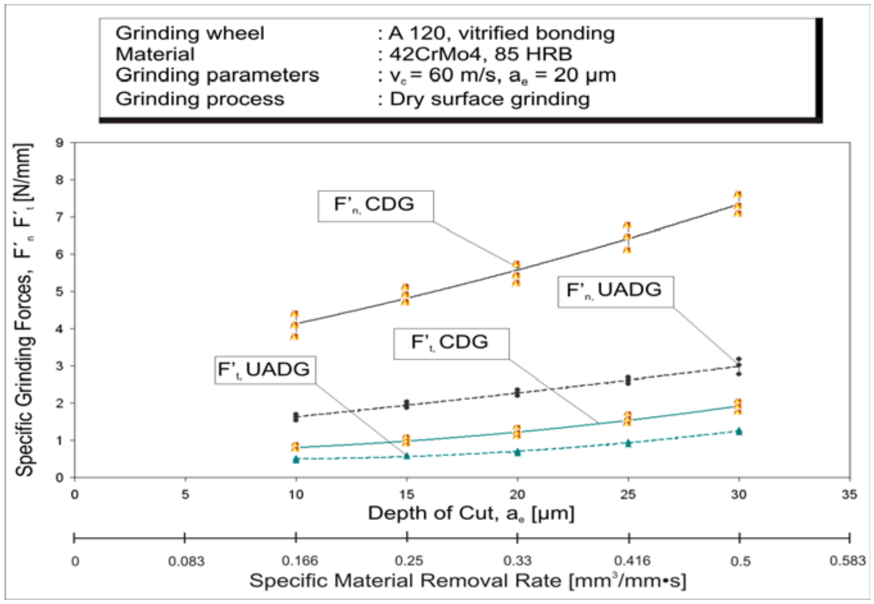


Fig4. Specific Grinding forces vs. Depth of Cut, v_{ft}=1000 mm/min (UADG: A=10µm, f=23 kHz).

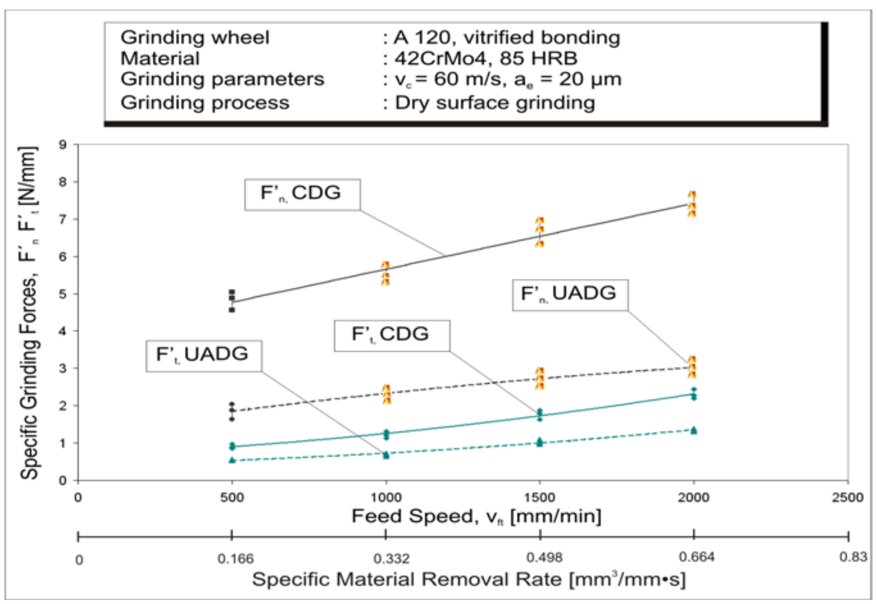


Fig5. Grinding normal force vs. Feed Speed, a_e=20 µm (UADG: A=10µm, f=23 kHz).

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

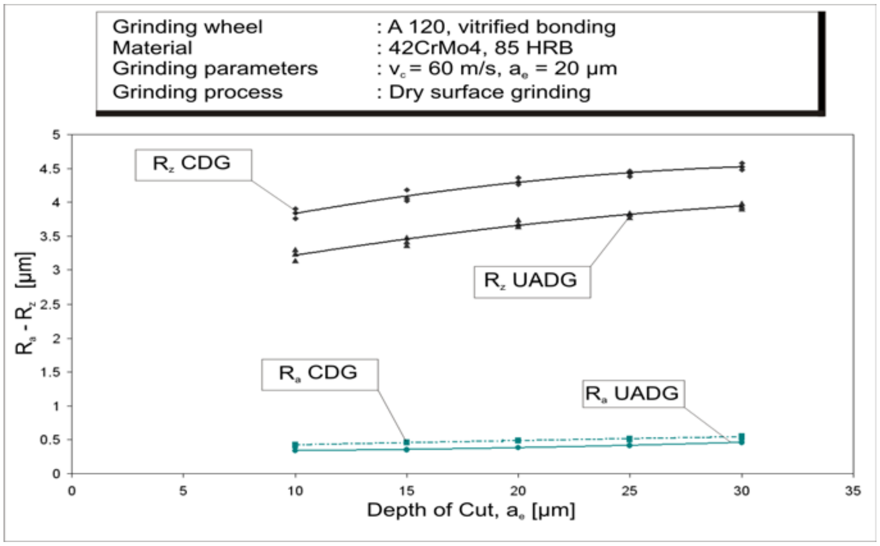


Fig6. R_a and R_z vs. Depth of Cut, v_{ft}=1000 mm/min (UADG: A=10µm, f=23 kHz).

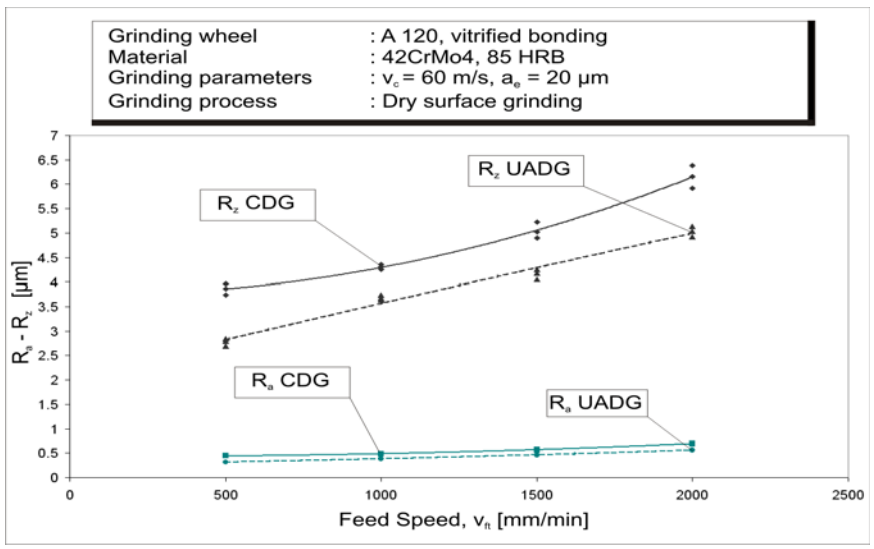


Fig7. R_a and R_z vs. Feed Speed, a_e=20 µm (UADG: A=10µm, f=23 kHz).

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.

References

[1] F. Klocke, G. Eisenblaetter, “Dry cutting” , *CIRP Ann. Manufact. Technol*. Volume 46 (2) (1997) 519–526.

[2] P.S. Sreejith, B.K.A. Ngoi, “Dry machining: machining of the future”, *J. Mater. Process. Technol.* 101 (1) (2000) 287–291.

[3] C. Heinzel, “Methoden zur Untersuchung und Optimierung der Kühlschmierung beim Schleifen“, Dissertation Universität Bremen, 2003.

[4] T. Tawakoli and M. Rabiey, “Trockenschleifen, Grenzen und Möglichkeiten“, *6. Seminar „Moderne Schleiftechnologie und Feinstbearbeitung“ in Stuttgart, Hrsg. T. Tawakoli*, 17.05.2006.

[5] T. Tawakoli and M. Rabiey, “An Innovative Concept for Dry grinding with Resin and Vitrified Bond CBN Wheel”, *International Grinding Conference ISSAT* 2007/ISME.

[6] L.B. Zhang, L.J. Wang, X.Y. Liu, H.W. Zhao, X. Wang, H.Y. Luo, “Mechanical model for predicting thrust and torque in vibration drilling fibre-reinforced composite materials”, *International Journal of Machine Tools & Manufacture* (41) (2001) 641–657.

[7] H. Takeyama, S. Kato, “Burrless drilling by means of ultrasonic vibration”, *Annals of CIRP* 40 (1) (1991) 83–86.

[8] B. Azarhoushang, J. Akbari, “Ultrasonic-assisted drilling of Inconel 738-LC”, *International Journal of Machine Tools and Manufacture*, Volume 47, Issues 7-8, June 2007, Pages 1027-1033

[9] P.D. Prabhakar, P.M. Ferreira, M. Haselkorn, “An experimental investigation of material removal rate in rotary ultrasonic machining”, *Transactions of the North American Manufacturing Research Institution of SME* Vol. 20,(1992) pp. 211-218.

[10] E. Uhlmann, “Surface Formation in Creep Feed Grinding of advanced Ceramics with and without Ultrasonic Assistance”, *Annals of CIRP*, Vol.47/1/1998.

[11] T. Tawakoli, E. Westkaemper, A. Rasifard, “Ultrasonic Assisted Dressing of vitrified CBN Grinding Wheel”, *40th CIRP International Seminar on manufacturing Systems*, Liverpool, UK, 2007.

[12] V.I. Babitsky, A.V. Mitrofanov, V.V. Silberschmidt, “Ultrasonically assisted turning of aviation materials: simulations and experimental study”, *Journal of Ultrasonics* (42) (2004) 81–86.

SUMMARY PREPARATION FOR PAPERS