Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 14 (2014) 13 – 18

www.elsevier.com/locate/procedia

6th CIRP International Conference on High Performance Cutting, HPC2014

Study on Hydrodynamic Pressure in Grinding Contact Zone Considering Grinding Parameters and Grinding Wheel Specifications

Alireza Vesali [a]*, Taghi Tawakoli [a]

(a) Institute of Grinding and Precision Technology (KSF), Furtwangen University, 78054 VS-Schwenningen, Germany

* Corresponding author. Tel.: +49-7720-99798-12; fax: +49-7720-307-4208.E-mail address: vesali@hs-furtwangen.de.

Abstract

In the grinding process, coolant lubricant is used to lubricate and mainly to transmit the heat generated in the contact zone. Grinding wheel accelerates a portion of the coolant lubricant into the contact zone. As e resault of the wedge effect between grinding wheel and workpiece in the contact zone a hydrodynamic pressure is generated, which influences the grinding results. In this paper, a new model for the hydrodynamic pressure of the coolant in the contact zone is presented. The simulation results show that the hydrodynamic pressure is proportion to grinding wheel velocity, and in inverse proportion to the minimum gap between wheel and workpiece. Furthermore, it could be investigated that the specification of the grinding wheel can affect the value of this pressure. The experimental results correspond to the simulation results, which show the validity of the simulation.

© 2014 Elsevier B.V. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of the International Scientific Committee of the 6th CIRP International Conference on High Performance Cutting

Keywords: Hydrodynamic Pressure, grinding, contact zone, wheel specification

1. Introduction

Grinding, as the oldest machining processes, is commonly used as the final process in production of the components requiring fine surfaces and close tolerances. However, grinding involves high specific energy compared to other machining processes due to the high negative rake angles of the abrasive grains [1] and the relatively large contact length [2]. A major part of the energy is converted to heat through friction and plastic deformation, which may have detrimental effects on workpiece surface integrity, such as thermal damages [3], tensile residual stresses [4] and crack on the workpiece surface and subsurface [5]. Exploiting the proper coolant-lubricants during grinding operation is one of the most common solutions for this problem, which can severely increase the potential of the grinding process. The coolant-lubricant is mainly used for transmitting the heat, which is generated in the contact zone, reducing the friction between the abrasive grain and workpiece material, evacuation of chips from the contact zone, cleaning the grinding wheel and reducing the corrosion of metal components [2, 6, 7]. Various investigations have already been done to obtain the maximum possible fluid flux into the contact zone, which leads to optimized grinding results [8, 9].

Coolant can also have a major impact on the hydrodynamic pressure value, created by high wheel speeds. The hydrodynamic pressure affects the grinding efficiency and machining accuracy. In view of its importance, numbers of investigations has focused on the coolant delivery method to minimize hydrodynamic pressure effect [10-13], although the effect of the hydrodynamic pressure on the machining accuracy may not completely be eliminated.

Some investigations focused on modeling and measurement of hydrodynamic pressure [11-18]. Chang [13], Schumack et al. [14] and Yi. [15] analyzed the distribution of hydrodynamic pressure based on the Reynolds Equation. Hryniewicz et al. [16] established 2-D model of hydrodynamic

2212-8271 © 2014 Elsevier B.V. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of the International Scientific Committee of the 6th CIRP International Conference on High Performance Cutting
doi:10.1016/j.procir.2014.03.053

pressure. Junyi et al. [17] studied the distribution of hydrodynamic pressure based on k-ε and RNG k-ε turbulent model, introducing the pressure boundary condition.

The hydrodynamic pressure in the grinding zone has been already simulated by some authors using different mathematical models. However, a comprehensive model, which considers the grinding wheel specifications, has not yet emerged. The purpose of this paper is to present the results obtained with simulated hydrodynamic pressure in the grinding contact zone, considering the specification of grinding wheel and grinding parameters. The hydrodynamic pressure simulated by means of MTALAB will be discussed and its variation depending on the grinding wheel specification will be explained. Furthermore, this paper presents some of the results of the investigation on the hydrodynamic pressure with different grinding parameter. These results will be compared with the simulation results.

2. Illustration and model for hydrodynamic pressure in contact zone

During grinding a portion of the supplied coolant is forced into the pores of the grinding wheel. The grinding wheel accelerates this part of coolant-lubricant into the contact zone. In the grinding zone, the coolant also creates a considerable hydrodynamic pressure just like a hydrodynamic bearing. This hydrodynamic pressure in grinding process has a significant influence on the grinding results. Especially grinding force can be affected by hydrodynamic pressure in the contact zone between grinding wheel and workpiece, which in turn affect the machining accuracy.

The hydrodynamic pressure and its negative effect on grinding results could be illustrated by the following tests. First, one slot was ground with a depth of cut of 0.5 mm, a cutting speed of 140 m/s, and a feed rate of 2000 mm/min. Subsequently seven passes were ground without other extra infeed to spark out. The first four spark outs were conducted with coolant-lubricant, and the other three without coolant-lubricant.

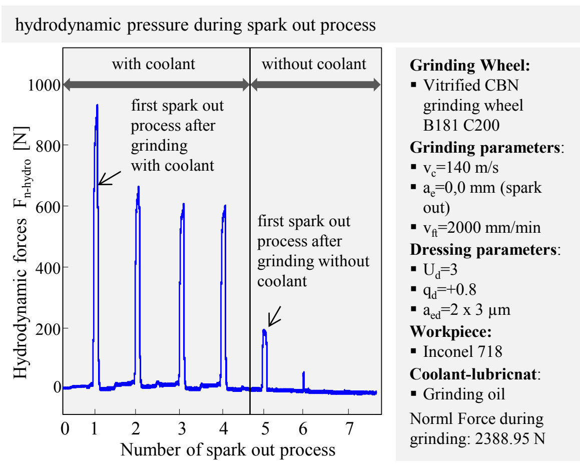

Fig 1: Hydrodynamic pressure during spark out process

Fig. 1 shows that the first spark out process has a normal grinding force of about 950 N. The next three spark out processes have constant normal forces of 600 N, since no material was removed during these processes. The measured force, namely 600 N, presents the hydrodynamic pressure between grinding wheel and workpiece generated by the coolant-lubricant. After these four spark out processes, the coolant lubricant was switched off. Fig. 1 shows that in the first spark out step without coolant-lubricant the workpiece has been again ground, which has grinding force of 200 N (spark out number five). Considering the high thickness of the workpiece this material removal can be contributed to the deformation of the grinding wheel under hydrodynamic pressure. After turning off the coolant-lubricant, the grinding wheel and the workpiece got in contact, which lead to a small material removal. After the spark out number five the measured forces drop on *0* N.

Fig. 2 demonstrates the distribution of the hydrodynamic pressure in the contact zone between the grinding wheel and workpiece during grinding operation. As shown in Fig. 2, the combination of the rotating Air barrier and accelerated coolant-lubricant by grinding wheel leads to a hydrodynamic pressure at mid-plane of the wheel.

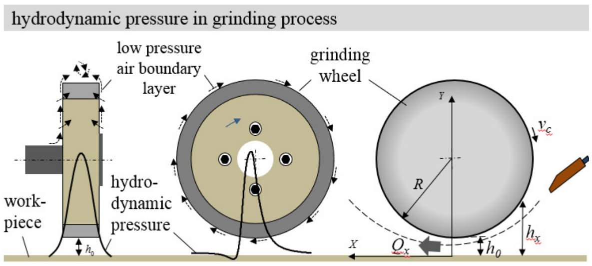

Fig. 2: The hydrodynamic pressure in the contact-zone between the grinding wheel and workpiece

In this paper, in order to simulate the hydrodynamic pressure, the coolant lubricant is assumed as an ideal fluid. It means that its density and viscosity are constant. The rotating grinding wheel is located above the workpiece. The gap height between the grinding wheel and workpiece is *h*. It has been also assumed that both grinding wheel and workpiece are rigid.

As mentioned above, the hydrodynamic pressure in grinding contact zone can be considered as a hydrodynamic bearing, which its pressure in infinitely wide gap can be calculated by the following Navier-Stokes equation with neglecting the phrase $\partial^2 u/\partial^2 x$ in the x-momentum equation:

$$\frac{\partial p}{\partial x} = \eta \frac{\partial^2 u}{\partial y^2} \tag{1}$$

Here η is the coolant viscosity, *u* is the fluid velocity in the grinding zone along x-axis, and *p* is the hydrodynamic pressure in the contact zone. The equation of continuity, i.e. coolant flow rate, *Q*, can be written as:

$$Q = \int_0^{h(x)} u dy \tag{2}$$

Application of the kinematic boundary conditions (at *y=0*, *u=0* and *y=h*, *u=v_c*) yields:

$$u = \frac{v_c \cdot y}{h(x)} - \frac{1}{2\mu}\frac{dp}{dx}\left(y^2 - yh(x)\right) \tag{3}$$

Where v_c is the grinding wheel speed and h represents the clearance between the grinding wheel and workpiece. It should be mentioned that *p* and $\partial p/\partial x$ vary along x-axis. At the point of maximum pressure, $(dp/dx) = 0$, hence:

$$u = v_c \frac{y}{h(x)} \tag{4}$$

Combining the equations 1 to 4 yields the equation for hydrodynamic pressure in the grinding contact zone during grinding process:

$$\frac{1}{12\mu}\frac{dp}{dx} = -\frac{Q}{h^3(x)} + \frac{v_c}{2h(x)} \tag{5}$$

The film thickness along the x-axis can be calculated by the following equation:

$$h(x) = h_0 + \frac{x^2}{2R} \tag{6}$$

Where R is the grinding wheel radius. Treffert [18] proposed that the clearance between the grinding wheel and workpiece can be defined as a function of the grinding wheel specifications. He developed his Model for h_0 as follow:

$$h_0 = 0.6d_k - 0.248q_m w_m \tag{7}$$

Where d_k is the grain size and w_m represents the mesh size of the grinding wheel. The q_m indicates the relationship between the edge lengths and the height of the octahedron grain. It is equal to 1.41 for the electroplated CBN grinding wheels [19].

Q_x is the coolant flow between the grinding wheel and workpiece during grinding and can also be calculated from the following relation:

$$Q_x = v_c h_0 = v_c(0.6d_k - 0.248q_m w_m) \tag{8}$$

Substituting Eq. 6 and 8 into Eq. 5 gives the following equation:

$$\frac{1}{12\mu}\frac{dp}{dx} = -v_c\left[\frac{(0.6d_k - 0.248q_m w_m)}{(0.6d_k - 0.248q_m w_m)^3(1 + x^2/(2R(0.6d_k - 0.248q_m w_m))^3} + \frac{1}{2(0.6d_k - 0.248q_m w_m)^2(1 + x^2/(2R(0.6d_k - 0.248q_m w_m))^2}\right] \tag{9}$$

3. Simulation

It is already apparent from equation 9 that the hydrodynamic pressure generated in the grinding zone is directly proportional to the cutting speed of the grinding wheel, v_c. The effect of cutting speed on the hydrodynamic pressure has been simulated for a wheel rotating with 80, 120 and 160 m/s. The specifications of the grinding wheel are listed in Table 1.

Table 1: The simulation parameter of the hydrodynamic pressure in the contact zone grinding wheel radius

Grinding Wheel			Coolant-Lubricant	
Radius R [mm]	Mesh Size w_m [µm]	Grain size d_k [µm]	Density ρ [kg/m3]	Viscosity µ [Pa.s]
225	215	252	900	0.018

The calculated hydrodynamic pressure under different grinding wheel speeds is shown in Fig. 3. It can be seen that the higher cutting speed leads to a clearly higher hydrodynamic pressure in the grinding zone.

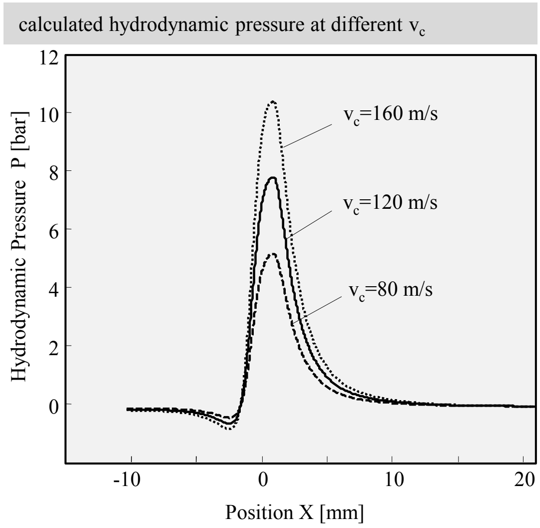

Fig. 3: The Simulation of the hydrodynamic pressure in the contact zone in different v_c

The effects of the cutting speed and grit size are simultaneously shown in Fig. 4. It can be seen that the increased cutting speed generates higher hydrodynamic pressure in the contact zone when using the wheel with the same grit sizes (d_k= 48 µm). Furthermore, an increase in the grit size from 48 µm to 181 µm leads to a lower hydrodynamic pressure. This can be attributed to the fact that the wheel with larger grit size is more porous. Because of the high pressure in grinding contact area the grinding fluid penetrates in the open structure of the grinding wheel which, in turn, reduces the generated hydrodynamic pressure.

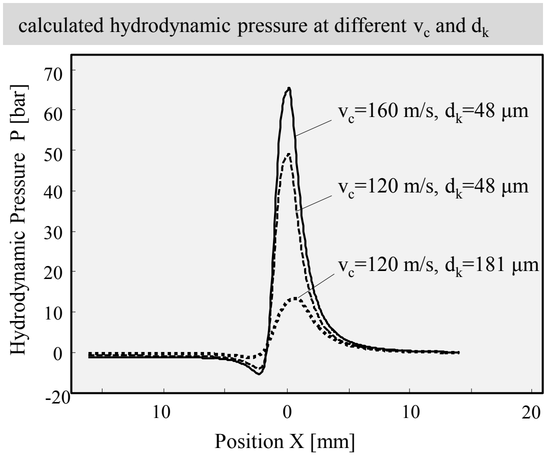

Fig.4: The Simulation of the hydrodynamic pressure in the contact zone in different v_c and d_k

4. Experimental results

In the last section, the hydrodynamic pressure in the grinding zone has been calculated using a mathematical model. The real pressure in grinding contact zone can be measured by an embedded pressure transducer on or under the workpiece surface. In order to measure the hydrodynamic pressure during grinding process, a measurement set up was made using a special pressure sensor.

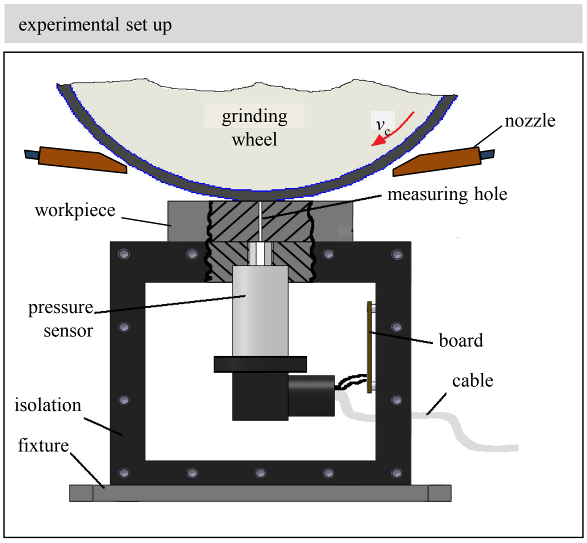

Fig. 5: Schematic of the experimental set-up

As shown in Fig. 5, the generated hydrodynamic pressure in the grinding zone can be transferred to the pressure sensor under workpiece through a hole with a diameter of 0.5 mm. The acquired signals by the pressure sensor are transmitted through a spectrum analyzer (PicoScop, Type 4424) to a personal computer. The grinding parameters are shown in Tables 2. The grinding oil was applied with a flow rate of 100 l/m.

Table 2: The Experimental Conditions

Wheel Type	CBN Grinding Wheel, Tyrolit TN470305 6*450 B252
Pressure transducer	ADZ-SML-10.0
Workpiece	Steel S235JR
Coolant-lubricant	Grinding Oil (ρ=900 kg/m3 and µ=0.001 Pa.s)
Grinding Machine	Gühring-FS 126
Grinding process	Up grinding
Cutting speed	120 m/s
Feed rate	2000 mm/min
Distance from the Workpiece surface	0 µm (i.e. during Grinding), 2 µm (over ground surface)

One grinding experiment with a depth of cut of 0.5 mm, a cutting speed of 120 m/s and a feed rate of 2000 mm/min have been conducted to verify the results obtained by simulation (Fig. 6). Both measured and simulated results show the same trend when grinding with grinding oil. The 4th-order Runge-Kutta method was used to simulate the hydrodynamic pressure in the grinding zone. The good correlation between experiment and simulation results indicate the validity of the simulation. For the simulation, the extinguishing nozzle has not been considered. It leads to a deviation on the right side of pressure curve, as it can been seen in Fig. 6.

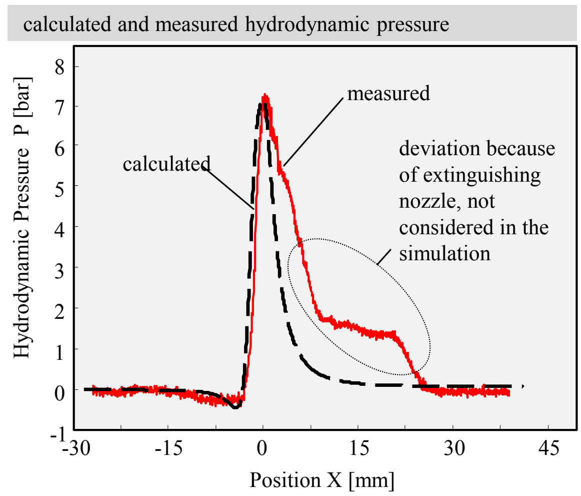

Fig. 6: The pressure P of experiment and simulation with v_c=120 m/s

The hydrodynamic pressures in the grinding zone for two different gap heights are compared in Fig. 7. It demonstrates a direct relation between the cutting speed, v_c, and the measured hydrodynamic pressure, p. The higher cutting speed the higher hydrodynamic pressure in the grinding zone. The observed trend corresponds to the simulation results, shown in Figures 2 and 3. Besides, bigger gap height reduces the pressure between the grinding wheel and workpiece, as expected. In other words, the higher hydrodynamic pressures were measured during grinding when the gap height is zero. Furthermore, Fig. 7 shows that at higher cutting speeds the pressure difference between two certain gap heights is evidently larger.

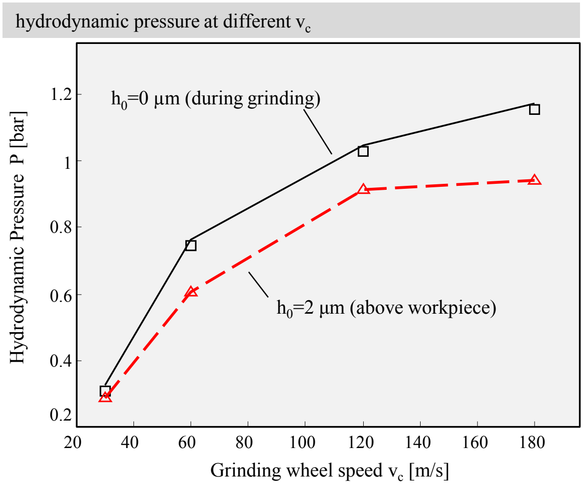

Fig. 7: The Influence of Grinding Wheel Speed on Pressure considering two different gap heights

The hydrodynamic pressure distribution along the wheel axial direction, i.e. along wheel width, is demonstrated in Fig. 8. It can be measured using the table movement in axial direction without grinding process. This figure shows that from the wheel edge (x=±3 mm) to its centre (x=0 mm) the hydrodynamic pressure increases rapidly. The maximum hydrodynamic pressure occurs obviously at the centre of the grinding wheel. The deviation of the curve center from zero can be attributed to the adjustment of the coolant-lubricant nozzel, which probably is asymmetrical adjusted. Moreover, at the wheel edges (±3 mm) the hydrodynamic pressure decreases smoothly to zero at the distance of ±5 mm from the wheel center.

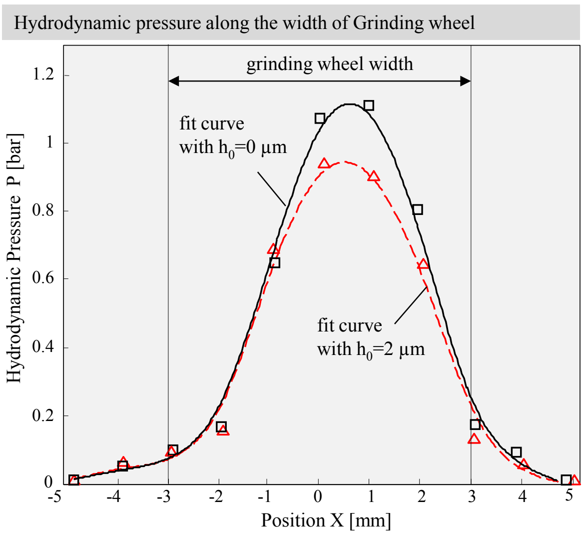

Fig. 8: The hydrodynamic pressure along the wheel width with two different gap heights

5. Conclusion

In grinding process, the coolant lubricant, which is accelerated by the grinding wheel into contact zone, builds up a hydrodynamic pressure in the grinding zone. This pressure affects the grinding process and its results.

The model for the calculation of the hydrodynamic pressure presented in this paper is based on grinding parameters and wheel specifications. This model indicates that the increased grinding wheel speeds lead to higher hydrodynamic pressures. Besides, an increased grain size leads to a decreased hydrodynamic pressure in the grinding zone that can be attributed to higher porosity of the grinding wheel. The calculated results are consistent with experimental results, which prove the validity of the simulation. It is also investigated that maximum hydrodynamic pressure in the grinding zone occurs at the center of the grinding wheel if it is measured along the width of the wheel.

References:

[1] Tawakoli T, Rabiey M. Macro-topography effects on dry grinding with CBN wheels. International Journal of Mechatronics and Manufacturing Systems. Vol. 1, No.4, 2008, p. 415-431.

[2] Marinescu I.D., Hitchiner M, Uhlmann E, Rowe W.B., Inasaki I. Handbook of machining with grinding wheels. Printed: in the United States of America, CRC Press, Taylor & Francis Group; 2007

[3] Rowe WB,. McCormack DF, Jin T. Controlling the surface integrity of ground components. Abrasives (DEC/JA). 2001, p. 24-30.

[4] Chen X, Rowe WB,. McCormack DF. Analysis of the transitional temperature for tensile residual stress in grinding. Journal of Materials Processing Technology, 107 (1–3), 2000, p. 216–221.

[5] Tawakoli T, Rabiey M. Trockenschleifen, Grenzen und Möglichkeiten, 6. Seminar Moderne Schleiftechnologie und Feinstbearbeitung, Stuttgart, 2006.

[6] Klocke F, König W. Fertigungsverfahren, Band 2 – Schleifen, Honen, Läppen. 4. Auflage, Springer-Verlag, 2005.

[7] Tawakoli T, Rasifard A, Vesali A. Effect of the Coolant Lubricant Type and Dress Parameters on CBN Grinding Wheels Performance. ISAAT 2009, Australia

[8] Ebbrell S.,Woolley NH, Tridimas YD, Allanson DR, Rowe WB. Effects of cutting fluid application methods on the grinding process. International Journal of Machine Tools and Manufacture, vol. 40, no. 2, 2000, p. 209–223.

[9] Gviniashvili VK, Woolley NH, Rowe WB. Useful coolant flowrate in grinding. International Journal of Machine Tools and Manufacture, vol. 44, no. 6, p. 629–636, 2004.

[10] C. Heinzel, Methoden zur Untersuchung und Optimierung der Kühlschmierung beim Schleifen. Dissertation, university Bremen, 2003.

[11] Lee SK, Miyamoto Y, Kuriyagawa T, Syoji K. Effects of minimizing hydrodynamic pressure in ultra-precision mirror grinding. International Journal of Machine Tools & Manufacture, 44, 2004, p. 1031-1036.

[12] LI C, Cai G，Xiu S，Liu F. Hydrodynamic Pressure Modeling and Verification of Contact Zone on Abrasive Jet Finishing with Grinding Wheel as Restraint. ACTA ARMAMENTARII , 28(2), 2007, p. 202-205.

[13] Chang CC. An application of lubrication theory to predict useful flow-rate of coolants on grinding porous media. Tribology International, vol. 30, no. 8, 1997, p. 575–581.

[14] Schumack MR, Chung JB, Schultz WW, Kannatey-Asibu E. Analysis of Fluid Flow under a Grinding Wheel. J. Eng. Ind. 113(2), 1991, p. 190-197

[15] Yi ZJ. Theoretical Analysis and Experimental Research on Grinding Jet for cooling. Dissertation, Wuhan University of Technology, 2008.

[16] Hryniewicz P,. Szeri AZ, Jahanmir S. Application of lubrication theory to fluid flow in grinding: part I—flow between smooth surfaces. Journal of Tribology, vol. 123, no. 1, 2001, p. 94–100.

[17] Junyi Z, Yijun X, Zhengfeng J. Numerical Simulation Investigation of Grinding Fluidic Field with High Reynolds Number. Lubrication Engineering, Vol.33, No.4, 2008.4, p.56-58.
[18] Treffert C. Hochgeschwindigkeitsschleifen mit galvanisch gebundenen CBN-Schleifscheiben, PhD Thesis, RWTH Aachen, 1994.
[19] Thorsten Beck. Kühlschmierstoffeinsatz beim Schleifen mit CBN, PhD-Thesis, RWTH Aachen, 2001.