VITREOUS BOND CBN WHEEL FOR HIGH SPEED GRINDING OF ZIRCONIA AND M2 TOOL STEEL

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ABSTRACT
High speed grinding experiments using a vitreous bond CBN grinding wheel were conducted to investigate the effects of wheel speed, truing, and coolant flow rate on cylindrical grinding of zirconia and hardened AISI M2 steel. The highest grinding wheel speed tested was 127 m/s. Experimental results show that high wheel speed can significantly reduce grinding forces and specific grinding energy for zirconia grinding. A method to reduce the wheel speed during truing was investigated and its benefits to lower the grinding forces were quantified. Over 50% reduction of grinding forces was achieved by truing at low wheel surface speed, compared to truing and grinding at the same speed. High coolant flow rate was tested and shown to eliminate wheel loading for zirconia and grinding burn for M2 steel at high wheel speed.

1. INTRODUCTION

The benefits of high grinding wheel surface speed have been investigated and documented by Koenig and Ferlemann (1993), Kovach et al. (1995) and Inada et al. (1996). Experimental results show that increasing the grinding wheel speed reduces the average chip thickness and increases the effective hardness of the wheel, resulting in more efficient workpiece material removal rates. This behavior occurs whether the workpiece material is ceramic or steel. High speed grinding machines are more expensive due to the extra cost for the high speed spindle, wheel burst containment, and special coolant delivery system. Grinding wheels capable of running at high speed also cost more due to the requirements for the high strength bonds and strong, light-weight cores. In order to justify these additional costs of high speed grinding in production operations, savings must be realized through higher material removal rates and better surface finish and form tolerances. The goal of this study was to investigate the benefits of high speed grinding using a vitreous bond CBN wheel. CBN was selected as the abrasive because it is capable of grinding both ceramics, such as silicon nitride and zirconia, and hardened steels. The grinding machine with a CBN wheel has the flexibility to be utilized for high-volume production of steel parts and limited production of ceramic components.

The high wheel speed creates high tangential tensile stress which is maximum in the bore of the wheel (Shaw, 1996). Most of the previous high speed grinding experiments used metal bond wheels for this reason. However, metal bond wheels are difficult to true to the µm-scale precise form and need to have an additional dressing operation to condition the wheel. Vitreous bond wheels are very popular in high-volume production grinding because they, in general, have longer wheel life, can be trued and dressed simultaneously, and can achieve tighter form tolerances and surface finish. In recent years, the advancements in the vitreous bond and light-weight, high-strength core material have broadened the speed range of vitreous bond wheels and made them suitable for high-volume production grinding. A vitreous bond CBN grinding wheel with carbon fiber composite core was used in this study.

The grinding machine used in this study had four force transducers built under the workhead swivel table to measure the normal and tangential grinding forces F_n and

F_t. A hydraulic-driven rotary diamond truing device was used to true and dress, or form and condition, the vitreous bond CBN wheel. At higher wheel speeds, the wheel becomes more difficult to true due to the increase in effective hardness of the wheel. In this study, the grinding wheel speed was reduced during truing and increased during grinding. The variable wheel speed was achieved by using a servomotor-driven grinding spindle. One of our goals was to quantify the benefits of such truing strategy.

In this paper, the experimental setup is presented first. The experiment design is then discussed. Grinding results, including forces, force ratio (F_n/F_t), specific grinding energy, and roundness and surface finish of the ground parts, are then compared and analyzed.

2. EXPERIMENTAL SETUP

The grinding and truing experiments were conducted on a Weldon AGN5 CNC cylindrical grinding machine. Detailed setup parameters on machine, truing, grinding, coolant, and work-material are summarized in Table 1.

2.1. Wheel Truing and Dressing.

The set up for rotary truing of the CBN grinding wheel is shown in Fig. 1(a). The X- and Z-slides are used to position the grinding wheel and rotary truing device for truing. During truing, the X-slide was positioned to give a 2.5 μm radial feed for truing. The X-slide remained stationary when the Z-slide traversed across the wheel at 2.12 mm/sec rate. At least six truing passes were conducted between each grinding test to ensure the wheel had been restored to the correct condition.

This grinding machine was specially built with four Kistler piezoelectric transducers underneath the Z-slide to measure the normal and tangential grinding forces, F_n and F_t, and to study the effect of grinding speed on the grinding force ratio, F_n/F_t. F_n and F_t can be converted into the specific normal and tangential grinding forces (f_n and f_t) by dividing F_n and F_t by the width of plunge grinding, h, which was set to 6.35 mm in all tests.

2.2. Grinding the Workpiece.

After truing, the X- and Z-slides were positioned for cylindrical plunge grinding of the workpiece. During grinding, as shown by the arrow sign in Fig. 1(b), the Z-slide remained stationary and the X-slide plunged the wheel into the workpiece.

During cylindrical grinding, the grinding forces gradually diminish over time because both the workpiece diameter and specific material removal rate continuously decrease during the grinding cycle at constant infeed rate. Only the peak grinding force is recorded in this study.

The peak tangential grinding force can be converted to the peak specific grinding energy, u, the maximum energy required to remove a unit volume of work-material at the start of the plunge grinding.

Table 1. Summary of grinding and truing parameters.

Machine	
Machine	Weldon AGN5 cylindrical grinding machine
Grinding spindle motor	Variable speed AC servomotor, 11.25 kW
Grinding spindle bearing	Angular contact Si_3N_4 ball bearing
Workhead speed	600 rpm
Workhead rotational dir.	Same direction as grinding wheel
Force dynamometer	Kistler model 9117A1.5 and 9118AB1.5 piezoelectric transducers (2 each) and 5010 amplifier
Width of plunge grinding	6.35 mm (0.25 inch)
Slide resolution	0.25 μm (0.00001 inch)
Grinding	
Wheel	Cincinnati Milacron 2BN 320-Q164-VMB
Bond	Vitreous bond, carbon fiber composite core
Balancer	SBS Balancing System, adjusted to below 0.2 μm vibration level
Grinding wheel diameter	406 mm (16 inch)
Grinding wheel speed	***Setup parameter #1***: 35, 61, 91, 127 m/s
Radial plunge speed	42.4 μm/sec (0.1 inch/min)
Specific matl. removal rate	1.27 mm^3/sec/mm for zirconia 1.20 mm^3/sec/mm for steel
Dwell time	None
Width of plunge grinding	6.35 mm (0.25 inch)
Truing	
Truing spindle	Norton hydraulic-drive truing spindle
Truer manufacturer	Universal Beck, Metal Bond
Dimension of truer	101.6 mm diameter and 2.54 mm wide
Type of diamond	30/35 ANSI mesh, GE MBS 960 diamond
Truing wheel speed	2400 rpm
Speed ratio	***Setup parameter #2***: Various speed ratios listed in Table 2
Radial feed in truing	2.5 μm (0.0001 inch)
Truing traverse speed	2.16 mm/sec (5 inch/min)
Coolant	
Type	Cincinnati Milacron, Cimtech 500, 5-6% concentration
Pressure	0.07 MPa (10 psi)
Filtration	None
Temperature control	None
Tank capacity	567 liter (150 gallon)
Flow rate	***Setup parameter #3***: Regular: 22.7 liter/min (6 gallon/min) High: 62.5 liter/min (16.5 gallon/min)
Workpiece	
Material	***Setup parameter #4:*** Zirconia or M2 steel
Zirconia:	
Material	Transformation toughened zirconia (MgO)
Hardness	1100 kg/mm^2 Knoop (500g load)
Average grain size	0.06 mm
Flexural bending strength	620-690 MPa (90-100 kpsi)
Density	5.6-5.8 g/cm^3
Dimension of blank	9 mm (0.355 inch) diameter
Material removal	2.667 mm (0.105 inch) diametrical material removal
M2 steel:	
Material	AISI M2 tool steel, through hardened
Hardness	770 kg/mm^2 Knoop (62 Rockwell C)
Dimension of blank	9.525 mm (0.375 inch) diameter
Material removal	2.667 mm (0.105 inch)
Diametrical material removal	

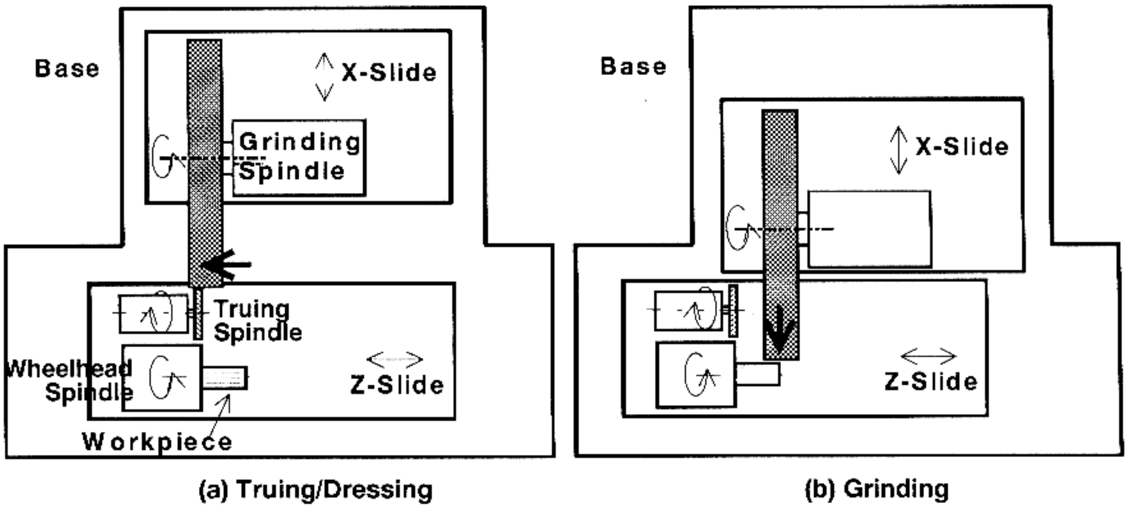

Fig. 1. Configuration of the truing and grinding in a Weldon AGN5 CNC cylindrical grinding machine.

$$u = \frac{f_t v_s}{\pi d v_g h}$$

where d is the diameter of the workpiece and v_s is the surface speed of the grinding wheel.

2.3. Workpiece Measurement.
The roundness of ground parts was measured using a Mahr Perthen MMQ40 cylindrical measurement machine. The average of two roundness traces, 2 and 4 mm from the side face, was used to represent the roundness of the ground part. Surface finish was measured longitudinally on a Rank Taylor Hobson Form Talysurf. Only the arithmetic average surface finish, R_a, is reported.

3. EXPERIMENT DESIGN

The reduction of wheel speed during truing affects the truing speed ratio, q_d, which is defined as the ratio of the rotary truer surface speed, v_r, over the wheel surface speed, v_s. v_r is set at 12.8 m/s in this study. Depending on the rotational direction of the truer relative to that of the grinding wheel, q_d can be positive or negative. q_d is defined as positive when the surface velocity vectors of the grinding wheel and truer are pointed in the same direction at the contact area. All the truing tests conducted in this study were set to have positive q_d.

Most of the parameters in Table 1 were set to fixed values. Only four variables, v_s, q_d, type of work-material, and coolant flow rate, were varied. Sixteen grinding tests, as listed in Table 2, were conducted for each work-material. Four grinding speeds, v_s, were set at 35 (conventional), 61, 91, and 127 m/s. Test results at v_s = 35 m/s were used to benchmark the benefits of high speed grinding.

The first row in Table 2 represents the four tests in which the grinding wheel was slowed down to v_s=19.3 m/s during truing (q_d = 0.661) and speeded up to 35, 61, 91, and 127 m/s during grinding. In the second and third rows, eight more grinding tests were conducted to true the CBN wheel at higher wheel speeds, v_s=25.4 and 33.9 m/s (q_d = 0.503 and 0.381), and grind at v_s=35, 61, 91, and 127 m/s. The last four rows in Table 2 are the four tests designed to have the same wheel speed for truing and grinding, a practice used in most conventional grinding machines due to the lack of capability to vary the grinding wheel speed easily. These four tests were used to benchmark the benefits of this truing strategy.

Table 2. Selection of the sixteen grinding tests for each work-material.

Truing wheel surface speed (v_t), m/s	Grinding wheel surface speed (v_s), m/s				
	35	61	91	127	q_d
19.3	x	x	x	x	0.661
25.4	x	x	x	x, H	0.503
33.9	x	x	x	x, H	0.381
35	x (q_d=0.364)				Same wheel speed for truing and grinding
61		x (q_d=0.209)			
91			x (q_d=0.140)		
127				x (q_d=0.101)	

x: Selected for the test
H: High coolant flow rate tested

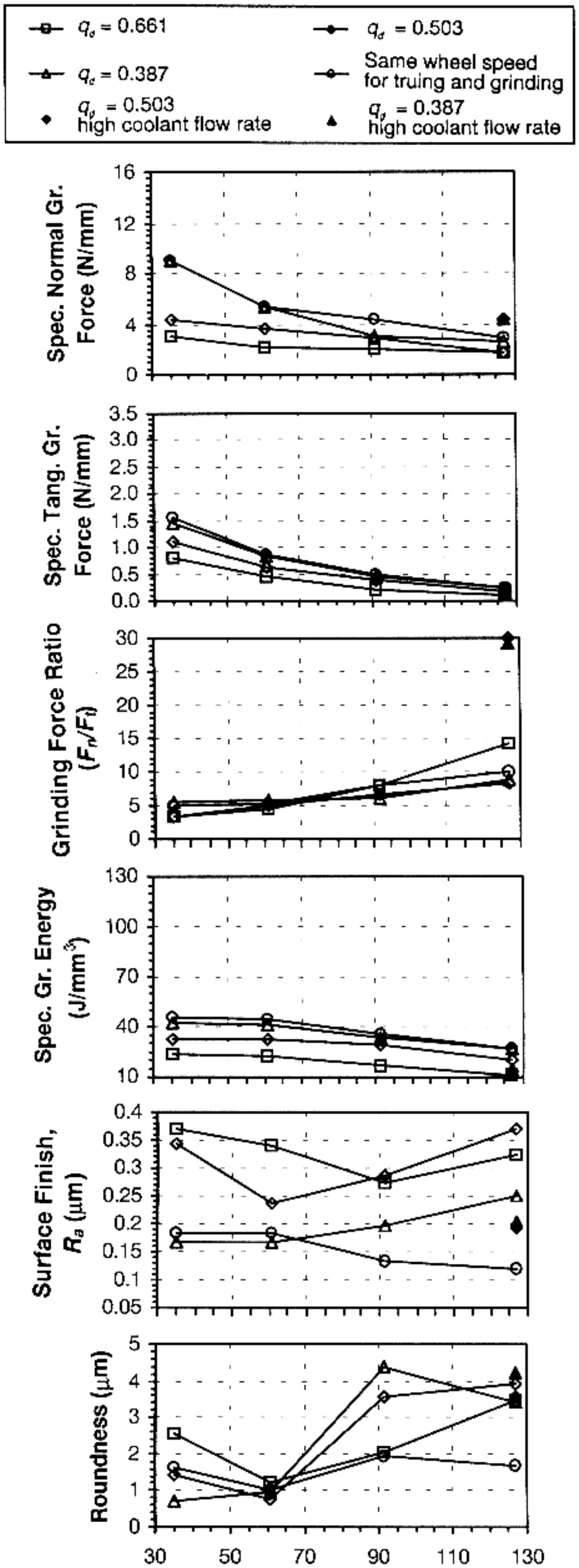

Fig. 2. Specific grinding forces, grinding force ratio, specific grinding energy, surface finish, and roundness of CBN grinding of zirconia.

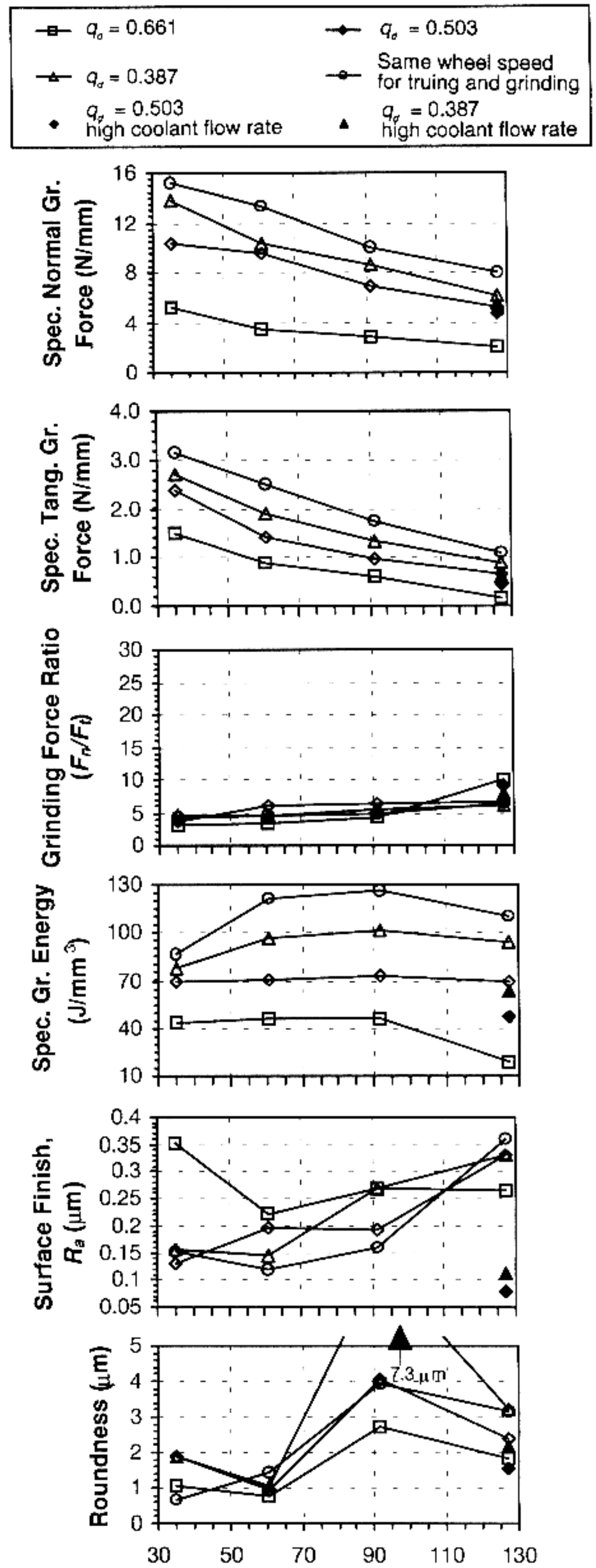

Fig. 3. Specific grinding forces, grinding force ratio, specific grinding energy, surface finish, and roundness of CBN grinding of M2 steel.

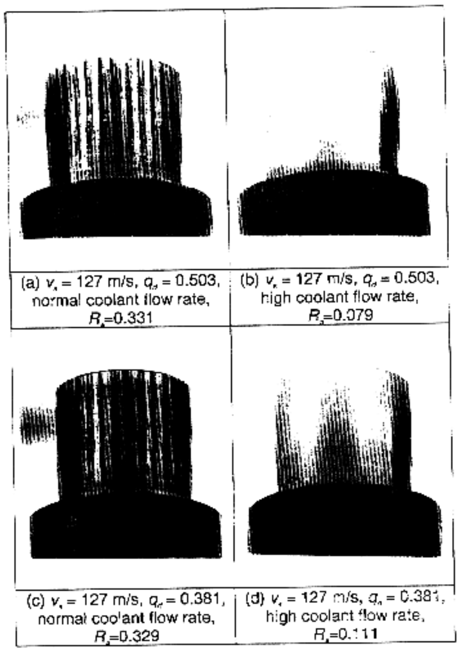

Fig. 4. Comparison of ground M2 steel parts with normal and high coolant flow rates.

4. GRINDING RESULTS

The grinding results are summarized in Fig. 2 for zirconia and Fig. 3 for M2 steel. Each figure includes the specific normal and tangential grinding forces (f_n and f_t), grinding force ratio (F_n/F_t), specific grinding energy, and roundness and surface finish (R_a) of the ground parts. The scale of each parameter in these two figures is intentionally set to be the same for mutual comparison.

4.1. Specific Normal and Tangential Grinding Forces, f_n and f_t, and Grinding Force Ratio (F_n/F_t)

The specific grinding forces were influenced by the four setup parameters: v_s, q_d, coolant flow rate, and type of work-material.

Effect of v_s The benefit of high speed grinding is obvious. Lower normal and tangential grinding forces can be seen at higher v_s. For example, comparing the specific normal grinding force at normal speed (v_s=35 m/s and q_d=0.364) and high speed (v_s=127 m/s and q_d=0.661), its magnitude is reduced from 9.0 to 1.8 N/mm for zirconia and 15.2 to 2.1 N/mm for M2 steel. This is the most attractive feature of high speed grinding. It also confirms the trend reported by Koenig and Ferlemann (1993) and Kovach et al. (1995).

The effect of v_s in the reduction of F_t is even more significant because the grinding force ratio (F_n/F_t) steadily increases at higher v_s. The reciprocal of F_n/F_t is analogous to the coefficient of friction. For single-point machining of metal, typical F_n/F_t is less than 1. For grinding 35 m/s, F_n/F_t is about 5 for zirconia and 4.2 for M2 steel. The force ratio is significantly higher for zirconia grinding. At v_s=127 m/s and high coolant flow rate, F_n/F_t reaches as high as 30. At v_s=127 m/s, the F_t for zirconia grinding is so small that accurate force measurement becomes a problem. For M2 steel, F_n/F_t increases at a lower pace. It reaches about 10 at v_s=127 m/s and q_d=0.661. The trend of increasing F_n/F_t illustrates that the abrasive cuts the work-material more efficiently at higher wheel speed.

Effect of q_d Four distinctly different levels of grinding forces and force ratios can be seen at different q_d for both work-materials. This trend clearly demonstrates the advantage of the proposed truing method. For grinding M2 steel, the CBN wheel trued at v_s= 19.3 m/s (q_d=0.661) requires the lowest level of grinding forces. As the wheel speed increases during truing, q_d decreases and grinding forces increase.

Effect of Coolant Flow For zirconia grinding, high coolant flow rate increases the F_n and slightly decreases the F_t . For M2 steel grinding, high coolant flow rate decreases both F_n and F_t. At normal coolant flow rate and v_s=127 m/s, a white layer of zirconia powder could be seen on the wheel after grinding zirconia. Similarly, at normal coolant flow rate and v_s=91 and 127 m/s, burning marks were found on the ground surface of the M2 steel. Figure 4 shows the comparison of the steel parts ground under the same grinding and truing conditions but at different coolant flow rates. Chatter marks can be seen on parts ground at normal coolant flow rate. The CBN abrasive has very high thermal conductivity, 1590 vs. 29 (W/mK)(kg m/Ks^3) for aluminum oxide. For steel grinding, CBN wheels generally are not prone to the grinding burn problem. It is known that high wheel speed creates a boundary layer of air that keeps coolant away from the grinding zone, resulting in the undesirable phenomena of wheel loading and part burning. At the high coolant flow rate, both wheel loading for zirconia and part burning for M2 steel were eliminated.

Effect of Work-Material The vitreous bond CBN wheel was selected because it could grind both zirconia and M2 steel. Although zirconia is much harder than the hardened M2 steel, it is surprising to see that the forces generated in grinding zirconia are less than half of those generated in grinding M2 steel. The difference in F_n/F_t can be attributed to the fracture toughness of the zirconia material, since there is no ductile elongation of the workpiece material to consume energy.

4.2. Specific Grinding Energy, *u*

Under the setup condition in the conventional grinding machine, i.e., grinding and truing at 35 m/s, u= 46 and 92 J/mm^3 for zirconia and M2 steel, respectively.

Effect of v_s For zirconia, u steadily decreases at high v_s. This trend demonstrates the advantage of high wheel speed for grinding zirconia. At v_s=127 m/s and q_d=0.661, u=11.7 J/mm^3, which is very close to zirconia's melting energy per unit volume, 11.5 J/mm^3. This trend was not observed for the M2 steel. On the contrary, for the M2 steel, u increases to the peak at v_s=91 m/s and then decreases at v_s=127 m/s. The lowest u for grinding M2 steel is 19.8 J/mm^3. It occurs at v_s=127 m/s, q_d=0.661, and normal coolant flow rate. The melting energy per unit volume for M2 steel is close to that of iron, 10.5 J/mm^3.

Effect of q_d Four distinct levels of u can be seen at different q_d. Similar to the effect of q_d on grinding forces, truing at higher q_d creates a sharper, more aggressive wheel topography which requires lower u. This confirms the trend reported by Klocke and Koenig (1995).

Effect of Coolant Flow At high coolant flow rate and high speed, very efficient grinding of zirconia can be seen, i.e., u is close to its melting energy per unit volume. Grinding burns were observed on the M2 steel parts when grinding at high speed and normal coolant flow rate. High coolant flow rate helped to eliminate the grinding burn problem.

Effect of Work-Material Although zirconia is harder than M2 steel, it has lower u than that of the M2 steel.

4.3. Surface Finish, R_a

The grinding force and specific grinding energy results in the previous sections have demonstrated that high-speed grinding can be used for high stock removal rates. Grinding results in Figs. 2 and 3 show the high speed grinding did not achieve better surface finish or roundness (discussed in the next section) on ground parts. There are several factors that influence the surface finish. For example, at high v_s, the imbalance in the wheel will induce vibration in the grinding machine, which will adversely affect the surface finish. This is an area which is under investigation.

The effect of v_s, q_d, and work-material on surface finish is not as clearly defined as on the grinding forces and grinding force ratio. The surface finish for both work-materials are in the range of 0.1 to 0.4 μm R_a. In general, more efficient grinding conditions, i.e., lower grinding forces, tend to generate rougher surface finishes.

The effect of coolant flow rate on surface finish is significant. High coolant flow rate at high v_s improves the surface finish, especially for M2 steel.

4.4. Roundness

Similar to the surface finish, the results for roundness are mixed. The effects of v_s, q_d, and work-material on the roundness are not as obvious. The high coolant flow rate, although it helps to improve the surface finish, does not help to improve the roundness for zirconia grinding. It does help to improve the roundness for M2 steel grinding.

5. CONCLUDING REMARKS

In this paper, experiments of high speed grinding of zirconia ceramic and hardened M2 steel were conducted to quantify the benefits of this new technology. The benefits of using high grinding wheel speed to reduce both the normal and tangential grinding forces and the grinding force ratio were obvious. High grinding wheel speed, however, did not improve the surface finish and roundness of the ground parts.

A method to slow down the wheel during truing and speed up during grinding was studied. Such truing strategy helped to reduce the grinding forces. It worked especially well for M2 steel. Two levels of coolant flow rate were tested. At normal coolant flow rate (22.7 liter/min) and v_s=127 m/s, a layer of zirconia powder was found on the wheel after grinding zirconia, and burning marks were found on ground M2 parts. High coolant flow rate (62.5 liter/min) helped to eliminate both problems.

This study also generates several interesting topics for future research. Some phenomena observed, such as the lowering of grinding force ratio at high speed, peaking of u for grinding of M2 steel at v_s=91 m/s, grinding damage induced by high speed grinding of ceramics, roundness pattern generated at high speed, etc., still lack full explanation and require detailed analytical modeling or dedicated experiments to understand the mechanism and benefits of high speed grinding.

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