Use of actively cooled and activated coolant for surface quality improvement in ductile material grinding

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Abstract. An active cooling and activation approach for coolant during ductile material grinding is proposed and examined. The aim is to enhance the surface quality of the workpiece being machined by the grinding process. Problems in the existing cooling approaches, such as activation, cryogenic cooling, and chilled air cooling, are discussed. Experimental and computational studies of the effects of actively cooled and activated coolant for ductile material grinding were conducted. Experimental results show that the proposed approach is able to improve surface quality by up to 36.68% on average in terms of surface roughness R_a . In addition, it was found that surface roughness could be reduced if the coolant temperature is reduced. The results of the XRD tests show that the proposed method could, in general, produce low residual stress values. Further studies of this topic are necessary. Results of optical and SEM examinations also confirmed that the proposed approach is advantageous.

Keywords: active cooling, activated coolant, grinding, surface roughness, residual stress.

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1 Introduction

Heat generated in grinding could cause thermal deformation in grinding wheel and workpiece. This could affect the machining accuracy during a grinding process (Ramesh et al. 2004; Wang and Kou 1998). Heat effects can be reduced by use of coolant to be applied between the wheel and the workpiece (Wang and Kou 1997). However, the process of heat conduction by coolant would need a long period of time to achieve an equilibrium state (Gao et al. 2003). Prior to the equilibrium state, the coolant temperature would continuously increase, which will seriously affect the accuracy of the machining process and make the production output unstable (Choi et al. 2001).

Megasonic coolant can excite the coolant which will infiltrate more efficiently into the grinding zone to provide better cooling (Suzuki et al. 2004; 2003). Improvement in surface roughness of ductile material by 20-30% can be obtained and wheel wear was reduced. The problem of continuous increase in coolant temperature will remain.

Cryogenic cooling can rapidly take heat away from the grinding zone. However, a significant temperature gradient, as large as 100°C, could be generated by the fast cooling action. This could cause excessive thermal stresses on the workpiece surface (Tsai and Hocheng 1998). This is undesirable and could affect the machining accuracy. In addition, frequent replenishment of liquid nitrogen is costly and it requires great care for safety

(Paul and Chattopadhyay 1995; 1995; 1996). The cooling air approach could cause strong noises as the delivery speed is very high (Ramesh et al. 2003; Choi et al. 2002).

In order to address the above problems, an actively cooled and activated coolant approach is proposed and the working principle is introduced. Experimental and computational studies of the effects of actively cooled and activated coolant for ductile material grinding were conducted to assess the proposed method. The grinding wheel speed was determined by a number of experimental tests. Different values in depth of cut, feedrate and coolant temperature were applied. The machined workpieces were examined using an optical profiler, a microscope, and an instrument for SEM for characterization. Experimental results show that the use of actively cooled and activated coolant is able to improve the surface quality by up to 36.68% on average in terms of surface roughness R_a .

2 Use of actively cooled and activated coolant

A cooling and activation system will be used to deal with the coolant used for precision grinding. The system is based on forced convection of heat generated during the machining process and high frequency activation was applied. A compact heat pump and nozzle were used. The coolant temperature, noted as t_c , could be reduced to approximately 2°C under no load condition, and to approximately 9°C under loading. The cooling tank capacity was 25 l. The working principle is illustrated in Fig. 1.

Figure 1 Active cooling and activation system

3 Computational testing for cooled and activated coolant

Computational testing for cooling and activation effects was conducted to examine the temperature reduction through the use of the cooled and activated coolant (Fig. 2) (Gao and Lai 2005). The grinding length $l=(d_c D)^{1/2}$ (Wang and Kou 1998), where d_c is the depth of cut. In the model (Fig. 2), the heat is assumed to be uniformly distributed over the contact region and is given as $q=F_t v_s / l b$ (Wang and Kou 1998), where b is the width of the grinding wheel, F_t is the tangential grinding force, and v_s is the grinding wheel velocity. The heat being taken away by the coolant is given as $q_c=(1-R_c)R_{Qw} q/(1-r)$ (Wang and Kou 1998), where r is the wear flat ratio, R_c is the ratio of heat in workpiece which is related to the effectiveness of the coolant, and R_{Qw} is the fraction of heat into the workpiece at the wear flat area. To avoid the complexity in activation modeling, the activation effects are lumped into q_c , noted as $q_{ac}=(1-R_{ac})R_{Qwa} q/(1-r)$ (Table 1). In addition, the model was simplified to be without details of fluid through the grinding zone (Hryniewicz et al. 2000; Ramesh et al. 2001; Jin et al. 2003; Gviniashvili et al. 2004). In the computational testing, the heat was generated for $\Delta t=1s$ and was then taken

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away from the grinding zone (Fig. 2 and Table 1). Totally five cases were examined to investigate the heat generation and heat transfer process (Table 2 and Fig. 3), where v_c is the coolant velocity. From Table 2 and Fig. 3, it can be seen that the maximum and the average temperatures in the grinding zone, noted as t_{gmax} and t_{gavg} (Fig. 2 and Table 2), respectively, can be reduced when using the proposed approach.

Table 1 Conditions for computational testing

Analysis device	CPU: P4 2.2GHz, 2GB RAM
Software	Solid model: SolidWorks 2004 Fluid analysis: ANSYS CFX 10
Physical properties type	Workpiece: Steel Fluid: Water and air
Fluid models	Heat transfer model: Thermal energy Turbulence model: Shear stress transport
Analysis conditions	Depth of cut: $d_c = 5\mu m$, Grinding length: $l = 0.9354mm$ Grinding wheel diameter: $D = 175mm$ Grinding wheel width: $b = 6mm$ Grinding wheel speed: $n_s = 2600rpm$ Grinding wheel velocity $v_s = 23.82m/s$ Wear flat ratio: $r = 0.5$ Fraction of heat into workpiece: $R_{Qw} = 0.5$ Fraction of heat into workpiece under activation: $R_{Qwa} = 0.45$ Ratio of heat in workpiece: $R_c = 0.95$ Ratio of heat in workpiece under activation: $R_{ac} = 0.924$ Heat removal increment due to activation: $\Delta q_c = 36.68\%$ Heat removal: $q_c = 6.36 \times 10^6 W/m^2$ Heat removal under activation: $q_{ac} = (1 + \Delta q_c)q_c$
Timescale	Physical timescale: 0.02s Max. no. of iterations: 50
Mesh statistics	Number of nodes: 16869 Number of elements: 87528 Element: Tetrahedral type

Figure 2 Models for computation testing

4 Experimental results and discussion

To validate the proposed method, a number of experimental tests were conducted and comparison made. Effects of workpiece table speed v_w and depth of cut d_c on the response variables such as surface roughness, surface morphology, and sub surface residual stress were studied under the condition of normal coolant and actively cooled and actuated coolant. Totally, 40 tests (Table 3) were conducted. For d_c tests, 20 grinding trials were conducted. The wheel feed profile was $n_g \in [1, 10]$, where n_g is the grinding

pass number, for grinding at $v_w=80\text{mm/s}$, and $n_g \in [1,10]$ for sparking. For v_w tests, 20 grinding trials were realized. The wheel feed profile was $n_g \in [1,10]$ for grinding at $d_c=1\mu\text{m}$, and $n_g \in [1,10]$ for sparking. To minimize the wear effect of the grinding wheel, dressing was applied before each type of the grinding tests.

Table 2 Computational testing results

Type	t_c (°C)	v_c (mm/s)	$t_{g\text{max}}$ (K)	$t_{g\text{max}}$ (°C)	$t_{g\text{avg}}$ (K)	$t_{g\text{avg}}$ (°C)
No coolant	25		310.2	37.2	304.1	31.1
Air	25	105.82	308.7	35.7	303.3	30.3
Normal coolant	25	105.82	298.1	25.1	298.1	25.1
Cooled coolant	9	105.82	282.1	9.1	282.1	9.1
Cooled and activated coolant	9	105.82	282.076	9.076	282	9

Figure 3 Temperature distributions on a workpiece surface

Table 3 Experimental test conditions

Workpiece	Mild steel plate 105mm x 25mm x 12mm
Grinding wheel	Al ₂ O ₃ 91A120K5AV217 175x6x31.75mm
Wheel speed	$n_s = 2600\text{rpm}$
Workpiece table speed	$v_w = 40 - 120\text{mm/s}$
Depth of cut	$d_c = 1 - 5\mu\text{m}$
Feed profile	Grinding: $n_g \in [1,10]$ Sparking: $n_g \in [1,10]$
Grinding fluid	Soluble type at 5% dilution, 9°C, 0.8 l/min
Grinding machine	ESG-818ASD

For wheel speed selection, totally five grinding tests on steel plates were conducted at the wheel speed $n_s=1400, 1700, 2000, 2300$, and 2600rpm , respectively. The maximum wheel speed was approximately 2880rpm . The workpiece table speed $v_w=80\text{mm/s}$. Based on the results of surface roughness measurement, $n_s=2600\text{rpm}$ was found to be suitable for producing better workpiece surface quality. A Renishaw laser interferometer was used

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to measure the workpiece table speed v_w . A lower workpiece table speed combining with a higher grinding wheel speed would generally give better surface (Nakayama et al. 2004). The workpiece table speed was selected as $v_w=40, 60, 80, 100$, and 120mm/s , respectively, for the study (Gao and Lai 2005).

The test samples were measured using a Wyko optical profiler in the vertical scanning interferometry, or VSI, mode, which has a resolution of 1nm . The surface roughness results in terms of R_a , R_z , and R_t or R_y , respectively, are shown in Fig. 4-5 and Table 4-5. It can be seen that the surface roughness was generally reduced when the proposed method of use of cooled and activated coolant was utilized (Fig. 4-5 and Table 4-5). In addition, if d_c was increased, surface roughness would generally increase (Fig. 4-5). Lower table speed v_w would normally give lower roughness values (Fig. 4-5) with a few exceptions, where lower v_w did not give improvements (Fig. 5(b)-(c) and Table 5) due to increased vibrations. It is noted that the maximum d_c value was set to be less than $6\mu\text{m}$ (Table 4 and Fig. 4) to avoid a large grinding force. The measurement equipment conditions are shown in Table 6.

Table 4 Surface roughness improvement for d_c tests

Depth of cut d_c (μm)	1	2	3	4	5	Avg. improvement
Improvement in R_a (%)	38.08	36.43	39.74	35.10	34.04	36.68
Improvement in R_z (%)	26.50	36.04	33.33	21.78	27.68	29.07
Improvement in R_t (%)	22.62	34.03	30.83	19.18	24.07	26.15

Table 5 Surface roughness improvement for v_w tests

Workpiece speed v_w (mm/s)	40	60	80	100	120	Avg. improvement
Improvement in R_a (%)	15.56	21.71	37.01	32.06	34.78	28.22
Improvement in R_z (%)	-3.09	-1.30	31.72	20.69	21.62	13.93
Improvement in R_t (%)	-5.62	-5.42	31.43	15.43	19.14	10.99

Table 6 Measurement equipment and conditions

Olympus optical microscope	Magnification 800x
JSM SEM	Magnification 2500x
Wyko optical profiler	Magnification 75x Measurement area $816.5 \times 621.4\mu\text{m}$

Results of the workpiece surface inspection (Table 6) for typical d_c and v_w values and 2 coolant conditions are shown in Fig. 6-9. From Fig. 6, it can be seen that, when using normal coolant in the depth of cut test, the grinding marks are significant in the grinding direction (Fig. 6(a) and Fig. 6(c)). There are spots of peak and valley on the sample surface (Fig. 6(a)). From Fig. 7, it can be seen that, when the proposed method was applied, not only the grinding marks are less significant and there are larger flat regions (Fig. 7(c)). There are less and smaller spots of peak and valley distributed over the sample surface (Fig. 7(a)). From Fig. 8, when normal coolant was applied in the table speed test, the grinding marks remained along the grinding direction (Fig. 8(c)). There are also spots of peak and valley visible on the sample surface (Fig. 8(a) and Fig. 8(c)). The spots of peak and valley are relatively smaller when Fig. 8(c) is compared with Fig. 6(c). From Fig. 9, when using the proposed method, the spots of peak and valley and grinding marks are smaller and less significant which provided larger flat regions (Fig. 9(a) and Fig. 9(c)). The advantage of the proposed method is confirmed (Fig. 6-9) as found in the grinding test (Fig. 4-5 and Table 4-5) (Gao and Lai 2005).

Figure 4 Effects of d_c on R_a , R_z and R_t

Figure 5 Effects of v_w on R_a , R_z and R_t

A number of samples used in the depth of cut and table speed tests under 4 coolant conditions were examined by using X-ray diffraction for residual stress assessment (Table 7). Results of the X-ray diffraction measurement at a typical scanning depth of $z_{sc} = -10\mu\text{m}$ are shown in Fig. 10 and Table 8. For the depth of cut test, where $d_c = 5\mu\text{m}$ and $v_w = 80\text{mm/s}$, it can be seen that an average residual stress of $\sigma_{zsc} = -311.825\text{MPa}$ was obtained (Fig. 10 and Table 8). For the table speed test, where $d_c = 1\mu\text{m}$ and $v_w = 120\text{mm/s}$, an average residual stress of $\sigma_{zsc} = -228.325\text{MPa}$ was obtained (Fig. 10 and Table 8). The

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difference between the two sets of data is 83.5MPa (Table 8). This was jointly contributed by d_c and v_w , but it may be mainly due to the much reduced depth of cut (Fig. 10 and Table 8).

Figure 6 Results of using normal coolant in a d_c test

Figure 7 Results of using the proposed method in a d_c test

Figure 8 Results of using normal coolant in a v_w test

Figure 9 Results of the proposed method in a v_w test

For the d_c test, it can be seen that the proposed method delivered the lowest residual stress (Fig. 10 and Table 7-8). Activation seems produce lower residual stress values and a joint action of active cooling (Gao and Lai 2005) and activation produced better results (Table 8). However, in the d_c test, the result of active cooling alone produced a higher residual stress value (Fig. 10 and Table 8). This would require further study of the approach of active cooling alone. For the v_w test, the residual stress values are similar for the normal and cooled coolant conditions (Fig. 10 and Table 7-8). The joint action of cooling and activation produced better result (Table 8). This shows that the proposed method is advantageous compared to the approach of activation alone. However, in the v_w test, it seemed that the activation produced higher residual stress values (Fig. 10 and Table 8). This would again require further study of the technique.

Table 7 XRD residual stress test conditions

Test	Coolant conditions	Depth of cut d_c (μm)	Table speed v_w (mm/s)
Depth of cut test	Normal coolant	5	80
	Cooled coolant		
	Activated coolant		
	Cooled and activated coolant		
Table speed test	Normal coolant	1	120
	Cooled coolant		
	Activated coolant		
	Cooled and activated coolant		

Table 8 Results of the XRD tests

	Residual stress	σ_{zsc}	(MPa)	Avg. value (MPa)	
	Normal coolant	Cooled coolant	Activated coolant	Cooled and activated coolant	
Depth of cut d_c test	-324.2	-338.95	-308.4	-275.75	-311.825
Table speed v_w test	-208.75	-201.85	-263.8	-238.9	-228.325

To examine the effect of cooling temperature variation, further experimental tests were conducted (Table 9). A number of coolant temperature t_c values were selected. $t_c \in [9^\circ\text{C}, 21^\circ\text{C}]$. $\Delta t_c = 3^\circ\text{C}$. This means that the room temperature condition and the cooled coolant condition were included in the tests (Table 3 and Table 9). The wheel speed $n_s = 2600\text{rpm}$. Grinding was performed for 10 passes and sparking for 10 passes. The results are shown in Fig. 11-12.

Table 9 Variable coolant temperature test conditions

Experiment set n_c	Depth of cut d_c (μm)	Table speed v_w (mm/s)	Coolant type	Coolant t_c ($^\circ\text{C}$)
1	3	80	Cooled coolant	[21,18,15,12,9]
2	3	80	Cooled actuating	[21,18,15,12,9]
3	1	120	Cooled coolant	[21,18,15,12,9]
4	1	120	Cooled actuating	[21,18,15,12,9]

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From Fig. 11-12, it can be seen that, for every 3°C reduction, which was the value of Δt_c , in coolant temperature t_c , approximately 5-6% improvement in surface quality was obtained in terms of surface roughness for the variable t_c tests (Table 9). This is due to a relatively steady $\partial R_a / \partial t_c$ being obtained (Fig. 11-12). In addition, the surface quality was improved by using the proposed approach when compared with the active cooling technique alone (Fig. 11-12).

Figure 10 Results of residual stress measurement

Residual stress $\sigma|_{zsc=-10\mu m}$ (MPa)

Figure 11 R_a vs t_c for $n_c=1-2$

Figure 12 R_a vs t_c for $n_c=3-4$

5 Conclusions

Experimental and computational studies of the proposed approach of use of actively cooled and activated coolant for ductile material grinding were conducted. The results show that the use of the proposed approach can provide better surface quality with an average reduction up to 36.68% in surface roughness R_a . For every 3°C reduction in coolant temperature, approximately 5-6% improvement in surface quality could be obtained in terms of surface roughness R_a . In addition, the results of the optical and SEM examinations show that the machined surfaces could have significantly reduced grinding marks and spots of peak and valley, which represents that larger flat surface areas could be obtained. The results of the XRD tests show that the proposed method could, in general, produce low residual stress values. Further studies of this topic are necessary. The studies demonstrated that the proposed approach is advantageous.

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