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ORIGINAL ARTICLE

An experimental investigation of temperatures during conventional and CBN grinding

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Abstract In many grinding applications, the material removal rate is constrained by the undesired thermal effects such as surface burn, tensile residual stresses, and micro-cracks on the ground parts. Thermal damage is a common productivity limitation factor for conventional grinding wheels largely employed in industry due to their convenient cost and known behavior. The development of superabrasive materials having high heat conduction coefficients allowed for higher material removal rates, pushing up the limits of productivity previously achieved with conventional wheels. This paper presents the results of a comparative investigation of maximum surface temperatures generated during the plunge grinding of 52100 steel using Al_2O_3 and CBN wheels. The experiments were conducted under wet as well as dry grinding conditions. The temperatures measured experimentally were compared to those determined analytically. A discussion relative to heat partition coefficients concludes this paper.

Keywords Temperature · Heat · Aluminum oxide grinding · CBN grinding

1 Introduction

Grinding offers decisive advantages in comparison with other machining processes. In many cases, grinding shows itself to be the only economic material removal process. The trend in industrial production towards higher productivity with the same or increased part accuracy using harder-to-machine materials naturally leads to the increasing use of grinding to solve many machining problems. The development of high-performance grinding resulted from the demand to minimize the grinding costs and this was possible through the reduction of the machining time. Conventional abrasives (Al_2O_3 and SiC) though widely used, are sometimes unable to meet the production requirements, and in many cases, grinding with super abrasives (CBN and diamond) wheels seems to be the solution. The application of super-abrasive technology is not limited to hardened materials, but is expanding into more and more applications in the machining of annealed or mild steels. A few such applications are: grinding of camshafts, shock rods, brake rotors, bearings, fuel-injection parts, drive shafts, valves, gearing, tools, slots, tow levers, and steering-gear components.

Of particular importance in many grinding applications is the thermal effect on the surface integrity of the workpiece. In many applications, temperature becomes the limiting factor for productivity as surface burn or tensile residual stresses have to be avoided. Thus, the possibility to predict the temperatures generated by a specific grinding regime is of particular interest.

This paper presents the results of a comparative investigation of temperatures generated during the plunge grinding of 52100 steel using aluminum oxide and CBN wheels. The tests were run with and without coolant in an endeavor to better relate the experimental results to the analytical calculations.

2 Experimental setup

The experimental work was carried out on a CNC surface grinder instrumented with force, power, vibration, and

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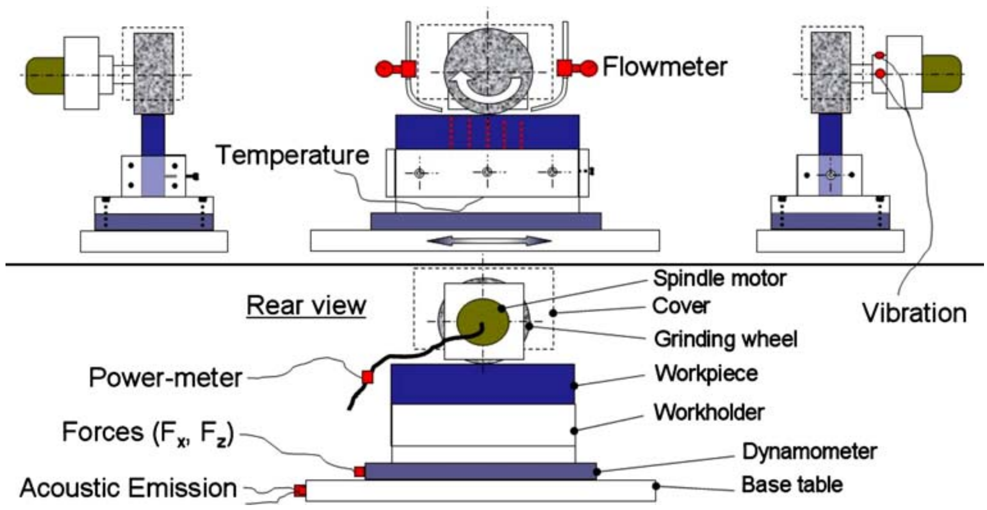


Fig. 1 The schematics of the test-bed setup

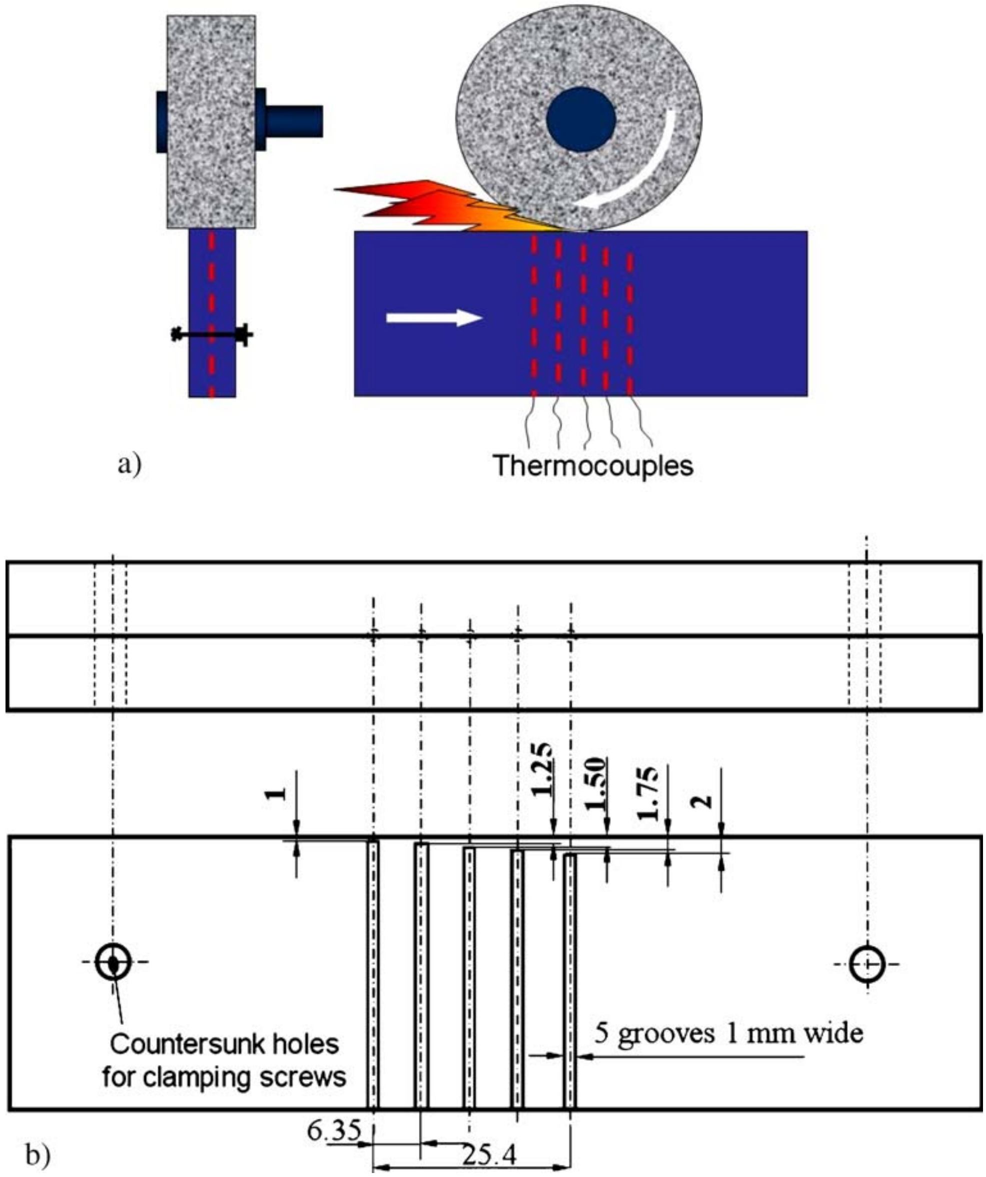


Fig. 2 Schematics of thermocouples setup: **a** Position of workpiece; **b** Position of thermocouples

Table 1 Grinding parameters for temperature tests

Infeed (mm)	Table speed (m/s)	Wheel speed (m/s)	Wheel radius (m)
0.0254	0.2115	35.56	0.1778
0.0381	0.2115	35.56	0.1778
0.0305	0.1480	35.56	0.1778
0.0127	0.2115	35.56	0.1778

acoustic emission sensors. Thus, besides temperature, parameters such as spindle power, normal and tangential forces could be acquired simultaneously. The schematics of the setup are presented in Fig. 1.

The workpieces used for these trials were made of AISI 52100 steel at 62 HRC hardness. The dimensions of the parts were 152.4 × 127 × 12.7 mm. The parts were sliced and thermocouples were inserted in grooves as presented in Fig. 2. The diameter of the thermocouple wire selected was very small (0.25 mm) so that the thermal properties of the workpiece material are not affected too much in the interface area and the thermocouple response speed is increased. Five thermocouples were inserted at different depths below the surface according to Fig. 2. There were two main reasons for this setup: (1) to record the temperature in the vicinity of the surface, and (2) the possibility to replicate certain cuts. However, this paper only presents the maximum temperatures recorded at the workpiece surface; the values recorded at different depths under the surface are still under investigation.

The test conditions adopted for both types of grinding wheels are presented in Table 1. The tests were conducted using an aluminium oxide wheel LA46-H-VPE, size 355.6 × 127 × 50.8 mm, and a CBN wheel VB151-C128-VCF10, size 355.6 × 127 × 25.4 mm, for both wet and dry conditions. The metalworking fluid was Cimtech 310 at 8% in water. The workpiece material was AISI 52100 at 62 HRC with properties presented in Table 2.

The outer diameter of the wheels and the area that had to be ground was the same for all tests. The difference between the two grinding wheels came from the material of the grits and bond, the size of the grits, and the way they were combined. The aluminium oxide wheel is a typical conventional vitrified bonded wheel while the superabrasive wheel is capable of creep feed grinding with CBN. The theoretical length of cut and width of cut is the same for both wheels. The wheels were selected from actual industrial applications and were not specifically manufactured for this type of test.

Table 2 Properties of the workpiece (AISI 52100)

Temperature (°C)	k_w (W/mK)	ρ_w (kg/m^3)	c_w (J/kgK)	β_w (J/m^{2}sK)	K (m^2/s)
600	33.6	7,971.81	778	14,435.7	5.41755E-6
300	40.3	7,810	568	13,370.6	9.0846E-6

Table 3 C function of Peclet number for a triangular flux [4]

Peclet number (Pe)	C
Pe >10	1.06
$0.2 < Pe < 10$	$\frac{0.95}{\pi}\sqrt{2\pi + \frac{Pe}{2}}$
Pe < 0.2	0.76

3 Temperature calculation

In this section, the temperatures generated at the surface of the workpiece will be calculated using the moving heat source theory previously applied with success by different authors such as [1–3]. It is considered that a band heat source moves on the workpiece surface at a speed equal to the workpiece speed. The heat flux conducted into the workpiece, q_w , is only a fraction of the total heat flux q.

$$q = q_w + q_s + q_{ch} + q_f \tag{1}$$

where q_w is the heat flux which enters the workpiece within the contact zone, q_s is the heat flux entering the grinding wheel, q_{ch} is the heat flux carried away by chips, and q_f is the heat flux entering the metalworking fluid in the contact zone.

Depending on the particularities of each application, the heat flux distribution can be approximated, as uniform flux, triangular flux, square law flux, or trapezoidal flux [4]. For the current investigation, the uniform flux [5] and triangular flux hypotheses [6] were employed.

The heat flux entering the workpiece is usually expressed as

$$q_w = R_w q \tag{2}$$

where R_w is a proportionality coefficient denominated workpiece partition ratio.

The solution for the moving heat source was determined using Besel functions and it was found that the temperature

Table 4 R_w when grinding with Al_2O_3 wheel

Source	Thermal conductivity of abrasive grains k_g (W/mK)	Rw value for r_0= 0.005 mm	Rw value for r_0=0.015 mm
[10]	35	0.85	0.9076
http://www.MatWeb.com	6.3 at 800°C, and 30 at 25°C	0.96923 0.8687	0.982 0.9197
[11]	7.1	0.96546	0.9797
[9], [4]	30	0.8687	0.9197

Table 5 R_w when grinding with CBN wheel

Source	Thermal conductivity of abrasive grains k_g (W/mK)	Rw value for r_0=0.005 mm	Rw value for r_0=0.015 mm
[11]	290	0.406	0.5424
[4]	240 (pure-up tp 1,300)	0.4526	0.5888

distribution is strongly dependent on the heat source distribution and the so-called Peclet number (Pe) (i.e., [4]).

The Peclet number is expressed as

$$P_e = \frac{v_w l}{2K} \tag{3}$$

where l is half of the heat source length l_c, v_w is the workpiece speed, and K is the thermal diffusivity of the workpiece material:

$$K = \frac{k}{\rho c} \tag{4}$$

where ρ is the material density, k is the thermal conductivity, and c is the specific heat capacity of the workpiece.

The total heat flux in the grinding zone can be expressed as

$$q = \frac{P}{l_c v_w} \tag{5}$$

The maximum temperature is generally expressed as [6], [4]:

$$T_{\max} = \frac{CR_w q}{\beta}\sqrt{\frac{l_c}{v_w}} \tag{6}$$

where C is a constant given in Table 3, l_c is the length of contact, and $\beta = \sqrt{k\rho c}$ is the heat diffusion coefficient of the workpiece.

A similar expression was used by [1]; in his case, the heat flux was considered uniform and the value of C is taken 1.595 for Pe>5.

$$T_{\max} = 1.595\frac{R_w q_w}{k_w}\left(\frac{Kl_c}{2v_w}\right)^{1/2} \tag{7}$$

Table 6 Dry-grinding with Al_2O_3 wheel

Infeed (mm)	Temperature (°C)			
	Malkin [1]	Kato/Takazawa [5]	Chen [6]	Measured/calibrated
0.0127	566.66	535.25	526.64	514.62
0.0254	654.9	622.5	606.15	606.15
0.0305	845.29	792.36	777.71	683.86
0.0381	1,004.81	927.09	921.4	777.12

Table 7 Dry-grinding with CBN wheel

Infeed (mm)	Temperature (°C)			
	Malkin [1]	Kato/Takazawa [5]	Chen [6]	Measured/calibrated
0.0127	113.34	127.65	127.56	142.08
0.0254	226.76	240.56	237.91	237.91
0.0305	183.19	196.14	195.52	219.74
0.0381	263.22	278.12	273.38	272.60

where k_w=15.568 N/s deg F, K=0.00000413 m^2/s, with R_w=0.86.

[5] derives the maximum temperature from Takazawa's [7] solution to the steady-state temperature distribution:

$$T\max = T_s\exp(-\beta z) \tag{8}$$

where z is the depth where temperature is determined,

$$T_s = 0.947\,\alpha^{0.47}k^{-1}F_t' R_w v_s v_w^{-0.47} l_c^{-0.47} \tag{9}$$

and

$$\beta = 0.576\alpha^{-0.63} v_w^{0.63} l_c^{-0.37} \tag{10}$$

with F_t' the specific tangential force, and v_s the wheel speed.

The heat partition coefficient R_w can be determined experimentally or as a function of effective top flat radius of the grains, r_0, thermal conductivity of abrasive grains, k_g, wheel sped, v_s, and thermal properties of the workpiece $\beta_w = \sqrt{k_w\rho_w c_w}$ [8]:

$$R_w = \frac{q_w}{q_w + q_s}\left[1 + \frac{0.97k_g}{\beta_w\sqrt{r_0 v_s}}\right] \tag{11}$$

where q_w is the heat flux entering the workpiece, and q_s is the heat flux entering the grinding wheel.

Values of r_o were found in [8] (5 µm) and [9] (15 µm). For the current investigation, considering the grain size of each wheel, the values adopted for r_o were 5 µm for the CBN wheel and 15 µm for the Al2O3 wheel. Tables 4 and 5 present the calculated values of R_w for Al_2O_3 and CBN wheels, respectively.

Table 8 Wet-grinding with Al_2O_3 wheel

Infeed (mm)	Temperature (°C)			
	Malkin [1]	Kato/Takazawa [5]	Chen [6]	Measured/calibrated
0.0127	254.83	249.66	245.65	327.67
0.0254	444.16	427.48	416.26	416.26
0.0305	418.52	400.55	393.15	498.82
0.0381	682.09	651.62	630.65	746.51

Table 9 Wet-grinding with CBN wheel

Infeed (mm)	Temperature (°C) Malkin [1]	Kato/Takazawa [5]	Chen [6]	Measured/calibrated
0.0127	113.34	127.65	127.56	101.07
0.0254	197.08	211.37	209.03	209.03
0.0305	208.21	220.55	219.86	229.70
0.0381	240.23	255.37	251.01	261.86

The calculated values of R_w were adopted for the dry-grinding conditions. Also, in case of dry grinding with aluminium oxide wheel, the conductivity of the grains was related to temperature, so k_g was taken 7.1 W/mK resulting in R_w=0.9797. In case of dry grinding with CBN, R_w= 0.406. For wet-grind conditions, the values of R_w were approximated from published literature: R_w=0.86 for aluminium oxide wheel [4], and R_w=0.35 for CBN wheel [9].

4 Results and discussion

The values of maximum temperature were first determined from the analytical Equations (6), (7), and (8). The average workpiece temperature in dry grinding was 600°C and the workpiece properties were selected accordingly. For the case when metalworking fluid was employed, the workpiece properties were selected for a 300°C average temperature in the cut. The power used during grinding was calculated from the tangential grinding force measured experimentally:

$$P = F_t v_s \qquad (12)$$

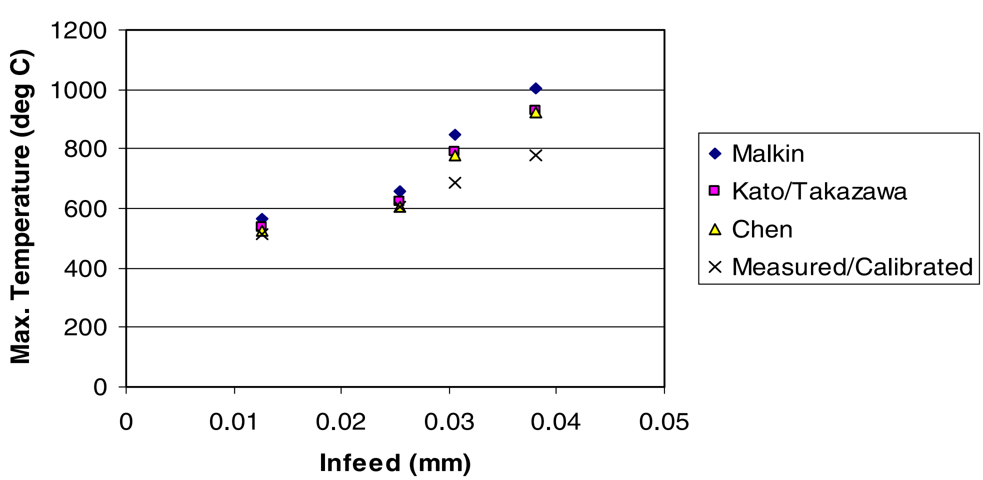
The measured temperatures were below the calculated values, nevertheless, they followed the same trend. A calibration was made by adjusting the experimental temperature for the 0.0254-mm infeed to the calculated value. The other measured temperatures were multiplied with the determined calibration factor and the results are presented in Tables 6, 7, 8 and 9 and Figs. 3, 4, 5 and 6, respectively. In the tables, the first column is the infeed (depth of cut) in mm; the next three adjacent columns contain the temperature values in degrees Celsius calculated according to reference analytical formulas. The last column contains the calibrated measurements of the actual temperatures.

The fact that the measured temperatures were below the calculated analytical temperatures was not a surprise considering that the response time of the thermocouples cannot be ideal. Despite the high sampling rate employed (1,500 Hz), some of the following factors will always have an influence on the acquired signal: electrical noise, thermocouple response time, thermocouple calibration, and thermocouple setup.

The temperature values determined/recorded for each case have shown that:

- The temperatures are much higher when grinding is done using aluminium oxide wheels comparing to CBN wheels. The CBN dry-grinding case generated much lower temperatures comparing to Al_2O_3 wet-grinding case.
- The differences between the calculated temperatures for dry and wet grinding with CBN wheel appeared to be small and this was attributed to the particular structure of the wheel which was designed for creep-feed grinding. The adopted heat partition coefficient R_w had its influence also.
- The temperature values calculated for the dry grinding with aluminium oxide are in the range of 700°C, which

Fig. 3 Dry-grinding with Al_2O_3 wheel



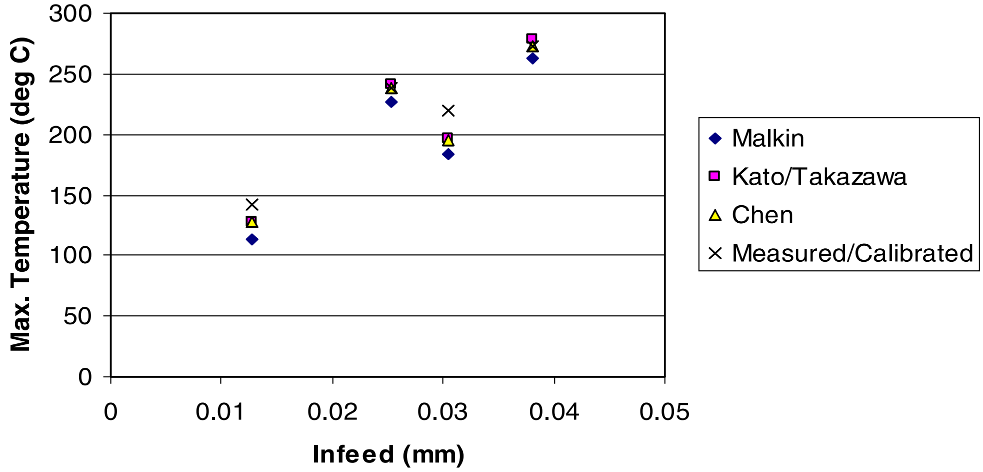


Fig. 4 Dry-grinding with CBN wheel

according to different authors (i.e., [12], [13]) is the border for burning. The burn could be observed by simple visual examination of the dry-ground samples; no apparent burn was noticed when grinding was done using metalworking fluid. No burn was observed when grinding with CBN wheels.

The analytical models existent in the technical literature could be successfully employed and the advantage of using CBN over Al_2O_3 grinding wheels in terms of temperature was demonstrated. The analytical model of the heat partition ratio based on Hahn model [8] provided reasonable results for the selected values of effective top flat radius of the grains (r_0).

R*w* has a great impact on calculated temperatures and therefore has to be determined based on carefully selected conditions. The same attention has to be paid to material properties, which in some papers were found taken at room temperature even though values over 450°C were observed during experimental trials. An evaluation of the calculated temperature values versus the experimental results should always be conducted for validation of adopted hypotheses.

5 Conclusions

The paper presents a comparative study of maximum surface temperatures generated when grinding 52100 steel with Al_2O_3 and CBN wheels under dry and wet conditions for a surface-grinding operation. The temperatures were determined using existent analytical models and were further compared to experimentally determined values. The experiments were run on a grinding machine instrumented with power sensor, force dynamometer, acoustic emission and acceleration sensors, and thermocouples. A good correlation was found between maximum temperatures determined analytically and those obtained experimentally. For both wet and dry conditions, the CBN wheels generated less heat comparing to Al_2O_3 wheels. Further

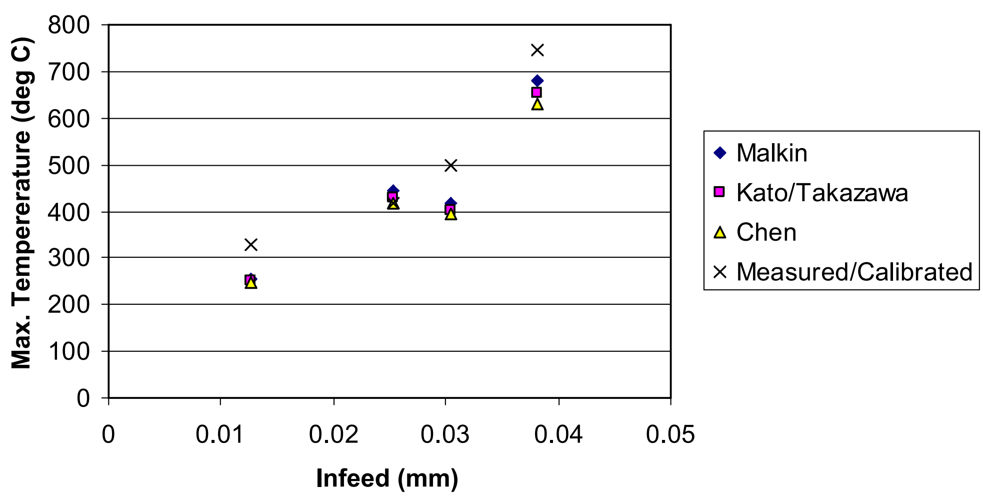


Fig. 5 Wet-grinding with Al_2O_3 wheel

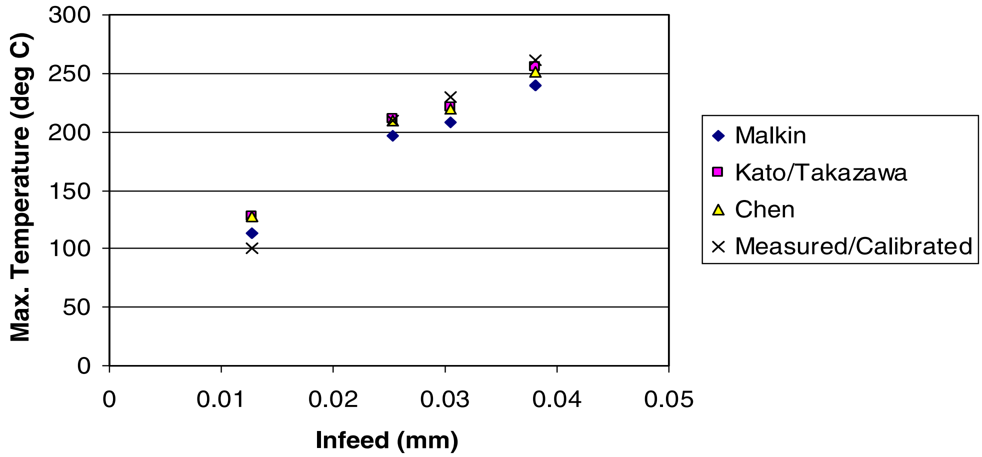


Fig. 6 Wet-grinding with CBN wheel

analysis of heat partition coefficient is necessary for better representation of dry and wet grinding conditions, which were found insufficiently discussed in published papers.

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