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Measurement of grinding temperatures using a foil/workpiece thermocouple

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Abstract

The high temperature generated in abrasive processes is the main factor responsible for thermal damage to a ground surface. It can be predicted through the thermal balance of the heat fluxes in the process. Such predictions can be experimentally verified using a foil/workpiece thermocouple. To estimate the thermal behaviour of such a sensor, it was dynamically calibrated with a laser beam to measure its frequency response. It was found that the response of the sensor has a time constant dependant on the thermal load and cannot be modelled by a simple first order function. In the calibration conditions used, the sensor is fast enough to measure the surface temperature with a time constant less than 100 microseconds. A high frequency acquisition system allows the signal to be measured at the local grit scale so that the activity of grits and the contact stability between the foil and the workpiece during grinding can be studied. By using the peak temperature and the local cooling after a peak, suitably processed, a local background temperature can be defined. It is shown that this background temperature can be evaluated more accurately by matching the global cooling curve to a finite element solution. The temperatures obtained from the local minima of the local diffusive cooling curve agree better with measured results than a temperature obtained by low pass filtering, which can overestimate the background temperature and so the partition ratio.

Keywords: grinding; temperature; thermocouple; dynamic calibration; heat transfer; signal processing

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Keywords: grinding; temperature; thermocouple; dynamic calibration; heat transfer; signal processing

Nomenclature :

a	mm	Real depth of cut
b	mm	width of cut
l_c	mm	Wheel / workpiece contact length
f	Hz	Frequency
τ	s	Time constant
H		Frequency response function
x, y, z	m	Cartesian Coordinates
r, ϕ, z		Cylindrical coordinates
r_l	m	$1/e^2$ radius in the waist of the laser beam
Z'_w	$\text{mm}^2 \cdot \text{s}^{-1}$	Workpiece removal rate per unit width
E_s		Systematic error
e_m, e_j	μm	Mica and junction thickness
V_s	$\text{m} \cdot \text{s}^{-1}$	Wheelspeed
V_w	$\text{mm} \cdot \text{s}^{-1}$	Workspeed
α_w	$\text{m}^2 \cdot \text{s}^{-1}$	Workpiece material thermal diffusivity
C_p	$\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$	Specific heat capacity
ρ	$\text{kg} \cdot \text{m}^{-3}$	Mass density
λ_w	$\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$	Workpiece material thermal conductivity
P	W	Grinding power
P_{wl}	W	Laser power entering the foil/workpiece thermocouple
u	$\text{J} \cdot \text{mm}^{-3}$	Grinding specific energy
Q	J	Heat source
q_m^t	$\text{W} \cdot \text{m}^{-2}$	Global heat flux dissipated at wheel / workpiece interface

q_m^w	$W.m^{-2}$	Global heat flux dissipated in the workpiece
q_m^j	$W.m^{-2}$	Global heat flux dissipated in the junction
q_{wl}	$W.m^{-2}$	Heat flux entering the foil/workpiece thermocouple
R_w	-	Fraction of total grinding heat entering the workpiece, (partition ratio)
ε_j	-	Ratio of the heat fluxes transmitted to the junction and to the workpiece
f_c	Hz	Cut-off frequency of the low pass filter
t_e	s	Contact time between the constantan foil and the grinding wheel
T	$^{\circ}C$	Temperature rise relative to the ambient temperature
T_{le}	$^{\circ}C$	Temperature obtained by the lower envelop curve
T_j	$^{\circ}C$	Junction temperature
T_{jf}	$^{\circ}C$	Filtered temperature with low pass filter
T_{wb}	$^{\circ}C$	Background temperature
δ	$^{\circ}C$	Temperature difference, temperature rise
θ		Dimensionless temperature

1. Introduction

Grinding processes are often selected as the final machining stage in the production of components because of their ability to obtain high surface quality with fine tolerance and roughness, especially with hard materials. However, the specific grinding energy can be extremely high and is essentially converted into heat, partitioned between the wheel, workpiece, chips and coolant. Thermal damage can occur if the ground surface gets too hot, limiting material removal rates.

In grinding and sliding processes, the literature generally distinguishes two transient temperatures: a background temperature rise and a local temperature rise. In grinding, the local temperature rise is due to plastic deformation and friction occurring at the interface between an individual active grit, the chips and the workpiece. The background temperature results from the cumulative effect of all local heat sources on the ground surface.

The background temperature damages the workpiece subsurface, whilst the temperature flashes and heat generated at the grain/workpiece interface increase the wear rate and attrition of the cutting grains. The optimisation of the grinding process requires good knowledge of both these temperatures. Environmental and economical considerations have led many workers to use the maximum background temperature as a performance indicator in order to validate the effectiveness of innovative cooling solutions, such as MQL [1,2], mist jet cooling [3] and to optimize the grinding hardening process using dry air and liquid nitrogen[4].

The local analysis at the grain scale is far more complex because of the stochastic nature of the distribution of abrasive grains. It depends on the active grit density, the evolving grain geometry, the apparent contact area, and the thermophysical properties of the grain [5,6]. Hahn [7] proposes a cinematic criterion for the existence of a well-defined continuous wheel source. If the displacement of the workpiece between two consecutive grits acting in the same interference region is small compared to the arc contact length l_c , a continuous band heat source of length l_c is a good approximation. In the opposite case, a large number of individual grit sources must be considered. If the thermal load is approximated by a continuous heat source moving at the workpiece velocity, the accurate determination of the heat partition ratio and the thermal balance requires the knowledge of the temperature close to the grinding zone (by thermocouple [1-3,8,9], optical fiber [10] or thermography method [11,12]), the actual

contact length between the wheel and the workpiece [13], the shape of the heat source (uniform, right angled triangle, scalene triangle [9], parabolic [11]), the effect of contact angle for deep grinding [12,14], the convective heat transfer to the coolant [2,9] and the quantity of heat carried away in the chips. The contact angle is neglected in shallow grinding leading to the assumption of a heat source moving in the plane of the ground surface.

Several thermoelectric methods have been developed to measure the grinding temperature: a standard thermocouple welded to the bottom of a blind hole [2,3,8,9], or a single or double pole grindable thermocouple in the shape of a foil or wire [1,15]. The intrusive method can require many corrections because of systematic errors due to the thermal inertia [16,17], the position of the junction in relation to the ground surface, the presence of the hole [18], the constitutive materials of thermocouples [19] and the contact resistance. In order to reduce the thermal resistance between the thermocouple and the workpiece, Shen et al. [9] have recently developed an embedded/double pole grindable thermocouple affixed with epoxy into a blind hole. During grinding, the thermocouple junction is exposed and bonded to the workpiece by smearing of the workpiece material, thereby providing direct contact with the workpiece surface.

The foil/workpiece thermocouple [3,15,16] is an interesting technique for measuring the grinding temperature because the junction is formed directly by several microcontacts along the foil at the ground surface with a thickness of about 1 μm [20]. But the high sensitivity of the junction has its drawbacks because the microcontacts are mechanically brittle and are in direct contact with the active grits, the chips and the cooling fluid.

In this work as well as in a previous paper [20], a triangular moving heat source is assumed combined with FE simulations using MSC-Marc software which take account of the thermophysical properties of the constantan foil and the C45 steel of the workpiece. In our previous study, the FE simulations showed that the grindable thermocouple is accurate in the cooling zone but the systematic error in the maximum background temperature rise (MBTR), cannot be neglected and depends on grinding conditions, on the junction and mica thicknesses, the thermal contact between the foil and the workpiece, and the heat flux conducted into the foil as the thermocouple is ground. The systematic error on the MBTR increases when the velocity V_w increases and the arc contact length decreases. As shown in Fig. 1 and in Table 1, this error is greatest at around $\pm 25\%$ for a 2 mm contact length and 300 mm/s workpiece speed with poor thermal contact between the foil and the workpiece.

However, when the junction has a thickness greater than $2\text{ }\mu\text{m}$, the error becomes less than 10 % with a ratio of heat flux $\varepsilon_j = q_m^j/q_m^w$ in the range 0-1.

The present investigation has been undertaken to define a method based on the foil/workpiece thermocouple for determining the background temperature and the heat partition ratio, which takes account of error analysis and the dynamic behaviour of the sensor at both local and global scales. The paper is in three main sections. It starts with a short description of the sensor, and how the thermoelectric signal is sampled at a high rate so as to understand the activity during the interactions between grains, chips and thermocouple junction. In the second section, the dynamic calibration of the single pole thermocouple with a laser beam and the determination of the frequency response function are described. The third part, is concerned with conventional grinding experiments which define the signal processing method to be used so as to determine the corrected background temperature and the heat partition ratio by fitting finite element calculations to the experimental results.

2. The dynamic behaviour of the thermocouple junction at a microsecond time scale

2.1 Description of the single pole thermocouple and acquisition device

The single pole thermocouple consists of a constantan foil insulated by two mica sheets sandwiched between two sections of the workpiece. The detailed description of this thermocouple can be found in [20]. In the case studied in this paper, the workpiece is a C45 carbon steel block (Hardness 88 HRB), 30 mm long in the grinding direction, 25 mm wide and 30 mm high. The thickness and the width of the constantan foil are respectively $20\text{ }\mu\text{m}$ and 0.35 mm, see Fig.2 in [20].

The contact duration between a grain and a point of the ground surface is a few microseconds (Shaw, 1996) [21]. It depends on many parameters such as the wheel speed, the grain size and the grain depth of cut. So the thermocouple and the signal conditioning system must have a wide bandwidth to measure the very short temperature flashes with a good degree of accuracy. This objective is achieved thanks to a 600 kHz full bandwidth amplifier. The thermocouple output voltage is amplified by a signal conditioning extension - SCXI 1100 - with cold junction compensation and sampled at 1.25 MHz by a NI 6071-E data acquisition device. The sampling rate and the dynamic response of the acquisition device are faster than Ueda's conditions ($1\text{ }\mu\text{s}$, 200 kHz) for the infrared Pyrometer method [10].

2.2 Junction formation process

During the grinding of the sensor, we cannot accurately know the formation process of microcontacts. It appears evident that the formation and the tearing of junctions are related to the chip formation process. In many works using the grindable thermocouple, several mechanisms of junction formation are proposed: by smearing of the thermocouple materials (Batako [15], Peklenik [22], Rowe [23]), by welding (Nee and Tay [16]), by metal particles freshly transported by active grains (Koziański [24]). Although the flash temperatures occurring under a grain may reach the melting point, Shaw [21] has demonstrated that this time is too short to activate the atomic diffusion involved in the melting process, which excludes the formation of junctions by fusion welding. In order to understand and explain the e.m.f. variation when the thermocouple is ground by the active grains, we have made measurements at a high sampling rate.

2.3 Signal analysis at high sampling rate

The tests were performed in up-grinding conditions without cooling on a LGB R5030 grinding machine. The workpiece velocity was 80 mm/s and the nominal depth of cut 30 μm . Fig. 2 shows a typical temperature signal obtained with the grindable thermocouple. The temperature evolution of the junction is the superposition of a background temperature and several temperature flashes. The measured time t_c for the wheel to traverse the constantan foil from the first to the last active grit and the workpiece velocity allow the real contact length to be estimated as:

$$l_c = V_w t_c \quad (1)$$

The high frequency response illustrated in Fig. 2 shows that flash temperatures fall into several categories:

- Type 1: The e.m.f. rises very fast (Fig. 2 b and c), implying a heating rate of 100 $^{\circ}\text{C}/\mu\text{s}$ and then decreases more slowly over about 100 μs . The temperature tends asymptotically toward the temperature just before the flash. The heat transmitted to the junction is conducted by diffusion into the workpiece through the mica sheets and microcontact thickness. By using the 3D moving heat source theory, we have proved that the local temperature decrease is compatible with a grain sliding over the junction [25]. The heating time t_{hj} ranges from 2.4 to 8 μs when the temperature increases smoothly.

- Type 2: the fall of the temperature in the cooling period after the peak temperature shows that the microcontact heated by a grain at the time $t = 21.7$ ms is destroyed (Fig. 2 b) by the following grain at time $t = 21.8$ ms and the asymptote corresponds to the flash at 21.6 ms. This signal type could be explained by a grain which evacuates a part of the heat from the microcontact into the chip.
- Type 3: the single peak or double peak e.m.f. The temperature does not vary after this peak. We can assign the single flash to a temporary contact between the workpiece and the foil. The deformed material, the chips and the metal particles in front of the grain make a connection, and the heat generated by the sliding and plastic deformation creates a positive e.m.f. variation of the thermocouple junction. Furthermore, the same heat source can realize two connexions when the grain moves from left to right; the first between the left side of the workpiece and the foil, and the second between the foil and right side of the workpiece. The instantaneous decrease of the e.m.f can be attributed either to the fracture of the microcontact, or to the evacuation of the heat generated with the chip.

Fig. 2b shows clearly that the whole signal is a superposition of these different types of event. Fig. 3 illustrates another thermocouple signal recorded with the same grinding conditions. It shows that the level of noise increases at $t = 6$ ms when the first grains contact the junction. During the time range $t = 6$ ms and 10.5 ms, the e.m.f. fluctuates and cannot be exploited because the contact between the foil and the workpiece is too brittle and unstable. The junction becomes stable from time $t = 10.5$ ms until $t = 12.5$ ms when it is destroyed by another grain. This instability cannot be detected without this high sampling rate analysis because the experimenter is not able to distinguish the temperature flashes due to the activities of grains from the noise due to a brittle junction. One of the major advantages of the high frequency acquisition system is its ability to detect the creation and the fracture of a microcontact.

3. Dynamic calibration of the thermocouple

3.1 Experimental procedure

The principal aim of this part is to make a dynamic calibration of the foil/workpiece thermocouple heated by a continuous argon laser (wavelength 514 nm). This non contact calibration by a radiant method is well adapted because the brittle microcontacts produced by the grinding wheel are not altered during application of the laser beam. The stresses produced

by the constant temperature slider proposed by Nee and Tay [16] for the double pole grindable thermocouple can change the contact conditions of the existing grinding microcontacts. A view of the dynamic calibration setup is shown in Fig. 4. The sensor, ground in grinding conditions defined in Table 2, is mounted on a positioning table and the junction of the thermocouple is set up on the axis of the laser beam using two perpendicular micrometer screws in the plane of the junction. The optimal position is adjusted by maximising the junction temperature. The laser beam is focused with a spherical lens reducing its radius to about 0.25 mm which would heat the full area of the junction. Step heating is achieved by using a mechanical locking (interlock) shutter; and periodic heating by an optical chopper having an excitation frequency range from 5 Hz to 1 kHz. It consists of a slotted rotating disc in the path of the laser beam.

3.2 Dynamic calibration results

In order to take into account the slight variations in laser power and to define the time constant of the thermocouple, the dimensionless temperature $\delta\theta_j$ of the junction corresponding to the temperature rises δT_j normalized by the steady state value $\delta T_{j\infty}$ is analysed:

$$\delta\theta_j = \frac{T_j - T_0}{T_{j\infty} - T_0} = \frac{\delta T_j}{\delta T_{j\infty}} \quad (2)$$

The steady state value $\delta T_{j\infty}$ corresponds to the temperature rise of the junction during continuous heating with the laser beam and T_0 is the initial junction temperature.

The time-temperature curves for the heating and cooling cycles are plotted in the Fig.5 of our previous paper [20]. The Fig. 5 represents the experimental dimensionless temperature curves for two tests $\{\delta\theta_{1h}, \delta\theta_{2h}\}$ and $\{\delta\theta_{1c}, \delta\theta_{2c}\}$ respectively during the heating and the cooling cycles. The time constant τ of the foil/workpiece thermocouple, i.e. time for the signal to reach 63 % of its final value, can be estimated from these curves as about 1 ms for the three tests performed in the cooling and heating cycles.

Two examples of the temperature response recorded during periodic heating are shown in Fig. 6 for the 60 Hz and 800 Hz chopper frequencies. The temperature differences δ , δ_c and δ_h defined in Fig. 6b, must be determined for each of the applied frequencies in order to calculate the frequency response functions H_c (cooling cycle) and H_h (heating cycle) :

$$H_c = 20 \log \left(\frac{\delta}{\delta_c} \right) \quad (3)$$

$$H_h = 20 \log \left(\frac{\delta}{\delta_h} \right) \quad (4)$$

The results obtained are plotted in Fig. 7. The cooling and heating frequency responses are very similar. The responses are obtained with similar boundary conditions on the thermocouple (natural convection at ambient temperature). These responses show that the – 3 dB sensor bandwidth seems to be about 1 kHz which is in accordance with the time constant of 1 ms established above.

In the works of Nee [16], the inertia of the sandwiched thermocouple is characterised by a first order response defined by the expression:

$$\theta_c = 1 - e^{-\frac{t}{\tau}} \quad (5)$$

The corresponding frequency function is given below.

$$H_c = 20 \log \left(\frac{1}{\sqrt{1 + (f/f_c)^2}} \right) \quad (6)$$

It appears from Fig. 7 that the experimental frequency response is not well fitted by this first order response with $f_c = 1$ kHz and that the slope of the experimental curve is shallower for frequencies greater than 100 Hz. So, it seems that the characteristic properties of the grindable sensor used by Nee do not correspond to the case of the foil/workpiece thermocouple. The time required to reach 95 % of the final value is 10 ms whereas it would be 3 ms for a first order function.

3.3 Analysis

When the surface of the workpiece is subjected to the heat flux, the temperature of a point on the surface cannot reach immediately its final value. The Fig. 8 shows a schematic view of the point source and the radiant heat source over the thermocouple area. For a semi-infinite body without a thermocouple, the increase of the surface temperature can be characterized by the time constant of the thermal load which is generally different from that due to the thermocouple inertia. In order to estimate the load time constant and the theoretical temperature, the unsteady linear heat conduction equation in a three-dimensional semi-infinite solid is resolved:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha_w} \frac{\partial T}{\partial t} \quad (7)$$

The sensor is considered as a homogeneous body by neglecting the influence of the mica and constantan sheets. This is justified because the diameter of the laser beam ($d_l = 0.5$ mm) is more than ten times as large as the foil thickness ($e_c = 20$ μ m). The heat fluxes exchanged by convection and radiation are negligible compared to the heat conducted into the workpiece. For the dynamic calibration presented above, the temperature rise is about ten degrees and consequently, the thermophysical properties of steel remain practically constant.

According to [26], the temperature rise at an arbitrary body point (x, y, z) due to an instantaneous point source of strength Q , generated at time $t = 0$ and located at point ($x', 0, z'$), is :

$$\delta T(x, y, z, t) = \frac{Q}{8\rho_w C_w (\pi\alpha_w t)^{3/2}} e^{-\frac{(x-x')^2 + y^2 + (z-z')^2}{4\alpha_w t}} \quad (8)$$

If a point source of power q_{wl} is absorbed by the solid between time $t' = 0$ and $t' = t$, the temperature rise at (x, y, z) after time t becomes, by integrating equation (8):

$$\delta T(x, y, z, x', z', t) = \frac{q_{wl}}{8\rho_w C_w (\pi\alpha_w)^{3/2}} \int_0^t \frac{e^{-\frac{(x-x')^2 + y^2 + (z-z')^2}{4\alpha_w (t-t')}}}{(t-t')^{3/2}} dt' \quad (9)$$

By introducing the Erfc function, this can be simplified as:

$$\delta T(x, y, z, x', z', t) = \frac{q_{wl}}{4\rho_w C_w \pi\alpha_w \left((x-x')^2 + y^2 + (z-z')^2\right)^{1/2}} \text{Erfc}\left(\frac{\left((x-x')^2 + y^2 + (z-z')^2\right)^{1/2}}{\sqrt{4\alpha_w t}}\right) \quad (10)$$

The classic power density of a Gaussian focused laser beam (Gaussian waist), can be expressed as [27,28]:

$$q_{wl} = q_{wl0} e^{-\left(\frac{2r^2}{r_l}\right)} \quad (11)$$

with

$$q_{wl0} = \frac{2P_{wl}}{\pi r_l^2} \quad (12)$$

where P_{wl} is the total beam power transmitted to the workpiece and r_l its $1/e^2$ radius at the waist.

The temperature field, due to a circular Gaussian heat source is, through integration of (9) in cylindrical coordinates (Fig. 8):

$$\delta T(x, y, z, x', z', t) = \frac{q_{wl}}{4\rho_w C_w \pi \alpha_w} \int_0^{2\pi} \int_0^{R_1} \frac{1}{\xi(r, r', \theta, \theta', z, z')} \text{Exp}\left(\frac{-2r'^2}{r_1^2}\right) \text{Erfc}\left(\frac{\xi(r, r', \theta, \theta', z, z')}{\sqrt{4\alpha_w t}}\right) r' dr' d\theta \quad (13)$$

where $\xi^2 = (r \cos(\theta) - r' \cos(\theta'))^2 + (r \sin(\theta) - r' \sin(\theta'))^2 + (z - z')^2$

The theoretical average temperature δT_{th} on the surface under the laser beam is calculated numerically for different radius values r as shown in the graph of Fig. 5. As the theoretical temperature decreases with the distance from the beam axis, the thermocouple measures an average temperature over the foil width. In order to compare the dynamic response of the sensor to a step heat flux with the theoretical dynamic response of the workpiece, the measured temperatures of the junction δT_j are divided by the quasi steady state temperature $\delta T_{j\infty}$ and the theoretical temperatures δT_{th} by the steady state average temperature $\delta T_{th\infty}$.

By comparing the analytical temperature response profiles with the measured temperature curve, it can be seen that the analytical profile fits the measurements well. The log-log graph of Fig. 5 with the four experimental curves indicates that the thermocouple response is attenuated below the first hundred microseconds. It can be concluded that the frequency and time response of the foil/workpiece are not due to the thermal inertia of the junction but imposed by the temperature of the workpiece heated by the laser beam. Finally, it is clear from the frequency and time responses to the step and periodic heat flux that the single pole thermocouple allows us to follow the heat flux imposed on the whole junction in these calibration conditions with a time constant lower than 100 μs . The time constant of the foil-workpiece thermocouple depends on the thermal load and the cooling conditions because the foil is directly in contact with the workpiece. When a microcontact of the junction is heated with a heat flux of about 50 μm diameter, the time constant of the thermal load is faster and the thermocouple detects a peak temperature. The dynamic calibration demonstrates that the response of the foil/workpiece thermocouple is in agreement with the theoretical temperature of a semi-infinite body heated by a disc heat source. If, during grinding, the junction is intensively heated by several active grains, the whole junction would appear to have a minimum time constant of about 1 to 2 ms. In this paper, an attempt will be made to measure the local temperature flashes of the active grains, and their cumulative action which determines the background temperature in the arc of contact.

4 Determination of the background temperature and heat partition ratio

4.1 Experiment Setup and grinding conditions

The global partition ratio was estimated by using this thermocouple together with a Kistler 9275 B table specially designed for measuring tangential and normal forces. The numerical thermal simulation of the grindable thermocouple has demonstrated that the maximum temperature rise is sensitive to the junction thickness, and to the choice of thermal boundary condition for the foil. The background temperature also depends on the interaction between the wheel and the junction [20]. For these reasons, the experimental tests were conducted within the range of grinding parameters defined in the introduction and in Table 3.

The junction changes several times during each grinding pass and it is difficult to perform systematically a calibration. In order to validate the repeatability of measurement, 5 tests were performed with the same nominal grinding conditions. In order to eliminate power fluctuation between tests, the temperature curves have been normalized by its average value over the whole test series.

4.2 Signal processing of the temperature measurement

The raw signal must be filtered in order to reduce temperature spikes and to obtain the background temperature. Some workers [29] consider that the inner envelope of small pulses on the signal curve reflects the macro temperature in the grinding zone. Batako et al. [15] have identified several sources of noise and flash temperature and use zero phase Butterworth filtering to reproduce the temperature without noise and drift. C. Fang et al. [19] uses a 300 Hz low pass filter. Xu and Malkin [30] used a 1 kHz low pass filter (with a minimum sampling rate of 3 kHz) and fitted it to the analytical temperature response profiles by neglecting periodic temperature flashes. The temperature distribution obtained by Rowe et al. [23,29,31] with a foil thermocouple attenuates the temperature spikes while better preserving the background temperature. This lower sensitivity can be put down to the finish grinding conditions used and to the choice of an A200 wheel with a 76 μm grain. Consequently, the junction temperature is also averaged with shorter heat pulses of many more active grits than with an A46 wheel (grain dimension 350 μm). In these conditions, the maximum temperature was obtained by putting a smooth curve through the measured signal.

In this study, the signal has been processed in three ways:

- filtering the signal with a 1 kHz low pass filter which is compatible with the 1 ms longitudinal time constant of the sensor under a thermal load,
- filtering the signal with a 100 Hz low pass filter allowing an average temperature distribution to be obtained without flash temperature, compatible with the global moving heat source,
- inner envelope on the signal, as defined below.

A simple signal processing technique was developed using Mathematica Software. It is based on the local points before each temperature spike determining the lower envelope of the 100 kHz low pass filtered signal. A local minimum on the temperature signal is defined by the condition $T_j(t_i)$ lower than the values $T_j(t_{i-1})$ and $T_j(t_{i+1})$ respectively at the previous (t_{i-1}) and following (t_{i+1}) time increments. The procedure is applied N times in order to delete the part of the signal due to the temperature peaks. As shown in Fig. 9 and Fig. 10, each signal processing technique gives different results: the maximum temperature rises are 222, 182 and 163 °C respectively for the 1 kHz, 300 Hz and 100 Hz low pass filter. Filtering at 300 Hz did not attenuate the flashes at 4, 7 and 12 ms as the diffusive cooling of the junction took about 1 to 2 ms. Filtering at 100 Hz gives a temperature curve with a single maximum of 163°C. The inner envelope is obtained after N=4 iterations in order to delete the local minima which result from larger local peak temperatures. The maximum temperature rise is also 136 °C, that is lower by 33°C and 20 % than the temperature obtained by 100 Hz filtering alone.

4.3 Experimental results and inverse method for determining the background temperature and the energy partition

As shown in the previous section, the method has to take into account the different sources of uncertainty, arising from repeatability, transparency and the signal processing.

The temperature curves for the five tests described below are defined in Fig. 11; the grinding conditions and experimental results are presented in Table 3 and in Fig. 12 respectively. The statistical analysis and the repeatability on the maximum temperature and the arc contact length l_e are evaluated by the mean values and the confidence interval at 95 % for the 5 tests. The 95 % confidence interval on the average maximum temperature rises are respectively 16 °C for a 110-140 mm/s workpiece velocity (Test A and B) and 60 °C for a 270 mm/s workpiece velocity (Test C). However, the confidence interval of the temperature decrease (averaged over 100 ms) is only 5°C as shown by the superposition of the cooling curves in

Fig. 11. This result indicates that the large uncertainty in the maximum filtered temperature rise is not due to the sensor, since it has good repeatability during the cooling phase, which shows that it combines correctly the cumulative effect of all the active grains. The background temperature is also difficult to define for small depths of cut of around 10 μm and a workpiece speed of 100 to 300 mm/s because of the short contact time ranging between 7 and 23 ms. Hahn's kinematic criterion l_c/s is evaluated respectively as {250,170,71} for the three workpiece velocities {107, 140, 270} mm/s, a 2 mm real arc contact length and the dynamic linear grain density of 0,45 mm^{-1} proposed by Hou and Komanduri for an A46H8V alumina wheel [5]. The confidence intervals on the maximum temperature rises obtained by filtering and by estimating the lower envelope increase with the workpiece velocity in both cases, and indicate that the background temperature is not clearly defined during the contact time between the wheel and the workpiece. The Hahn criterion is too low to justify the assumption of a continuous heat source. The contact time is not sufficiently long and the number of cutting points not large enough for the ground surface to attain a uniform background temperature.

The repeatability of the thermocouple once it moves out of the grinding zone is much better, since there are no grain contacts to disrupt the signal. It is therefore much more reliable to use the global cooling curve and the real contact length as the input to the inverse method of finding the heat flux transmitted to the workpiece q_m^w and the partition ratio defined by:

$$R_w = \frac{q_m^w l_c b_w}{P_t} \quad (13)$$

The quality of the assumptions (triangular heat source, 2D problem, quality of the measurements) can be evaluated by comparing the quasi steady state numerical temperature T_{qs} with the maximum background temperature obtained using the inner envelope and filtering method.

The maximum background temperature obtained with lower envelope processing agrees best with the calculated temperature obtained by fitting the global cooling curve and using the real (measured) arc of contact length. The maximum temperatures obtained with the 100 Hz low pass filtering are on average 20 % higher than the T_{le} and T_{qs} maximum temperatures. This difference is due to the fact that the filtering removes the electrical noise and temperature flashes of type 2 and 3 but takes into account the junction cooling when several type 2 flashes generate a cooling curve lasting a few milliseconds as defined in Fig. 9. Test C shows that the temperature T_{jf} is 64 % greater than the temperatures T_{qs} and T_{le} while the heat partition ratio

is substantially the same as in tests A and B. This test C also shows that the filtered temperature is affected by the heat pulses, by how the foil/workpiece thermocouple is ground, and by the assumption of a continuous and stationary triangular heat source which is not validated directly at the workpiece surface. All 5 tests were performed with good junction quality for the whole signal, so the 15-20 % differences between $\{T_{qs}, T_{le}\}$ and T_{jf} for test A and B are probably due to the interactions between the junction and the grains. For small depths of cut, short arc contact length and high workpiece speed, Badger et al. [32] have shown that the grinding forces and power can vary by several ten % around the mean value due to the wheel run-out and imbalance. Because of the high sensitivity of the junction to the chip thickness and the smearing of the ground material around the junction, the thermocouple measures every local variation in power along the workpiece, whether due to the run-out of the wheel or the dynamic behavior of the grinding machine. When the contact time between the wheel and the junction is ten ms, only 25 % of the wheel periphery grinds the thermocouple junction, which is not large enough to furnish a reliable statistical measurement of the grinding process at the global scale of the wheel. The Tests A, B and C are fitted by a finite element solution with the boundary conditions $\varepsilon = 1$ on the foil for a short contact length ($l_e = 2$ mm) and a workpiece speed in the range 100-300 mm/s.

The results indicate that the heat partition ratio of 0.67 is constant for all grinding conditions. This energy partition is in close to the 65 % value obtained with an AISI 1020 steel workpiece and aluminum oxide wheel by the two matching methods described in the article of Malkin and Guo [33]. The partition ratio (and so the heat flux transmitted to the workpiece) can be evaluated using the following expression [2,3,23]:

$$R_w = \beta b_w \sqrt{(\lambda \rho C)_w} V_w \frac{T_{\max i} \sqrt{l_e}}{P_t} \quad (14)$$

where β is equal to 0.88, 0.94, and 0.83 for uniform, triangular, and square heat flux distributions, respectively. In grinding conditions A and B, the systematic error in the background temperature due to the processing method - filtering with a 100 Hz low pass filter - is about $E(T_{jf}/T_{qs}) = 25$ %. This temperature would imply a partition ratio of 80-85%, leading to an overestimate of about 25 % compared to the partition ratio obtained with the cooling curve matching method and the inner envelope.

Conclusion:

A complete analysis of the temperature measured by the foil/workpiece thermocouple indicates the following:

- The dynamic response of the foil/workpiece thermocouple, as evaluated with a laser beam, has shown that the response of the thermocouple is very close to the response of a semi-infinite body heated by disc heat flux. The junction thickness provides a time constant lower than 100 μ s for normal heat flux but the longitudinal inertia is limited by the insulating mica layer with a maximum time constant of about 1 ms. When the thermocouple is loaded by a heat flux normal to the ground surface, the thermocouple provides a response in close agreement with the workpiece temperature.
- The analysis of the thermoelectric signal at the local scale shows that three types of flashes are superimposed on the background temperature. These temperature flashes increase rapidly, and then cool more slowly over a time of 10 μ s down to 1 ms. Where a simple peak is registered, fracture of the microcontact has occurred. The high sampling rate allows us to monitor the stability of the contacts, the partial grinding of a junction, and the fracture of several microcontacts during the contact between the wheel and the electrode. When the junction is of good quality, the signal is also of high quality in the time between two successive grain contacts.
- After a flash, the measured temperature falls asymptotically towards a background temperature which is defined by evaluating the local minima of the measured temperature between the local cooling curve and the subsequent flash. This method requires a high sampling rate and lot of memory for storing data but validates the reliability of the temperature measurement at the wheel/workpiece interface.
- It has been shown that the difference between the maximum background temperatures deduced with different signal processing techniques can reach 20 % or more. A more reliable signal processing method for determining the background temperature curve has been developed, defined by the local minima, and removing local temperature flashes. Using the low pass filtering method or simply the maximum background temperature can highly overestimate the partition ratio.
- In experimental dry grinding conditions, the possible uncertainties in the measurement due to the high sensitivity of the junction, the grinding of the foil, and the choice of signal processing have been demonstrated. The global cooling curve behind the arc of contact and the real arc of contact length are the best inputs for determining, with a

finite element model, the background temperature and the partition ratio, especially for short contact lengths and high workpiece velocity both in conventional grinding.

This study has shown the capabilities of the foil/workpiece thermocouple in dry grinding at the local and global scale together with its limitations. These conclusions apply to the test conditions studied here, which, as pointed out above, do not satisfy Hahn's conditions for the continuous heat source approximation. The dynamic response of the foil/workpiece thermocouple, the method developed for signal processing and fitting me allow a reliable value of the partition ratio to be determined and a local background temperature to be defined which can be used to understand the thermal performance of the grinding process at the local and global scales.

Figures

Fig. 1 : Comparison between the true temperature T_{qs} and the junction temperature T_j for several thermal contacts with junction thickness, and mica sheet thickness, for heat flux conditions on the constantan foil

Fig. 2 : Temperature signals for several time scales

Fig. 3 : Example of thermovoltage signal with a poor junction quality at several instants

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Table 1 : Systematic error in the maximal background temperature for several heat boundary conditions imposed on the thermocouple junction

Table 2 : Grinding conditions using the calibrated thermocouple.

Table 3 : Experimental data for 5 grinding passes and results of the global study with confidence interval at 95 %, wheel Velocity $V_s = 23.5$ m/s, $d_s = 295$ mm.

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Tables

	T_{j1}	T_{j2}	T_{j3}	T_{j4}	T_{j5}	T_{j6}
$e_m (\mu\text{m})$	10	10	10	10	5	5
$e_j (\mu\text{m})$	<1	<1	2	2	<1	2
$\varepsilon_j = q_m^j / q_m^w$	1	0	0	1	1	0
$E_s(\%)$	24	-25	-14	8	20	-9

Table 1 : Systematic error in the maximal background temperature for several heat boundary conditions imposed on the thermocouple junction

Wheel	3SG46HVS
Wheel speed	$N_s = 2400 \text{ rpm}$, $V_s = 27 \text{ m/s}$
Wheel diameter	$D_s = 212 \text{ mm}$
Dressing depth, dressing feed	$a_d = 10 \text{ }\mu\text{m}$, $f_d = 0.15 \text{ mm/tr}$
Nominal depth of cut	$a = 30 \text{ }\mu\text{m}$
Workpiece velocity	$V_w = 80 \text{ mm/s}$, Up-grinding

Table 2 : Grinding conditions using the calibrated thermocouple.

Wheel	a	V _w	P _t	u	Z' _w	l _c	q _t	δT _{jf}	δT _{le}	δT _{qs}	q _m ^w	R _w	E(T _{jf} /T _{qs})	E(T _{le} /T _{qs})	
	μm	mm/s	kW	J/mm ³	mm ² /s	mm	W/mm ²	°C	°C	°C	W/mm ²	-	%	%	
A	3SG46HVS	11±2	105	2.86±0.15	81	1.2	2.48±0.3	38.5±5	400±15	304±13	327±15	26.5±1	0.69±0.14	22	-7
B	3SG46HVS	9±2	140	2.66±0.2	71	1.25	2.28±0.15	39±3	340±20	271±14	273±12	26.3±1.3	0.67±0.1	24	1
C	3SG46HVS	6±2	270	2.56±0.2	52	1.6	1.82±0.15	47±6	270±60	164±12	164±8	29.5±1.8	0.63±0.14	64	0.1

Table 3 : Experimental data for 5 grinding passes and results of the global study with confidence interval at 95 %, wheel Velocity V_s = 23.5 m/s, d_s = 295 mm.

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Figures

Simulation parameters:

arc contact length $l_e = 2$ mm, workpiece velocity $V_w = 300$ mm/s,

heat flux $q_m^w = 30$ W/mm²

Thermocouple materials: C45, constantan, mica

Fig. 1 : Comparison between the true temperature T_{qs} and the junction temperature T_j for several thermal contacts with junction thickness, and mica sheet thickness, for heat flux conditions on the constantan foil

Grinding wheel: 3SG46HVS

Grinding parameters : $a_e = 20 \mu\text{m}$, $V_w = 80 \text{ mm/s}$, $V_s = 27 \text{ m/s}$, Dry

Material: C45 , hardness 88 HRB

Fig. 2 : Temperature signals for several time scales

Grinding wheel: 3SG46HVS

Grinding parameters : $a_e = 20 \mu\text{m}$, $V_w = 80 \text{ mm/s}$, $V_s = 27 \text{ m/s}$, Dry

Material: C45 , hardness 88 HRB

Fig. 3 : Example of thermovoltage signal with a poor junction quality at several instants

Fig. 4 : Photo of the dynamic calibration device of the thermocouple

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Fig. 7 : Frequency response of the thermocouple in the cooling cycle and heating cycle

Fig. 8 : A schematic view of the point source and the radiant heat source over the thermocouple area

Grinding wheel: 3SG46HVS

Grinding parameters : $a_e = 15 \mu\text{m}$, $V_w = 160 \text{ mm/s}$, $V_s = 27 \text{ m/s}$, Dry

Material: C45 , hardness 88 HRB

Fig. 9 : Determination of the background temperature with low pass filtering methods

Fig. 10 : Determination of the background temperature with an inner envelope based on the local minimum before temperature flash

Grinding wheel: 3SG46HVS

Grinding parameters : $a_e = 11 \mu\text{m}$, $V_w = 105 \text{ mm/s}$, $V_s = 27 \text{ m/s}$, Dry

Material: C45 , hardness 88 HRB

Fig. 11 : Repeatability of the temperature measurement for 5 grinding tests in n°A grinding conditions

Fig. 12 : Results, for five different grinding conditions for the maximal filtered temperature and lower envelop Temperature

Fig. 13 : Fitting of the experimental temperature curve to the FE solution

Highlights

- The foil/workpiece thermocouple is dynamically calibrated with a laser beam to measure its frequency response.
- In the calibration conditions used, the sensor is fast enough to measure the surface temperature with a time constant less than 100 microseconds
- A high frequency acquisition system allows to define a local background temperature
- This background temperature and the partition ratio can be evaluated more accurately by matching the global cooling curve to a finite element solution
- The temperatures obtained from the local minima of the local diffusive cooling curve agree better with measured results