



# An in-situ infrared temperature-measurement method with back focusing on surface for creep-feed grinding



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## ABSTRACT

In creep-feed grinding research, it is vital to measure surface temperature of workpiece in order to optimize process parameters, prevent potential thermal damage, improve the surface integrity of workpiece and provide reference for modelling of grinding. Various measurement techniques for grinding temperature have been developed by using thermocouples and infrared radiation techniques. However, some inevitable problems still exist with slow response, strong noise interference and high sensibility to coolants. In order to obtain precise and reliable temperature of workpiece surface during grinding, an in-situ infrared technique is designed by focusing on the back surface of workpiece. With the help of a two-dimensional sliding table, the focus of infrared thermometer can be adjusted to the small hole in the workpiece to measure grinding temperature accurately. This method can avoid the high-frequency signal interruption of mechanical vibration and electrical noises, since the measurement is contactless and has signal shielding. The procedures to set up the measurement facility and measure grinding temperature are described in this paper. This paper also includes the analysis of measurement results of grinding temperature. Compared with other measurement techniques, this method is not affected by mechanical vibration and grinding fluids. By using infrared technology, this method can measure accurate grinding temperature with a fast response.

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## 1. Introduction

Grinding is one of final manufacturing methods in production of parts to generate high surface quality. Fig. 1 shows that the cost of machining is high and mistakes can be very expensive due to the exponential increase in cost and lead time with the number of operations [1]. Creep-feed grinding is a highly accurate and efficient method of machining complicated forms and slots in a wide variety of materials. Creep-feed grinding has several advantages over other grinding methods, including increased accuracy, efficiency, improved surface finishes, burr reduction and the ability to grind heat treated materials. During the creep-feed grinding of hypoeutectoid Fe-C steel, the temperature of the workpiece surface rises rapidly over 727 °C, accompanied by austenite formation. Under some severe conditions, globular chips with dendritic morphology can be found on the surface of workpiece by SEM as shown

in Fig. 2, which proves that the peak grinding temperature has gone over the melting point of the steel and caused thermal damage to the workpiece. Thus, it is important to measure the change of grinding temperature to prevent potential thermal damage.

In grinding processes, transient grinding temperatures can be classified as either a background temperature rise or a local temperature rise. The local temperature rise results from plastic deformation and friction occurring at the interface between an individual active grain and the workpiece. The background temperature is due to the cumulative effect of all local heat sources on the surface. The background temperature damages the workpiece subsurface, while the local temperature rise increases the wear rate and attrition of the cutting grains [2]. In this work, we are more interested in the thermal damage of workpiece, thus the grinding temperature refers to the background temperature of workpiece in grinding.

In the paper, an in-situ infrared method with back focusing on surface (IMBFS) has been proposed to measure grinding temperature after an overview of reported methods. A developed infrared temperature-measurement device has been calibrated on cavity emissivity. The test results on grinding temperature prove that

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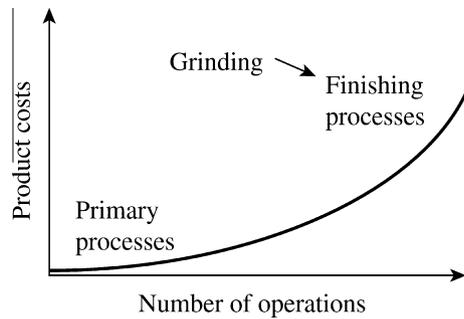


Fig. 1. The increase of costs and value added in product manufacture [1].

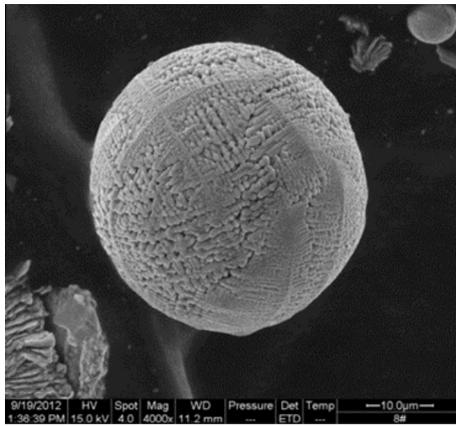


Fig. 2. Globular chips with dendrites of the hypoeutectoid Fe-C steel after grinding.

the in-situ infrared technology has a high reliability and a good precision to capture fast temperature change in grinding. The result shows that the peak temperature in creep-feed grinding goes above transition temperature in a short duration and then cools down. The accurate measurement technique of grinding temperature is the foundation for optimizing process parameters, preventing potential thermal damage, improving the surface integrity of workpiece and precise numerical modelling.

## 2. Techniques for measurement of grinding temperature

Komanduri and Hou made a review of experimental techniques for the measurement of temperature in some manufacturing processes, including thermocouples, infrared photography and infrared optical pyrometers [3]. Fig. 3 presents the historical outline of thermal measurements in material removal processes and compares the properties of different techniques [4].

As for grinding process, there are two common and promising measurement techniques of temperature, including thermocouples and infrared techniques.

### 2.1. Thermocouple techniques

Thermocouple techniques are widely used since they are easy to set up and economical to be applied in industries. There are two main techniques, namely, embedded thermocouples and foil-workpiece thermocouples.

#### 2.1.1. Embedded thermocouples

In Fig. 4, a thermocouple is inserted into the blind hole on the workpiece to measure the grinding temperature [5]. Although this method is convenient and able to obtain good temperature signal,

it cannot acquire the surface grinding temperature directly. In addition, it may be inaccurate to predict temperature by extrapolation since the temperature gradient near the surface could be steep and non-linear. Furthermore, the actual surface grinding temperature may be underestimated since the temperature measured is an average value over the junction of thermocouple and the size of junction ( $\sim$ mm) is large compared with the temperature gradient.

#### 2.1.2. Foil-workpiece thermocouples

To measure grinding temperature directly, as Fig. 5 shows, foil-workpiece thermocouples utilize two split workpieces to fix thermocouple foils, where the junction is formed during grinding by producing micro-contact between thermocouple material and workpiece [6].

This method measures more accurate surface temperature with a faster response since the junction is formed on the workpiece and the size of micro-contact is several micrometers. Thus, the response time of foil-workpiece thermocouples is at a microsecond time scale ( $\sim\mu$ s) while that of traditional thermocouples is at millisecond ( $\sim$ ms). Nevertheless, Fig. 6 proves that this method is sensitive to noises and its signal can be unreliable under wet grinding condition [6]. Also, it is hard to differentiate between flash temperature caused by grains and high-frequency noises. Therefore, in view of the difficulty on choosing an optimum cutoff frequency, the temperature signal may be inaccurate after signal processing like filtering.

### 2.2. Infrared radiation techniques

Infrared radiation techniques measure grinding temperature by detecting infrared radiation emitted by workpiece. This method eliminates noises of mechanical vibration since it is contactless, which can be divided into thermal imaging and infrared pyrometer.

#### 2.2.1. Thermal imaging

Thermal imaging presents the temperature distribution in real time using an array of sensors of thermal camera, as shown in Fig. 7 [7]. Unfortunately, this method fails to measure the temperature of contact zone and it is subject to grinding fluids. Moreover, this method's low sampling rate of about tens of hertz makes it fail to grasp the fast change of grinding temperature. In addition, thermal camera in high quality is expensive due to the expense of the larger pixel array.

#### 2.2.2. Infrared radiation pyrometer with optical fibers

Ueda et al. invented the infrared pyrometer technique, which uses optical fibers to guide infrared radiation and sense the temperature of active grains on the wheel with photon detectors [8]. Fig. 8 shows the configuration of two-color pyrometer with optical fiber, which does not need to calibrate the emissivity compared with single-color pyrometer [9]. Although the infrared pyrometer has a high spatial resolution ( $\sim\mu$ m) and a fast response ( $\sim\mu$ s), this method fails to measure the surface temperature directly and it is difficult to set up the measurement facility. In addition, the signal transmitting in optical fibers will decay and then reduce the accuracy of results. The end of fibers must be kept clean and neat, making it fragile under the terrible working condition. Moreover, this method is expensive and inconvenient to be applied in industries since the photon detectors need to work under low temperature ( $<100$  K).

In conclusion, thermocouple technique is suitable for measuring surface temperature directly, while infrared method is not subject to noises and it has a faster response. In this study, infrared technique is adopted to get good temperature signal.

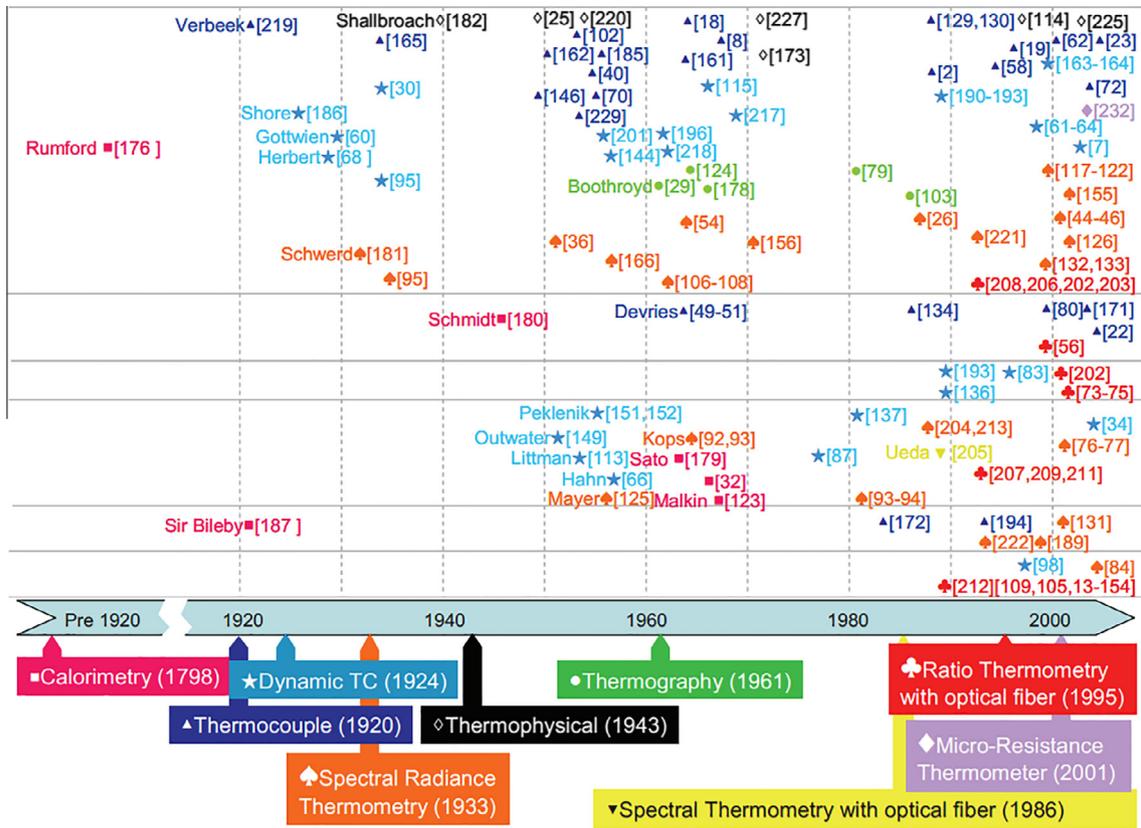


Fig. 3. Historical outline of thermal measurements during material removal processes [4].

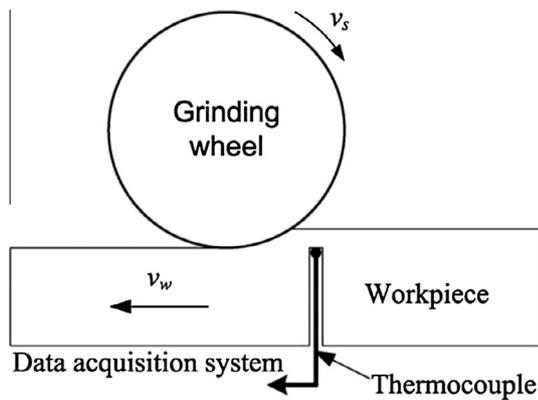


Fig. 4. Configuration of embedded thermocouples [5].

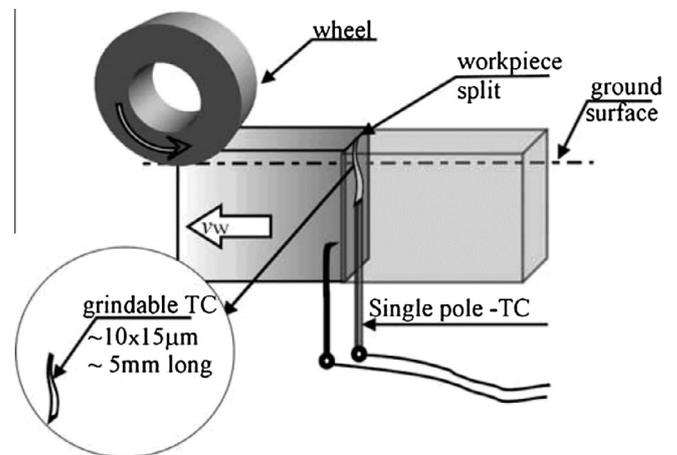


Fig. 5. Configuration of foil-workpiece thermocouples [6].

### 3. An in-situ infrared technique with back focusing on surface for grinding temperature

#### 3.1. Configuration of the measurement device

Given that infrared pyrometer technique is expensive and difficult to set up, an in-situ infrared technique with back focusing on surface is designed, which is more economical and does not need optical fibers. The CAD model and actual configuration of the measurement device are shown in Fig. 9. When the wheel grinds the workpiece, infrared radiation emitted by the surface will go through cavity in fixture and reach infrared sensor as shown in Fig. 9(a). Then the grinding temperature can be calculated by Stefan-Boltzmann Law as shown in Eq. (1),

$$P = A\epsilon\sigma T^4 \quad (1)$$

where  $P$  is total power radiated from the object,  $A$  is surface area,  $\epsilon$  is emissivity of cavity,  $\sigma$  is Stefan-Boltzmann constant and  $T$  stands for grinding temperature.

The M-2H infrared thermometer used in this study has a wide range of temperature from 385 °C to 1600 °C, which covers the austenitizing temperature. Besides, it possesses a high temperature resolution of 0.2 °C and good spatial resolution of 0.5 mm [10]. A short response time of 1 ms makes this thermometer faster than conventional thermocouples and thermal cameras. Thus, this thermometer is qualified for most of measurement conditions and it is

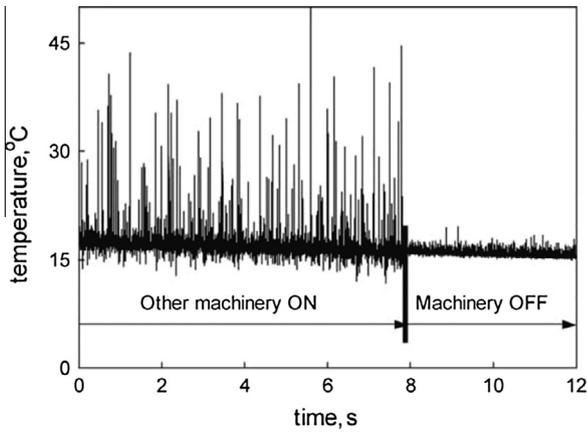


Fig. 6. The interference of machinery noises on temperature signal [6].

adequate to measure the rapid change of background temperature ( $\sim$ s) during grinding.

In order to acquire accurate grinding temperature, it is necessary to adjust the focus of infrared thermometer and calibrate the emissivity of cavity, which affects the accuracy of measurement results. In this measurement device, a small cylinder workpiece was placed on the fixture. The cavity was created in the fixture and workpiece to serve as an artificial blackbody as shown in Fig. 9(b), whose emissivity was close to 1. The actual configuration of the measurement device are shown in Fig. 9(c). Note that the hole in workpiece for experiment was blind while the hole in another workpiece for focus adjustment and calibration of emissivity was through. The distance between hole and surface was 0.5 mm, which was used to describe the distance between the top of cavity and the surface of workpiece. The machining accuracy of parts was guaranteed by advanced Computer Numerical Control (CNC) machines. When the distance between the top of cavity and the surface of workpiece reduced to zero after a certain number of grinding passes, it was reasonable to assume that the focus of infrared thermometer was on the surface, allowing thermometer to measure grinding temperature of surface accurately. It is assumed that the through hole on the surface has little effect on the emissivity of cavity because it is small.

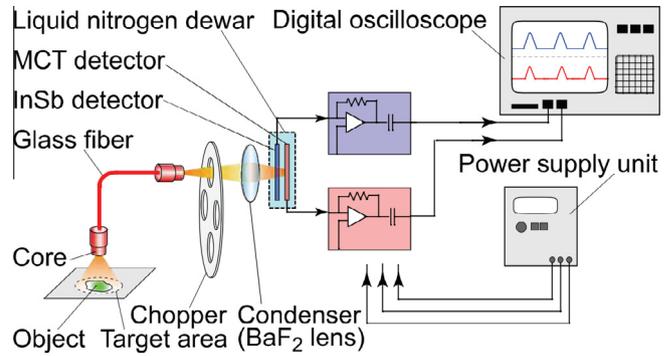


Fig. 8. Infrared pyrometer technique [9].

### 3.2. Adjustment of infrared thermometer focus

To adjust the focus of thermometer to the workpiece surface, a two-dimensional (2D) precise sliding table was used. Through a small through-hole on the workpiece, the lasers emitted by the infrared thermometer met at focus and helped to aim the focus at the center of hole. An illuminometer with resolution of 0.1 lx was applied to measure the illumination of lasers through small hole. The precise sliding table with a positioning accuracy of 0.02 mm could control the position of focus on X-Y plane. And four springs on sliding table were adopted to adjust the position of focus on the Z direction. When the focus was adjusted to the center of the hole in the workpiece, most lasers going through the hole made readings of illuminometer reach maximum. Then the adjustment of focus was completed.

### 3.3. Calibration of cavity emissivity

The emissivity of cavity can be obtained with Gouffé theory [11] as shown in Eq. (2),

$$\varepsilon = \frac{\varepsilon_0 \left[ 1 + (1 - \varepsilon_0) \left( \frac{\Delta S}{S} - \frac{\Delta \Omega}{\pi} \right) \right]}{\varepsilon_0 \left( 1 - \frac{\Delta S}{S} \right) + \frac{\Delta S}{S}} \quad (2)$$

where  $\varepsilon_0 = 0.65$  is the emissivity of materials,  $\Delta S = 176.71 \text{ mm}^2$  is the area of hole at the bottom of workpiece,  $S = 977.47 \text{ mm}^2$  is the

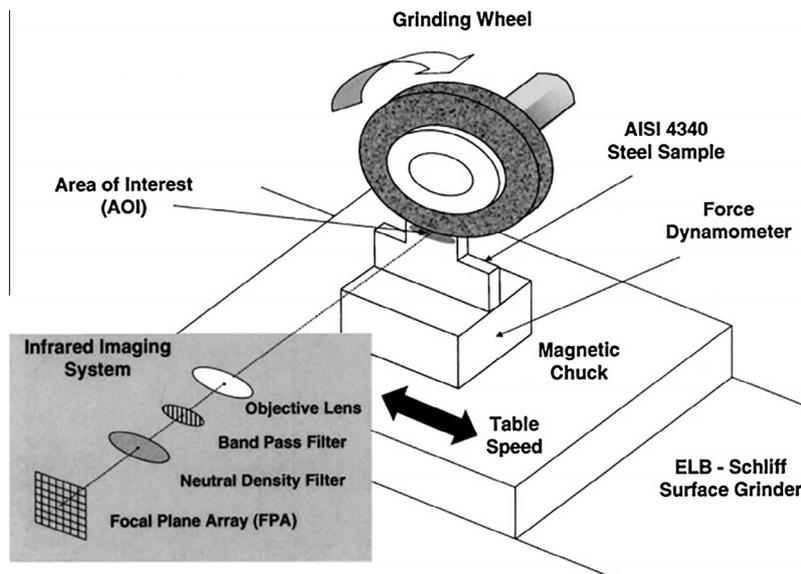
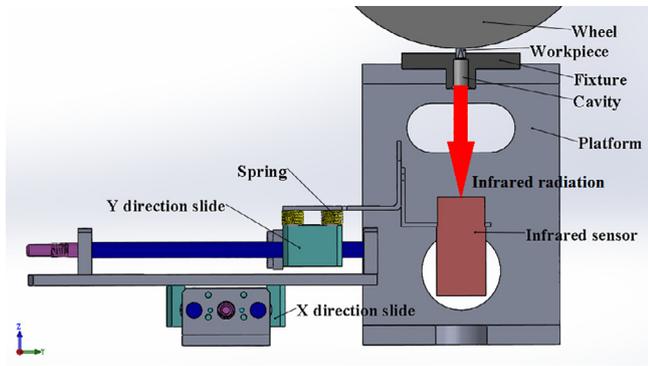
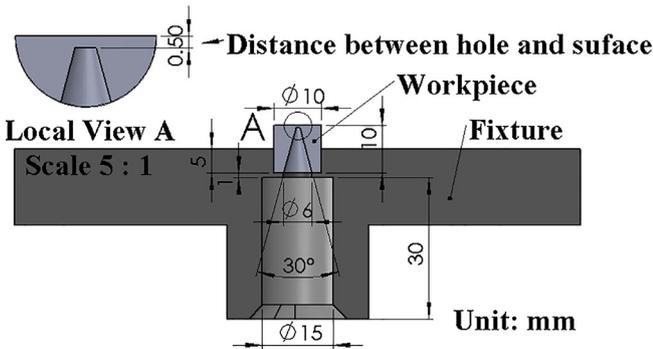


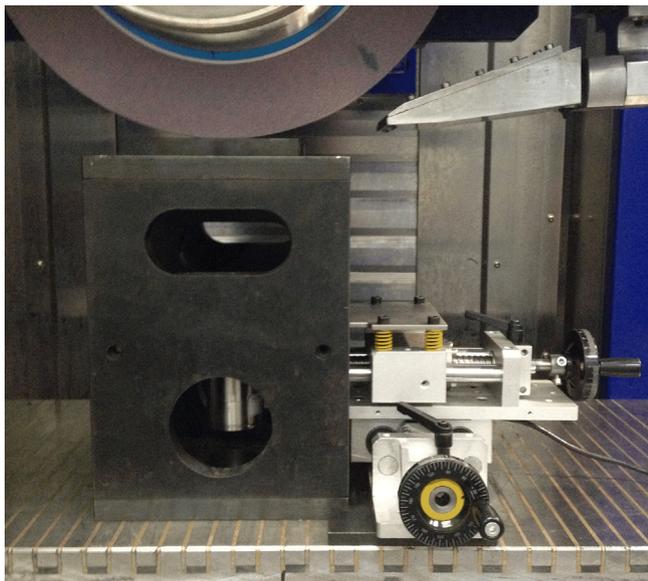
Fig. 7. Thermal imaging technique [7].



(a) Concept of in-situ infrared measuring method



(b) Structure of cavity



(c) Measuring device

Fig. 9. Design of IMBFS.

area of cavity and  $\Delta\Omega = 0.108$  is observable solid angle of the hole. The emissivity of cavity is 0.96 by calculation according to the theory.

For experimental calibration shown in Fig. 10, a resistance heating film was placed on a standard thermocouple. By heating the standard thermocouple with the heating film, the infrared radiation emitted by the thermocouple reached the thermometer. In this case, it is assumed that the thermocouple and thermometer measured the same temperature of heating area on thermocouple. Then the measurement result of thermocouple was used to

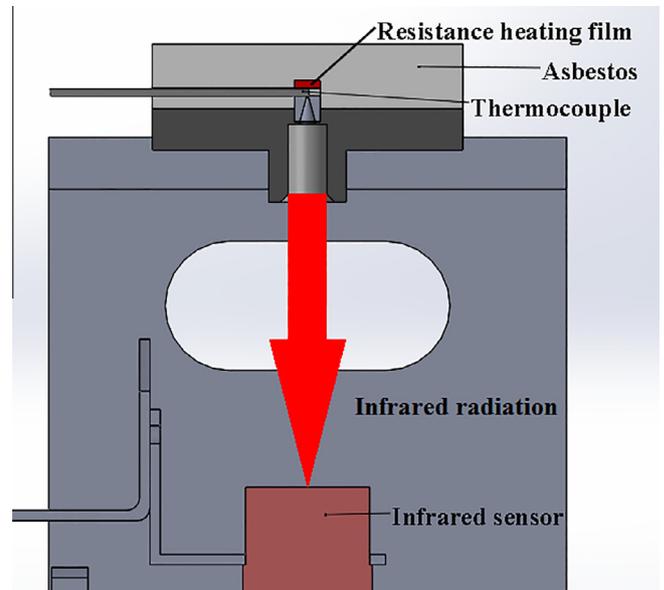


Fig. 10. Calibration of the emissivity of cavity.

calibrate the emissivity of cavity. The emissivity obtained by experiment was 0.98 and it was very close to the theoretical value.

#### 4. Experimental results and analysis

##### 4.1. Experimental results

The experimental scheme adopted creep-feed grinding with a  $\text{Al}_2\text{O}_3$  grinding wheel of diameter  $d_s = 400 \pm 0.1$  mm and width  $b_s = 15 \pm 0.1$  mm. Experiments were conducted in the down mode with a peripheral wheel velocity  $v_s = 20$  m/s, workpiece velocity  $v_w = 10$  mm/s, and cutting depth  $a_p = 50$   $\mu\text{m}$  without grinding fluids. The operating parameters were selected for machining the end rotor blade grooves of a 1000 MW nuclear steam turbine. The material used in experiments is a kind of martensitic stainless steel with hardness 54 HRC, whose chemical composition is presented in Table 1.

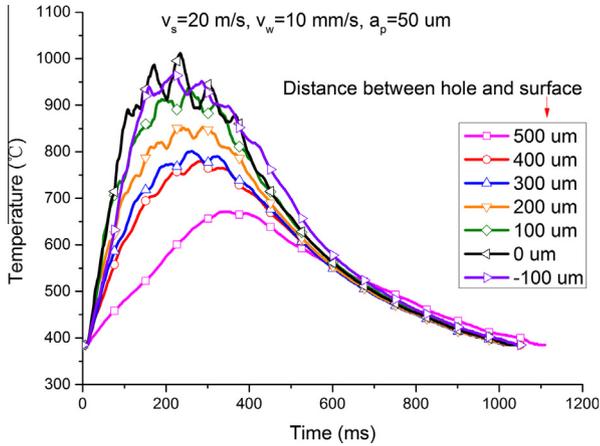
During the experiment, numerous grinding passes were taken until the hole on the top of cavity was exposed. The distance between hole and surface refers to the distance between the top of cavity and the surface of workpiece. After a grinding pass, the distance between hole and surface decreases a cutting depth. When the distance between hole and surface reduced to zero after a certain number of grinding passes, the focus of infrared thermometer was on the surface, allowing thermometer to measure grinding temperature of surface accurately. Experimental results of grinding temperature shown in Fig. 11 indicate that the signals had no high-frequency noises and signal breaks.

There were some low frequency noises in the temperature signals and they became obvious when the distance between hole and surface decreased. According to the power spectrum of signal in Fig. 12, the first harmonic is 15.399 Hz, which was very close to the frequency of rotation of spindle 15.92 Hz. Consequently, the noises were caused by the vibration of spindle since its vibration changed the position of measuring area of the workpiece. Noises higher than 15.399 Hz can be neglected because they were weak in power. To gain actual temperature profiles, the signals were filtered by the low pass filter with a cutoff frequency of 10 Hz, leaving good temperature signals shown in Fig. 13.

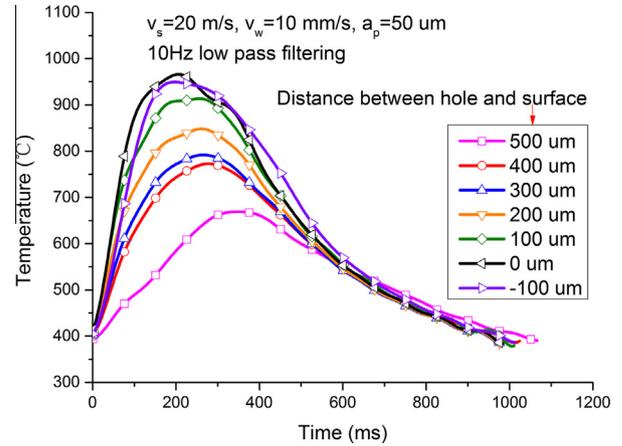
As the distance between the top of cavity and surface decreased, the grinding temperature increased gradually. Meanwhile, the

**Table 1**  
Chemical composition of martensitic stainless steel.

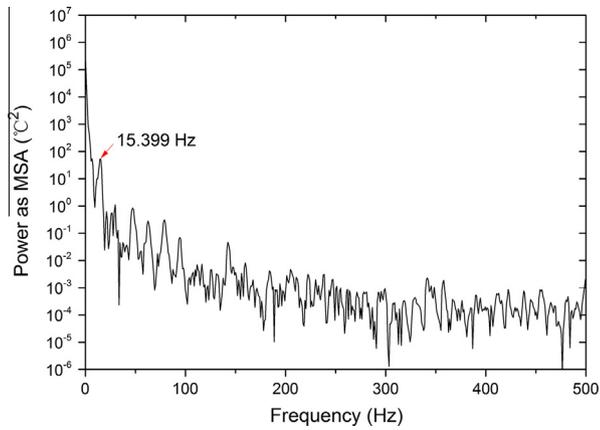
Element	C	Cr	Ni	Mo	Nb	V	N
wt.%	0.2	12.056	3.395	2.466	0.126	0.224	1.43



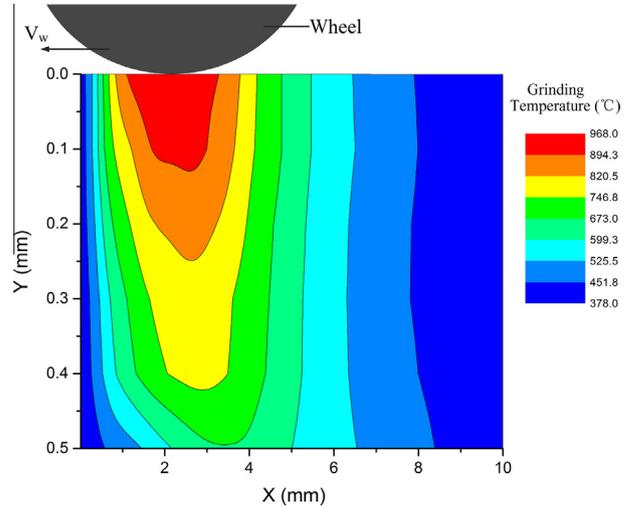
**Fig. 11.** Experimental results of grinding temperature.



**Fig. 13.** Grinding temperature after filtering.



**Fig. 12.** Power spectrum of grinding temperature.



**Fig. 14.** The middle cross-section temperature field of workpiece.

duration to reach peak temperature was shorter since the distance for heat conduction decreased. When the distance became 0  $\mu\text{m}$ , namely, the hole was on the surface of workpiece, the temperature rose rapidly at an average heating rate of 2821  $^{\circ}\text{C}/\text{s}$  and then decreased slowly at an average cooling rate of  $-715$   $^{\circ}\text{C}/\text{s}$ . The maximum grinding temperature was 1011.8  $^{\circ}\text{C}$  while the maximum temperature after filtering became 966.3  $^{\circ}\text{C}$ , which both exceeded the austenitizing temperature 727  $^{\circ}\text{C}$ . It means that the phase transition did ever happen on the workpiece surface during the grinding process.

It is assumed that the points at the same height of workpiece have a same temperature history. Then the middle cross-section temperature field of workpiece can be represented by using temperature profiles at different heights of workpiece as shown in Fig. 14.

The heating rate profile in Fig. 15 shows the rapid and complex change of temperature during grinding. The absolute value of heating rate and cooling rate both increased first and then came back to 0. Besides, the zero point of heating rate means that the end of contact zone between wheel and workpiece just passed through the measuring point. This characteristic time was 207 ms and it

conformed to the theoretical result of 224 ms well, which was obtained by Eq. (3).

$$t_c = \frac{\sqrt{d_s a_p}}{v_w} \quad (3)$$

In summary, the temperature field of workpiece was obtained by using infrared technique with back focusing on surface and this method can help to prevent potential phase transition by monitoring the change of maximum temperature.

#### 4.2. Moving surface caused by plastic flow of material

It is expected that when the distance between hole and surface became 0  $\mu\text{m}$  after 10 grinding passes, the hole would become through and the temperature would drop down dramatically. The reason is that the temperature of wheel was much lower than that of workpiece surface and the measurement area of wheel changed

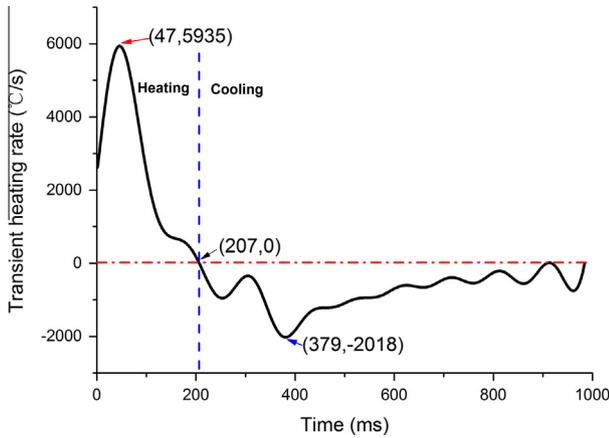


Fig. 15. Transient heating rate at a distance of 0 μm.

quickly. However, the hole was still blind and a concave formed on the surface because of the plastic flow of material in high temperature. Therefore, the surface of workpiece moved down and surface grinding temperature was measured repeatedly until the hole became through after 14 passes, as Fig. 16 shows.

The maximum grinding temperature increased gradually as grinding surface approached the measurement area where the focus of thermometer located. Then the maximum grinding temperature kept constant in a short distance and it finally decreased but not dropped down dramatically because of moving surface effect. Fig. 17 shows that the maximum grinding temperature decreased linearly with distance increasing and the vertical temperature gradient was about 644 °C/mm. This indicates that the grinding temperature is sensitive to the distance from the surface

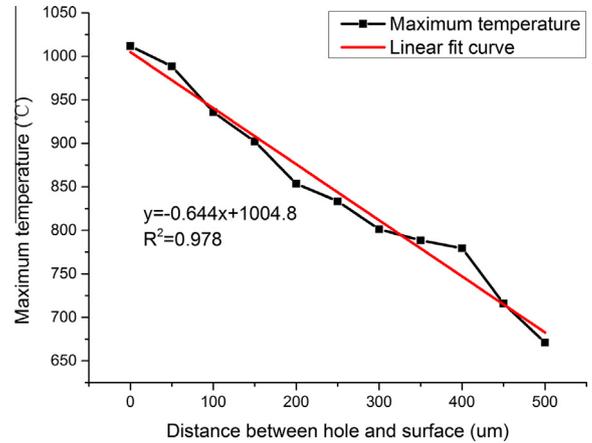


Fig. 17. Maximum grinding temperature at different distance from the surface.

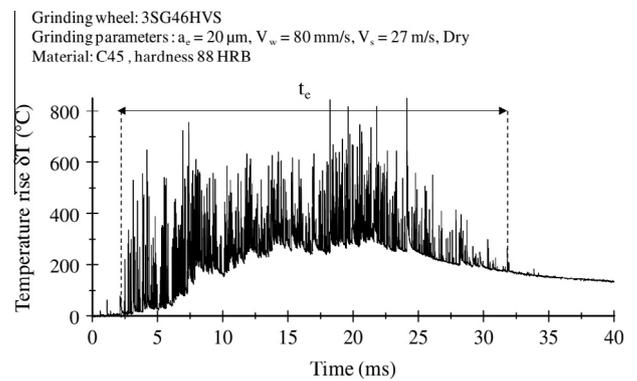


Fig. 18. The experimental result of grinding temperature by using foil-workpiece thermocouple [2].

and the distance between surface and the top of cavity should be as small as possible to get accurate temperature.

### 5. Comparison with other methods

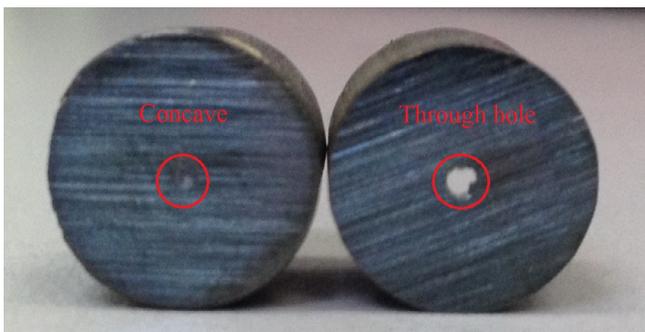
The new design of infrared technique with back focusing on surface performs better than foil-workpiece thermocouple technique because it avoids high frequency noises and complicated signal processing procedures. In Fig. 18, the signal of grinding temperature is compared with the signal obtained by Lefebvre et al. [2], which demonstrates IMBFS is able to gain better signals as shown in Fig. 11.

Compared with infrared pyrometer, infrared thermometer does not need to work under low temperature. Therefore this method is more convenient and easier to set up. Optical fibers used in infrared pyrometer can be broken easily or have transmission losses when wrapped around curves of only a few centimeters radius. In addition, the core and plastic sheathed layer of fibers will squeeze each other due to thermal expansion, causing loss of signals. In general, optical fibers cannot work over 300 °C due to the low melting point of plastic layer. Thus, infrared thermometer is more suitable than infrared pyrometer to be applied under bad working condition in industries. As for thermal imaging, it cannot measure the grinding temperature of contact zone and it responds slower than infrared thermometer.

In brief, IMBFS is not affected by mechanical vibration and grinding fluids. By using infrared technology, this method can measure accurate grinding temperature with a fast response. This



(a) Concave on the surface



(b) Through hole on the surface

Fig. 16. Moving surface caused by plastic flow of material.

method can be applied in other machining condition, like milling and planing as well.

## 6. Conclusions

In this paper, an in-situ infrared technique with back focusing on surface was designed to measure temperature of workpiece for creep-feed grinding. This method has a short response time of less than 1 ms and avoids the effects of vibration since it is non-contact by detecting infrared signals. The small focus area of infrared signals ( $0.25 \text{ mm}^2$ ) results in accurate measurement with a high temperature rate. The focus of infrared thermometer needs to be adjusted to the back surface of small hole in the workpiece by using a two-dimensional sliding table with a positioning accuracy of 0.02 mm. The cavity emissivity of the small hole was calibrated as 0.98 by comparing temperature results of thermocouple and infrared thermometer, which was close to theoretical value. By using this technique, the temperature history and distribution in grinding zone can be acquired precisely with little influence from vibration and high temperature rate or gradient.

According to the measuring results, under the classical operating condition of machining blades of turbine, the temperature rises rapidly to the maximum of  $966.3 \text{ }^\circ\text{C}$  at an average heating rate of  $2821 \text{ }^\circ\text{C/s}$  during creep-feed grinding without cutting fluid involved. The temperature field in grinding zone can be plotted by data analysis. The maximum grinding temperature increased linearly with a vertical temperature gradient of  $644 \text{ }^\circ\text{C/mm}$ . The measurement on grinding temperature is repeatable by using IMBFS, which shows a high reliability.

The accurate measurement technique of grinding temperature is the basis of optimizing process parameters, preventing potential thermal damage, improving the surface integrity of workpiece and precise numerical modelling. Compared with thermocouple techniques, the measurement by using IMBFS doesn't fluctuate with high-frequency signal interruption of mechanical vibration and electrical noises. And the cooling system and optical fibers are

not necessary, which is needed in regular infrared pyrometer methods.

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