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Estimation of Interface Temperature During Contact Sliding

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Abstract

In machining operation, heat generated on the contact interface is important for the performance of the tool and quality of the finished product. The effect of the interface temperature, particularly when it is high, is mostly detrimental to both tool and work piece. The machining and tool life can be improved by the knowledge of interface temperature between tool and workpiece. In this mini project, the variation of different parameters on interface temperature is evaluated. An experiment is sated up to measure the interface temperature developed between grinding wheel and workpiece, during grinding operation in a surface grinding machine, under different parameters. The metal cutting parameters considered are feed rate and depth of cut with dry and wet condition. In this experiment, an assembly of k-type thermocouple and digital thermometer are used for measuring the temperature. The grinding wheel used is of silicon carbide and work pieces are 42CrMo$_4$ Steel 16MnCr$_5$ Steel plate. These steel work pieces are used because it have large variety of applications like worms, gears, machine parts, components of tool die set, tool holder etc. From the data collected during the experiment, the effects of different grinding parameters on temperature developed between grinding wheel and workpiece interface and suitable grinding conditions can be understood for obtaining maximum material removal rate at lower temperature. The obtained results are tabulated and analyzed graphically.

Keywords

Interface Temperature, Contact Sliding, Flash Temperature, Temperature Measurement

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1. Introduction

There are several processes of manufacturing machining operations i.e., drilling, milling, turning and grinding processes that are important for the conversion of raw materials into finished goods. Most of these processes deal with giving a new shape and form to the raw materials either by changing their state or shape. One of the best method to produce a part or a work-piece that the material is too hard or too brittle and it require high dimensional accuracy and surface finish is by using abrasive machining. Therefore, one such important abrasive machining process is grinding, and it is very useful technique for metal removal at fast rates and for the high level finishing of final products. Grinding is typically a finishing process where quality is important and mistakes are costly. In order to attain high quality parts and high productivity it is necessary to properly choose the correct process parameters. These parameters are usually determined through testing and experience. Grinding is a

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material removal and surface generation process used to shape and finish components made of metals and other materials. Grinding employs an abrasive product, usually a rotating wheel brought into controlled contact with a work surface. The grinding wheel is composed of abrasive grains held together in a binder. These abrasive grains act as cutting tools, removing tiny chips of material from the work. As these abrasive grains wear and become dull, the added resistance leads to fracture of the grains or weakening of their bond. The dull pieces break away, revealing sharp new grains that continue cutting.

1.1. Application of the tool-chip Interface

Machining of metals is still not completely understood because of the highly non-linear nature of the process and the complex coupling between deformation and temperature fields. Metal cutting can be associated with high temperatures in the tool-chip interface zone and hence, the thermal aspects of the cutting process strongly affect the accuracy of the machining process. The deformation process is highly concentrated in a very small zone and the temperatures generated in the deformation zones affect both the tool and the work-piece. High cutting temperatures strongly influence tool wear, tool life, work piece surface integrity, chip formation mechanism and contribute to the thermal deformation of the cutting tool, which is considered, amongst others, as the largest source of error in the machining process [1]. The increase in the temperature of the work piece material in the primary deformation zone softens the material, thereby decreasing cutting forces and the energy required to cause further shear. Temperature at the tool-chip interface affects the contact phenomena by changing the friction conditions, which in turn affects the shape and location of both of the primary and secondary deformation zones [2], maximum temperature location, heat partition and the diffusion of the tool material into the chip.

Measuring temperature and the prediction of heat distribution in metal cutting is extremely difficult due to an arrow shear band, chip obstacles, and the nature of the contact phenomena where the two bodies, tool and chip, are in continuous contact and moving with respect to each other.

Several techniques have been developed over time for the measurement of temperature in various manufacturing processes and tribological applications. In the following, various techniques used for the determination of temperature and its distribution will be briefly covered. [3]

1. Thermocouple method
   a. Embedded thermocouples
   b. Dynamic thermocouples
   c. Thin film thermocouples
   d. Traverse thermocouple technique
2. Infrared photographic technique
3. Optical and infrared radiation pyrometers
4. Thermal paints
5. Temperature distribution using fine powders of constant melting point
6. Temperature distribution using PVD coatings of materials with known melting temperatures
7. Temperature distribution using metallographic methods

In many manufacturing processes as well as in tribological applications, it is desirable and often times necessary to have some knowledge on the amount of heat generated and consequent temperature rise (both maximum and average) as well as its distribution in the conduction medium. For example, the maximum temperature on the tool rake face or the clearance face of a cutting tool will determine the life of a cutting tool.

In tribological applications, as in the case of two contacting bodies in sliding contact, high surface temperatures (or flash temperatures), according to Kennedy [4], can have the following consequences: (1) surface melting, (2) oxidation and wear, (3) thermoelastic instabilities in the contact zone, (4) deterioration of solid or boundary lubrication films resulting in the exposure of the virgin surfaces and subsequent adhesion and galling between mating surfaces, (5) ignition of one of the contacting bodies, and (6) thermo–mechanical failure, such as thermal cracking, or warping.

Most of the energy expended in plastic deformation and friction in metal cutting and metal forming is converted into heat [5]. It is possible to estimate the heat generated in various manufacturing processes and tribological situations either by calorimetric methods or by measuring the forces generated. However, the measurement of temperature generally is not such a simple and straight forward matter. The heat partition between two bodies which are in contact and moving with respect to the other is also a difficult problem.

1.2. Chip-tool Interface Temperature for Turning Process

L. B. Abhang et. al [6] did work on prediction of temperature at chip tool interface during turning process. In this research, the metal cutting parameters considered are cutting speed, feed rate, depth of cut and tool nose radius. It can be seen that the cutting speed, feed rate and depth of cut are the most significantly influencing parameters for the chip-tool interface temperature followed by tool nose radius. The results show that increase in cutting speed, feed rate and depth of cut increases the cutting temperature while increasing nose radius reduces the cutting temperature.

Temperature on the chip-tool interface is important parameters in the analysis and control of machining process. Due to the high shear and friction energies dissipated during a machining operation the temperature in the primary and secondary shear zones are usually very high, hence affect the shear deformation and tool wear. In a single point cutting, heat is generated at three different zones i.e. primary shear zone, chip tool interface and the tool work-piece interface as shown in Figure 1. The primary shear zone temperature affects the mechanical properties of the work piece-chip material and temperatures at the tool-chip and tool-work piece interfaces influence tool wear at tool face and flank respectively. Total tool wear rate and crater wear on the rake face are strongly influenced by the temperature at chip-tool interface. Therefore, it is desirable to determine the temperatures of the tool and chip interface to analyze or control the process. To measure the tool temperature at the tool chip interface many experimental methods have been developed over the past century. Since at the interface there is a moving contact between the tool and chip, experimental techniques such as standard pre calibrated thermocouples cannot be used to measure the interface temperature.

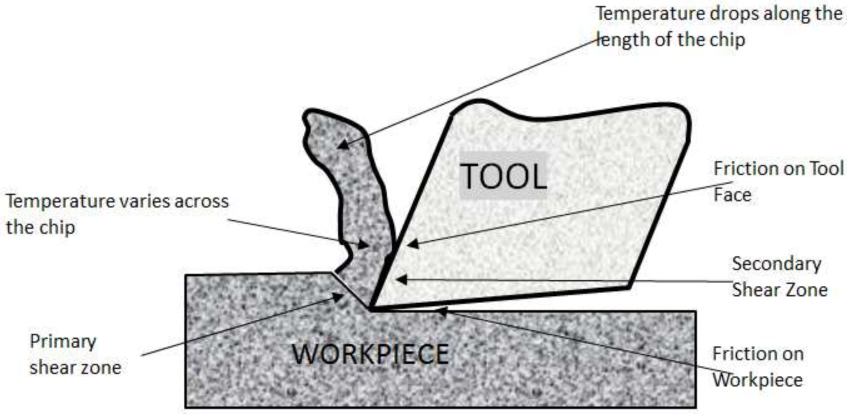

Figure 1. Heat Generated by Chip Formation.

Much research has been undertaken into measuring the temperatures generated during cutting operations. The main techniques used to evaluate the cutting temperature during machining are tool-chip thermocouple, embedded thermocouple, and thermal radiation method as reported by Barrow [7]. The thermocouple methods are based on the thermocouple principle that states that two contacting materials produce an electromotive force (emf) due to difference in temperatures of cold and hot junctions. The validity of assumptions made and possible sources of errors in different experimental techniques have been out lined by Barrow [7].

Tool-work thermocouple has become a popular tool to be used in temperature measurements during metal cutting. This method is very useful to indicate the effects of the cutting speed, feed rate, depth of cut and the tool parameters on the temperature. In tool-work thermocouple the chip-tool interface forms the hot junction, while the tool end forms the cold junction. The tool and workpiece need to be electrically insulated from the machine tool. This cutting temperature measurement technique is easy to apply for the measurement of chip-tool interface temperature during metal cutting over the entire contact area as reported by Shaw [8]. Based on these measurement using the thermocouple method, Stephenson [9, 10] stated that the average emf is generated a toolwork piece interface. The difficulty of this method is concerned with the necessity for an accurate calibration of the tool and workpiece materials as a thermocouple pair.

In order to measure the cutting edge temperature using a thermocouple two different methods can be used to fix the hot junction close to the cutting edge. In the first method, the thermocouple is clamped in a recess, which is ground off the rake face of the tool to locate the hot junction as close as possible to the cutting edge. In the second method, the thermocouple is inserted in a precisely grooved carbide chip breaker, which is clamped mechanically on the tool such that the hot junction is at the same distance as in the first method. Comparing results obtained by the two methods showed that both methods gave the same results [11]. Therefore it was suggested that the second method is better since the recess in the cutting tool would change the temperature distribution along the rake face. In addition the second method is considered easier to implement. In this paper the tool-work thermo couple technique was used to measure the chip-tool interface temperature during machining of EN-31 steel alloy.

In 1954 Lower and Shaw's [12] developed analytical prediction model for the measurement of cutting temperature during machining. They concluded that the cutting temperature is the function of cutting speed and feed rate.

$$\theta_t = V^{0.5} \times t^{0.3}$$

Where, θ_t = Average cutting temperature

V = cutting speed

t = undeformed chip- thickness or feed rate

The Lowen and Shaw's method was found to be the best predictor according to Stephenson [10]. Wardeny et al [11] suggested that the temperature distribution in the tool may be obtained by using information about the changes in the hardness and microstructure of the steel tool. It is necessary to calibrate the hardness of the tool against the temperature and time of heating and samples of structural changes at corresponding temperatures. These methods permit measurement of temperatures to an accuracy of ± 25°C within the heat affected region. However, Wright [13] commented that these methods are arduous and difficult to use. Trigger [14] investigated the tool-work interface temperatures using the thermo-couple technique. This work differs from the earlier work in that cemented carbide tools were used in machining steels instead of the HSS tools. Both the elements of tool-work thermocouple comprised of iron base alloys of similar basic lattice structure, a factor which can influence the tendency of the chip to form a built up edge on the tool and consequently cause erratic results. Grzesik [15] measured tool-work interface temperature when machining an AISI 1045 and an AISI 304 with coated tools used a standard K-type of thermocouple inserted in the work piece and reported that the friction on the flank face had a big influence on the heat generated at about 200 m/min cutting speed. Sullivan and Cotterm [16] measured the machined surface temperatures with two thermocouples inserted into the work piece when machining aluminum 6082-T6. The results indicated that an increase in cutting speed resulted in a decrease in cutting forces and machined surface temperatures. This reduction in temperature was attributed to the higher metal removal rate that resulted in more heat being carried away by the chip. Trent et al. [17] suggested that during the machining process, a considerable amount of the machine energy is transferred to heat through plastic deformation of the work-piece surface, the friction of the chip on the tool face and the friction between tool and the work-piece, about 99% of the work done is converted into heat. This results in an increase in the tool and work temperatures.

2. Methodology

The temperature of the grinding surface has been measured by simple technique by using a constantan wire fitted into a thin slit provided by wire cutting at the middle portion of the work specimens. The constantan wire has been properly secured and insulated in the slit. During grinding operation the wire tip contacted the work surface and formed the hot junction of the constantan-steel thermocouple pair. The voltage signals from the thermocouple were monitored using a suitable digital thermometer.

2.1. Experimental Setup

In our experiment we are setting up a temporary arrangement for measuring temperature between grinding wheel and workpiece during grinding operation in surface grinding machine. Temperature measuring device consists of an assembly of K type thermocouple and digital thermometer. The grinding wheel being used in the experiment is silicon carbide. A slot of 0.4mm width and 5 mm depth is made by CNC wire cut machine on the workpiece and probe of the thermocouple is inserted in the slot such that it touches the grinding wheel. The negative and positive end of the thermocouple is connected to the corresponding terminals of the digital thermometer. In this arrangement the temperature between the wheel and workpiece will develop an emf in the thermocouple which will be displayed in the digital thermometer. The digital thermometer reading is taken for different machining conditions by varying the cutting parameters like cutting feed, depth of cut, dry condition, wet condition etc.

A slot of 0.4mm width and 5mm depth was made from the top of the workpiece by CNC wire cut machine.

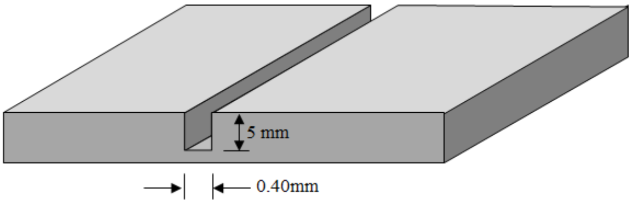

Figure 2. Slot dimension.

Figure 3. Overview of CNC wire cut machine.

Figure 4 Overview of slot cutting operation by CNC wire cut machine.

Figure 5 Overview of slot cutting operation by CNC wire cut machine.

During grinding, the thermocouple junction is exposed, and the deformed workpiece connects the thermocouple junction to the workpiece for temperature measurement. The sizes of the slot and thermocouple junction need to be closely matched. If the slot is too large, a good connection between the thermocouple junction and workpiece is not obtained.

The present experiments were conducted in a surface grinder in plunge surface grinding mode. The grinding experiments have been carried out under dry and wet condition (soluble oil). The conventional cooling system provided in the machine has been used for wet grinding tests.

2.2. Experimental Condition

The present experimental conditions are given in Table 1.

Table 1. Experimental conditions.

Machine	Horizontal Spindle Surface Grinding Machine with Rectangular Table (model: M7120A), 2.8 kW
Workpiece	a. 42CrMo4 Steel b. 16MnCr5 Steel
Workpiece Size	100mm × 68mm × 16mm
Wheel	D126R100 B60-3 mm
Spindle speed	3000 rpm
Table speed	6 m/min
In feed	10 µm, 20 µm, 30 µm and 40 µm
Environment	1. Dry condition 2. Flood cooling with soluble oil

Machining ferrous metals by carbides is a major activity in the machining industries. Machining of steels involves more heat generation for their ductility and production of continuous chips having more intimate and wide chip-tool contact. Again, the cutting temperature increases further with the increase in strength and hardness of the steels for more specific energy requirement. Keeping these facts in view the commonly used steel like $42CrMo_4$ steel and $16MnCr_5$ steel have been undertaken for the present investigations. The compositions, strength, hardness and industrial use of this steel are given in Table 2.

Table 2. Characteristics of the used steel [Rothman 1988 & Bagchi 1979].

Work material	**BHN**	**UTS (Kgf/mm^2)**	**Chemical composition (wt%)**	**Applications**
$42CrMo_4$	252	101	C=0.450%, Si=0.300%, Mn=0.75%, Cr=1.02%, Mo=0.30%, Ni=0.60%, P=0.035%, S=0.035%	1. Axles shafts 2. Induction track pins 3. Crankshafts 4. Connecting rods 5. Gears
$16MnCr_5$	201	111	C=0.17%, Si=0.30%, Mn=1.2%, Cr=1.02%, P=0.035%, S=0.035%)	1. Heavy duty gears 2. Pinions 3. Camshafts 4. Clutch plates

3. Experimental Results

3.1. Microscopic Study of the Chips

The chips were collected for all the treatments by placing a glass slide coated with petroleum jelly on the spark stream during grinding. The collection of the chips were carried out only after the grinding has reached the steady state indicated by almost no vibration in the magnitude of the grinding forces with the number of passes. Those chips were thoroughly washed with acetone and dried. Then the chips were observed under scanning electron microscope to study the morphological characteristics of the chips.

3.2. Microstructure of Chips

Figure 6 and Figure 7 show SEM micrographs of the chip at the down feed of 20µm and 30µm with dry condition.

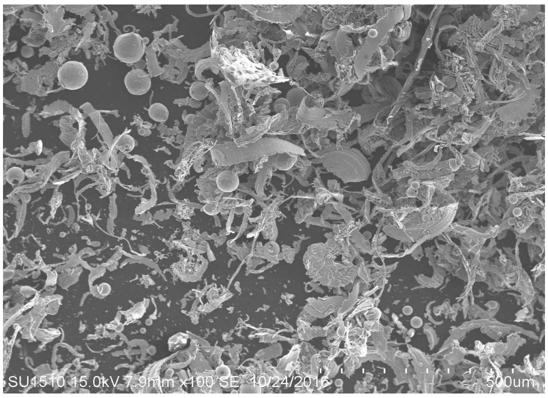

Figure 6. SEM micrographs of the chip at the down feed of 20µm.

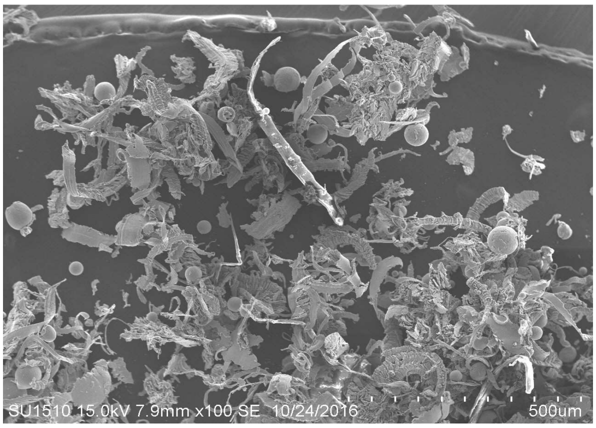

Figure 7. SEM micrographs of the chip at the down feed of 30µm

3.3. Grinding Temperature

The temperature of the grinding surface has been measured by simple technique by using a constantan wire fitted into a thin slit provided by wire cutting at the middle portion of the work specimens as indicated in Figure 6 & Figure 7. The constantan wire has been properly secured and insulated in the slit. During grinding operation the wire tip contacted the work surface and formed the hot junction of the constantan-steel thermocouple pair. The voltage signals from the thermocouple were monitored using a suitable digital thermometer. Figure 8 and Figure 9 show the vitiation of the grinding zone temperature observed in different environments at various in-feeds.

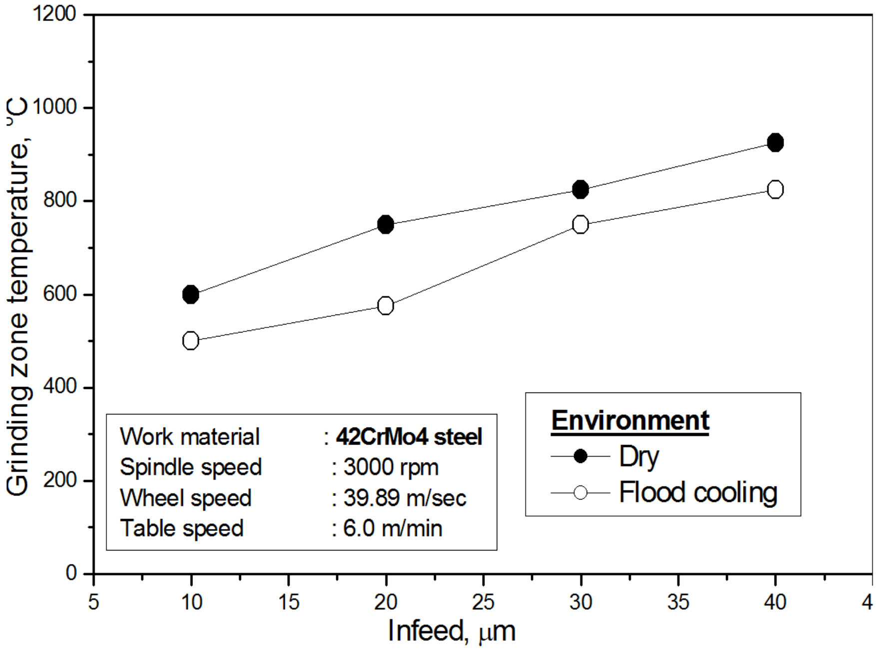

Figure 8. Variation in the grinding zone temperature with in-feed under dry and wet conditions while grinding 42CrMo$_4$ Steel.

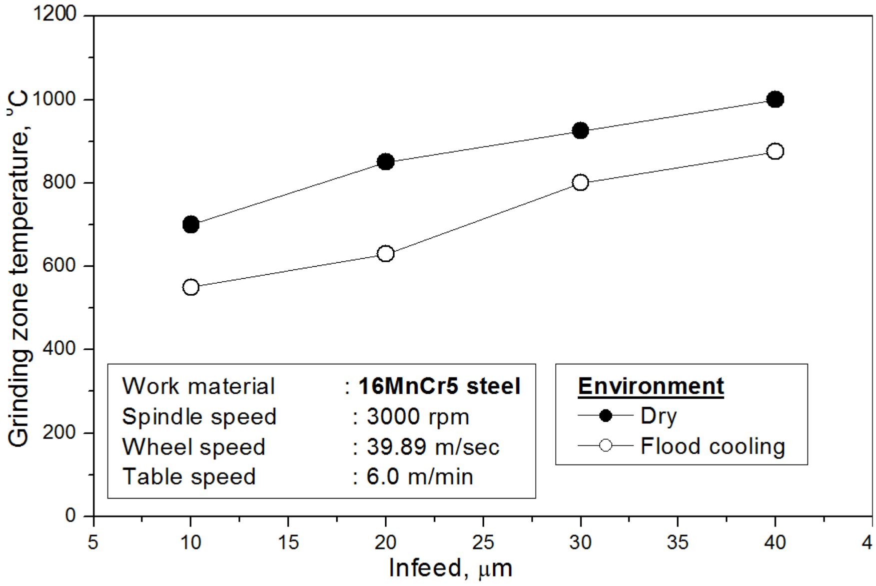

Figure 9 Variation in the grinding zone temperature with in-feed under dry and wet conditions while grinding 16MnCr$_5$ Steel.

4. Discussion on Experimental Results

4.1. Grinding Chips

The study of grinding chip is required to understand the mechanism of chip formation and those of material removal. The chips produced during grinding 42CrMo$_4$ steel at different in-feeds have been shown in the figures Figure 6 and Figure 7 under the dry condition. Dry grinding at both 20 µm and 30 µm in-feed provided different types of chips such as lamellar, spherical, irregular shaped and blocky particles. The clear lamellar structure of the chip indicates shearing to be one of the mechanisms of chip formation. Some small and medium size chips have taken up spherical shape possible due to excessive heating and exothermic oxidation. Higher grinding zone temperature and ductility of these steel specimens are expected to yield larger number of spherical chips.

At higher in-feed of 30 µm, dry grinding yielded almost similar types of chips suggesting similar mechanism of chip formation. The increased width of the chip depicts distinct ploughing. By studying the chip characteristics, it is evident that in dry grinding the mechanism of chip formation is primarily shearing, ploughing and rubbing. However, no indication was obtained regarding the change in chip formation mechanism with the increase in-feed.

4.2. Cutting Temperature

Grinding is associated with high temperature which is responsible for aggravating several problems like wheel loading, thermal damages of the ground surfaces, poor grind-ability etc. in the present work, the benefits expected out of wet condition over dry condition are also based mainly on the reduction in the grinding zone temperature. Therefore, to evaluate the major effects of wet condition in grinding different steels and to explore the main causes of such effects it is essential to determine the grinding temperature under various conditions. The magnitude and distribution of grinding temperature depends on many factors and their relations are quite complex for which it is difficult to evaluate the grinding temperature analytically. A simple technique by using a constantan wire fitted into a thin slit provided by wire cutting at the middle portion of the work specimens was used to measure the grinding zone temperature.

The experimental results shown in the Figure 5 and Figure 6 clearly indicate that the grinding zone temperature decreases due to wet condition. Whereas, the ability of cooling by the soluble oil has been quite poor and decreased further with the increase in in-feed possibly due to its inability to reach the grinding zone and film boiling at elevated temperature.

5. Conclusions

Based on the experimental results it can be concluded that flood cooling provided significant improvements expectedly, though in varying degree, in respect of chip formation modes, surface characteristics throughout the in-feed range undertaken mainly due to reduction in the grinding zone temperature. It was also evident that dry condition could not control the grinding temperature appreciably. Flood cooling by soluble oil provided relatively lower plastic deformation and rubbing, shearing and fracturing modes of chip formation and retention of the grit’s sharpness. The merits of different methods of temperature measurement have been thoroughly explored. The single-pole grind-able thermocouple technique was found to be the simplest and most reliable technique. It has been shown that it is important to optimize the thermocouple geometry to achieve reliable signals under dry and wet surface grinding conditions. The accuracy of a measuring system have been investigated and it has been shown that it is possible to achieve reliable temperature measurements under dry and wet grinding conditions.

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