A Technological Review on Temperature Measurement Techniques in Various Machining Processes

Vineet Dubey, Anuj Kumar Sharma, and Rabesh Kumar Singh

Abstract The cutting temperature and the amount of heat produced at the tool–chip interface during different machining operations have been recognized as main factors that influence the cost of machining as well as the cutting tool performance in terms of surface finish and the production time involved while machining. Cutting tool efficiency is largely affected by temperature generated while machining which limits the quality of the finished product. This paper presents a review of various methods for the measurement of tool and workpiece temperature distribution in different machining processes. Different temperature-sensing techniques are discussed along with their limitations. A comparison between several sensing methods has been done in terms of cost-benefit, accuracy, ease in measurement and response time in order to find out the best-suited method.

Keywords Cutting temperature · Sensors · Thermocouple · Infrared · Experimental method · Machining

1 Introduction

The surface quality of the part developed in material removal process is mainly dependent upon the efficiency of cutting tool. Hence, proper monitoring of the cutting tool is required. During the tool–workpiece interaction, large amount of heat is generated because of friction. Mainly, three types of deformation zones are encountered, namely primary, secondary and tertiary deformation zones as shown in Fig. 1. Primary deformation zone is affected largely as very high temperature is reported due to localized heating resulting in material softening. Further heat liberation is encountered in secondary zone in deformation of chips and to counteract the sliding friction at tool–chip interface. Due to the rubbing action between flank face of the tool and the machined surface, heat is liberated at the tertiary deformation zone in

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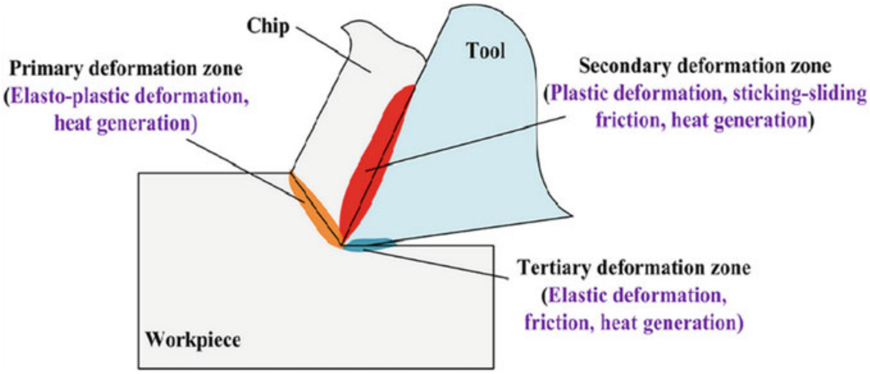


Fig. 1 Sources of heat liberation in the orthogonal machining process [1]

order to overcome friction. Various researchers have worked in this area to estimate the temperature at the tool–chip interface.

Shan et al. [2] performed orthogonal turning on titanium alloy Ti6Al4V for validating their experiment. In order to predict the temperature distribution, they developed an analytical model depending on moving heat source. K-type thermocouple was used for temperature measurement, and it was reported that the temperature difference recorded from the predicted model and the experiment performed are within 0.49–9%. Baumgart et al. [3] utilized two-color pyrometer to estimate the temperature in cylindrical grinding. It was observed that at low coolant supply variation in thermal load was from 265 K/s at 1.5 mm to 11,300 K/s at 0.5 mm. Ranc et al. [4] also used pyrometer along with CCD camera in machining of low-carbon steel and observed the highest temperature of 730 °C and minimum temperature of 550 °C. Using this setup, they also recorded the formation of chip during machining. Li et al. [5] inserted thin-film sensor on the rake face of tungsten carbide insert where the microgrooves were prepared and performed turning operation. Evaluation of temperature was seen in continuous as well as intermittent test. Sharma et al. [6] worked with in-house developed K-type thermocouple in the tool holder in machining AISI 304 steel using alumina and alumina–MWCNT hybrid nanofluid mist. They simulated using conjugate heat transfer method and found a variation of 5.79% with experimental work. Alvarez et al. [7] used two-color pyrometer technique while turning Inconel 718 at a different speed and feed rate. It was revealed that the temperature recorded reduced as the applied feed was increased. Davoodi and Hosseinzadeh [8] utilized infrared sensor in which voltage signal is inducted as the temperature raises. The amount of voltage is used in estimating temperature. High response rate was achieved with infrared sensor. Ghafarizadeh et al. [9] performed milling operation on CFRP and used K-type thermocouples for estimation of cutting temperature at low feed and medium-speed cutting. The temperature recorded raised linearly as per cutting speed. Chaudhary and Bartarya [10] performed orthogonal turning on EN 24 steel using HSS tool and utilized tool–work thermocouple method in order to sense the temperature. They observed rise in the temperature at cutting zone as the cutting speed as well as feed rate was increased. Yashiro et al. [11] employed various techniques for calculating temperature while machining of carbon fiber-reinforced plastics. Embedded as well as tool–workpiece thermocouple, and infrared camera was used. The temperature reached up to 180 °C at a speed of 25 m/min. The aim of the experiment was to control the glass transition temperature of the matrix resin. Prakash et al. [12] applied electrical discharge coating and achieved surface modification of Ti6Al4 V alloy using partially sintered Ti-Nb electrode. Uddin et al. [13] performed experiment on drilling in order to evaluate the hole quality in case of aluminum alloy. Gupta et al. [14] performed machining on Inconel-800 superalloy in near dry machining condition and observed reduction in cutting force as well as improvement in the surface quality. Pradhan et al. [15] used FEA modeling to investigate the performance of microgroove textured cutting tool and observed lower cutting temperature as well as cutting force. Dubey and Singh [16] studied powder-mixed EDM on aluminum alloy and found that recast layer is decreased at lower setting of parameters. Tiwari et al. [17] performed drilling operation and studied the effect of drilling speed on micro-residual stress distribution in the proximity of hole using nanoindentation.

The present paper discusses the research work of past ten years in various machining processes such as turning drilling and milling. An attempt has been made to measure the cutting tool–workpiece temperature while machining. The researches focused on temperature measurement technique during machining as given in Table 1. The table describes the machining process, the tool–workpiece material used, along with the various sensing techniques involved in machining. Furthermore, the paper discussed the different temperature-measuring methods.

2 Study of Various Temperature-Sensing Techniques

Temperature-measuring techniques are basically categorized into conduction and radiation method. In case of conduction, interaction of energy among the particles from higher energy to lower energy happens. The temperature difference between the two regions in contact is calculated. Different methods under conduction techniques are shown in Fig. 2. The radiation technique depends upon the emissivity and temperature of the body. The accuracy of emissivity decides the precise measurement given by the radiation measurement instrument. The sub-categories of conduction and radiation methods are discussed.

2.1 *Thermocouples*

Thermocouples work on the principle of Seebeck effect. This effect produces difference in the voltage within the hot and cold junction whenever there is temperature difference [30]. In order to measure temperature rise at cutting zones, the obtained

Table 1 List of past work done in estimating temperature in various machining operations

Authors	Machining processes	Temperature-sensing technique/equipment	Tool/workpiece	Remarks/findings
Shan et al. [2]	Turning	K-type armored thermocouple	Carbide tool insert	With rise in feed rate, the high-temperature area is changing away from nose of tool
Zhang et al. [18]	Drilling	Thermocouple and platinum resistors	S45C steel	Temperature rise was maximum at bit regolith region
Kesriklioglu [19]	Milling	K-type thin-film thermocouple	Tungsten carbide	It was noticed that in case of climb and conventional milling the peak temperature is very close
Li et al. [5]	Turning	K-type thin-film thermocouple	Tungsten carbide insert	Proper linearity and uniformity are seen in estimating when the sensors are insulated with the alloy substrate
Baumgart et al. [3]	Cylindrical grinding	Two-color pyrometer	Cold work tool steel	Variation in thermal load can be seen from 265 to 11,300 K/s
Nunez et al. [20]	CNC milling	Infrared camera/thermogram	High-speed steel end milling tool	For finding of the interest zones, the image collected was useful
Urgoiti et al. [21]	Grinding	Pyrometer	GG-30 cast iron	There has been a decrease of measurement error by 60% when temperature estimation of the surface was done while grinding operation using this technique

(continued)

Table 1 (continued)

Authors	Machining processes	Temperature-sensing technique/equipment	Tool/workpiece	Remarks/findings
Rizal et al. [22]	Milling	Thermocouple	ACK 300 tungsten carbide tool	Thermocouple used was found to be reliable for interpreting machining signals. The signals obtained are co-related to flank wear stare
Werschmoeller and Li [23]	CNC milling	Thin-film micro-thermocouple	Polycrystalline boron nitride (PCBN)	Thin-film micro-thermocouple exhibited good linearity as well as quick response time
Alvarez et al. [7]	Turning	Two-color pyrometer	Triangular uncoated carbide insert	It was reported that despite harsh environmental conditions, this pyrometer technique has shown good performance in measuring temperature where emissivity can play an important role
Sorrentino et al. [24]	CNC drilling	K-type thermocouple	Tungsten carbide	The highest temperature estimated on the tool rises with the cutting speed and decreases with increasing feed rate
Tapetado et al. [25]	Turning	Two-color pyrometer	Carbide insert	The experiment results revealed a temperature error of 14%
Gosai et al. [26]	Turning	K-type thermocouple	Coated carbide insert	The obtained mathematical model was validated, and the error reported was less than 10%

(continued)

Table 1 (continued)

Authors	Machining processes	Temperature-sensing technique/equipment	Tool/workpiece	Remarks/findings
Baohai et al. [27]	End milling	Single-wire thermocouple	Milling cutter with carbide insert	An inverse trend of temperature change was found against cutting speed
Sugita et al. [28]	Turning	Micro-thermocouple sensor	Carbide insert	This sensor can be used with non-conducting materials and applied to medical devices

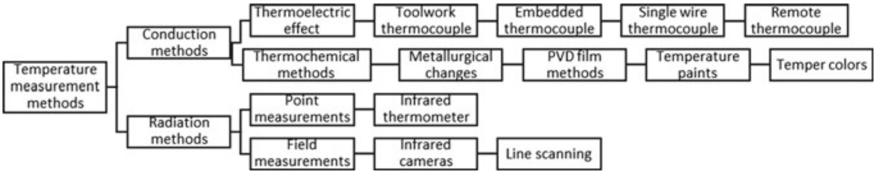


Fig. 2 Temperature-sensing methods [29]

voltage difference is calibrated. This mode of temperature measurement is beneficial to relate various machining parameters like depth of cut, feed rate and the speed involved to the variation of temperature. Different thermocouple techniques are discussed below.

2.1.1 Embedded Thermocouple

This technology involves introducing thermocouples into suitable sized hole in the workpiece material referring to as an ‘embedded thermocouple.’ These thermocouples are generally mounted in proximity to the surface where the temperature needs to be calculated. Figure 3 depicts the use of embedded thermocouples in case of milling operation.

2.1.2 Tool/Workpiece Thermocouple

The experimental setup of this technique is quiet simple as shown in Fig. 4. In this case, the machining temperature is associated with the emf produced across the hot interface between tool and workpiece. Application of this methodology is largely seen in case of tool inserts. This technique poses limitation in finding temperature

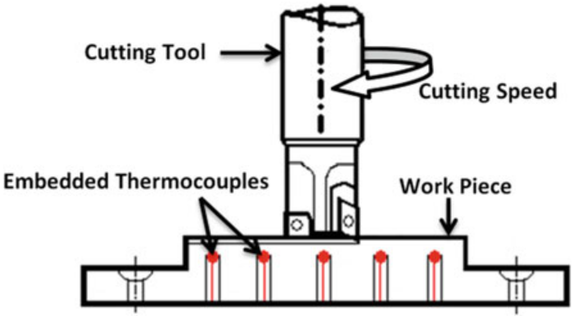


Fig. 3 Milling temperature measurement using embedded thermocouples [31]

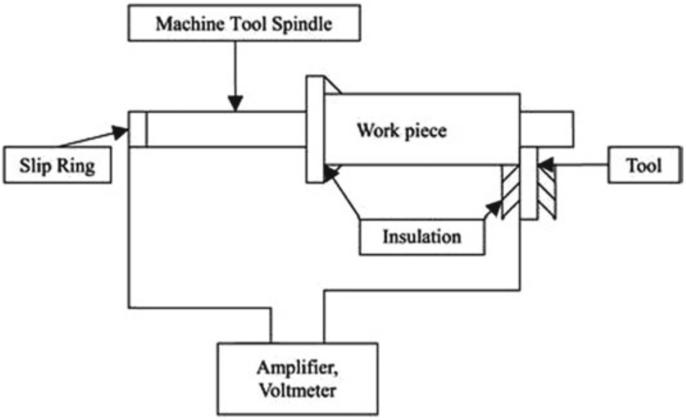


Fig. 4 Tool/workpiece thermocouple experimental setup [31]

distribution at various points of the tool in single setup. Like embedded thermocouple, this technique is too limited to dry cutting while it has a good dynamic response.

2.1.3 Single-Wire Thermocouple

In this thermocouple as the name suggests, an insulated wire is inserted through the workpiece by dividing the part into two across the line of cutting as depicted in Fig. 5.

The thin wire is cut during milling, exposing it and forming a thermocouple between the wire and the cutting tool [32] as shown in Fig. 6. In this method, very short signal duration is seen only during electrical contact with the wire. Thus, high sampling rate is necessary in order to record the signal during the short measurement interval [29]. With this technique, remote measurement is feasible and setup is simple. Several repetitions as well as variance analysis are desirable due to short contact times and electrical conduction problems.

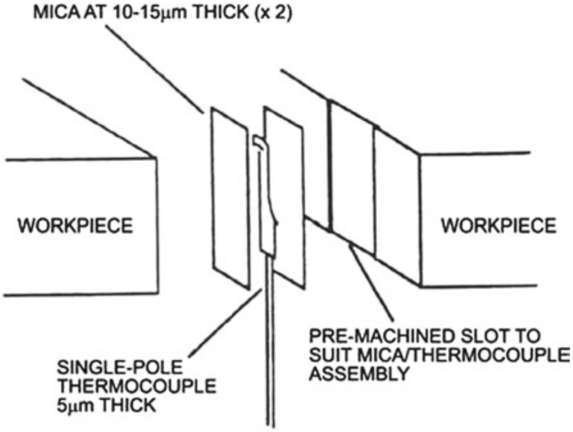


Fig. 5 Installation of single-wire thermocouple

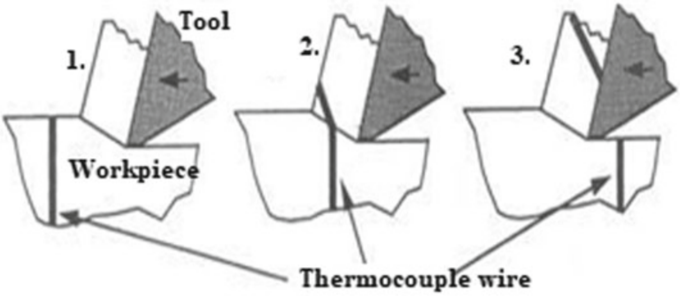


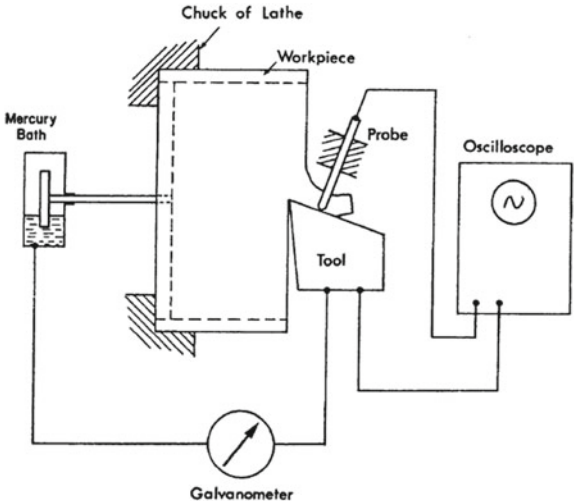
Fig. 6 Single-wire thermocouple measuring process

2.1.4 Transverse Thermocouple

These thermocouples are used in finding the tool temperature distributions on the rake face of the tool at the chip–tool interface [33]. The setup of transverse thermocouple arrangement is depicted in Fig. 7. The thermoelectric junction comprises the tool material and the probe material. As the position of the sharp probe changes, the readings of the temperature distribution relative to a specific edge are recorded [33].

Therefore according to the need, wherever the temperature is of interest the sharp probe can move on the tool surface which enables measurements of 3D temperature distribution. Though the experimental setup is complex, yet this method helps in predicting the position of tool wear.

Fig. 7 Transverse thermocouple setup [16]



2.2 *Thermochemical Powders*

This method involves shaping the cutting tool in two divisions having symmetrical interface. While assembling, a coating of powder is applied to the region. Thermochemical powders having varying melting points are used, at a time, and the temperature distribution is determined by repeating the experiments. Isotherms are generated using this method which indicate temperature distribution as seen in Fig. 8. With this technique, it is simple to detect boundaries and also no calibration is required, because of the constant melting points of the powders used. The different thermochemical powders used in this technique along with their melting and boiling point are mentioned in Table 2.

Fig. 8 Temperature isotherms on rake face [34]

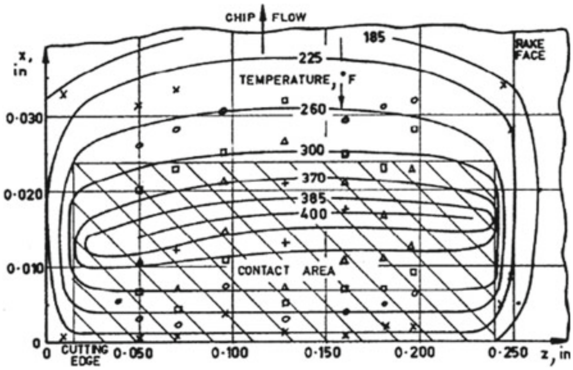


Table 2 Thermochemical powders and their respective melting points [31]

Chemical substance	Melting point (°C)	Boiling point (°C)
NaCl	800	1413
KCl	776	1500
CdCl	568	960
$PbCl_2$	501	964
AgCl	455	1550
Zn	419	907
KNO_3	339	–
Pb	327.4	1750
$SnCl_2$	246.8	623
Sn	231.9	2270

2.3 Thermal-Sensitive Paint Method

In order to estimate the temperature distribution, another method called thermal-sensitive paint method is employed, in which the specimen is coated with the thermo-sensitive paints which change their color at known temperatures. For tracing the isothermal lines, this technique is found to be suitable [30]. It is reported that this method finds its best suitability for qualitative comparison of temperatures. The limitations of this method are the response time and accuracy for small temperature variations. This technique is of low cost and is easy to use. The limitation of this method is that it requires controlled heat transfer environment and is not suitable for use with cooling/lubrication.

2.4 Metallurgical Method

This method utilizes metallurgical deformation and hardness change which the cutting tool possesses post-machining operation which can be correlated with temperature. With the help of metallographic investigation, the structural changes can be examined. The microstructure obtained from the tool/workpiece is matched to reference microstructures, which aids in calculating temperature. These structural changes make it suitable to map the temperature distribution. On the other hand, micro-hardness measurements can be performed on the tool after the cutting to determine temperature counters. This method is time consuming and requires accurate hardness measurement [33]. Application is restricted to suitable conditions like high range of temperature and materials like high-speed steel. This method proves to be insensitive when there is no microstructural change.

2.5 Infrared Camera

It is a technique to estimate the surface temperature of the body based on the thermal energy produced by the body. This technique is accessible for point measurement as in case of infrared pyrometers and infrared thermograph. The radiation method offers rapid response and material safety, and allows measurements on objects over thermoelectric technique. However, proper measurement location has to be opted as it may hinder the accuracy by chip obstruction. Calculation of the tool–chip interface temperature also becomes difficult due to chip obstruction, hence avoided. Exact emissivity of the surface is desirable as it affects the measured temperature [8].

3 Results and Discussion

As per the review from the above works mentioned on various techniques of temperature-sensing, an exact approach for measuring temperature depends as per the problem, like the ease with the sensor can be installed to the location desired, accuracy required, setup cost, data acquisition and analysis, innovations in sensor technology measurement. In case of embedded thermocouple, frequent repetition as well as several variance analyses has to be performed. In case of transverse thermocouple using sharp probe, temperature can be determined at different locations. Using infrared technique, safety of the workpiece as well as tool can be ensured as no harm is imposed on the material unlike other sensing techniques. Some of the techniques find itself suitable for a particular condition in temperature detection, while some methodology poses limitation on temperature calculation. In the present paper, it can be seen that the temperature detection techniques are applied on turning, milling as well as grinding operations with tool material especially tungsten carbide.

4 Conclusion

- In metal cutting, most of the literature is related to turning, milling and grinding operation. There is a scope of estimating temperature in various other conventional as well as non-conventional machining operations.
- Calculation of temperature in the close proximity of the chip–tool interface is still a challenge.
- The use of embedded thermocouple is found to be better in terms of cost, ease of calibration and response time.
- Infrared techniques have certain advantages over other sensing techniques, but its limitation is the lack of emissivity value of novel materials as well as the hard and soft coatings done on the cutting tool.

- This review can help the new researchers working in the field of thermal sensors in machining as well as the industries in getting a brief idea of work carried out in recent years in different machining operations.

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