Temperature Field Measurement in a Cutting Tool by Laser Interferometry

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Abstract. To increase machining efficiency, in addition to determining the temperature distribution on the tool surface, it is also necessary to determine the internal temperature distribution. The existing methods for determining the cutting tool temperature distribution and temperature field measurement have significant disadvantages, which limit their applicability and accuracy. The purpose of this study is to develop and test a novel cutting tool temperature field measurement method. The method involves recording the cutting tool thermal expansion fields by laser interferometry and calculating the tool material temperatures with its coefficient of thermal expansion (CTE). Compared with the methods employing infrared thermometry, the method developed in the present study has a higher spatial resolution and a lower achievable field of view due to its usage of light in the visible region. In addition, since the oxidation film has a higher reflection coefficient for visible light, the present method is less sensitive to the thin-film interference on an oxidized tool surface than those using infrared thermometry, eliminating the false shift of the measured temperature. Moreover, by utilizing cheaper optical components and equipment for interference fringe pattern registration, this method is more affordable. Unlike the emissivity coefficient in infrared thermometry, CTE is independent of changes in the surface quality and can be measured with high accuracy by modern dilatometry. Therefore, the developed method, which employs CTE to calculate the temperature, has a higher reliability. In the present study, the efficiency of this method is tested by the orthogonal turning of difficult-to-cut martensitic heat-treated steel with a cemented tungsten carbide tool. Through the experiment, the temperature distributions along the rake face and flank of the tool, as well as the temperature field inside the tool, were obtained. The results can improve the temperature field measurement in machining cutting tools.

1. Introduction
Temperature is one of the most important factors that influence various aspects of the metal cutting process. The thermal state of the cutting tool, which is one of the most important elements in machining, is extremely non-uniform. To increase machining efficiency, it is necessary to determine the temperature distribution on both the surface of the cutting tool as well as the interior. The study of temperature gradients allows the determination of thermal stresses and characteristics of thermal flows inside the tool. Moreover, it is useful for determining the tool material state and the nature of the contact processes in the cutting zone.

Currently, researchers focus on analytical methods of determining cutting tool temperature distribution. Idealized cutting zone models are used in those methods to calculate power and distribution
character of the heat sources and sinks [1-3]. Moreover, the accuracy of temperature calculations varies widely, and a good result can be achieved for only a narrow range of cutting parameters. Due to the disadvantages of the analytical methods, only experimental methods can give the most reliable results at the present time.

The cutting zone has a small size and a relatively high power of heat sources. Therefore, the temperature field of the cutting tool can have a high gradient, and temperatures at some points can become very high. These properties cause difficulty in the experimental determination of temperature fields. There are, however, a number of experimental methods developed to attempt to measure the temperature distribution in the cutting tool.

The split tool method is a variation of the tool-work (natural) thermocouple method that provides an opportunity to determine temperature distributions along the rake and clearance faces, but not a temperature field. Moreover, since the tool consists of two parts composed of dissimilar materials with a gap between them, the properties of the split tool differ from the real cutting tool significantly.

A method employing embedded artificial and semi-artificial thermocouples [4, 5] that are distributed on the faces or into the body of tool differs in the complexity of the tool-making process, and it does not allow for temperature measurements near the cutting edge area.

The running thermocouple method [6] is a time-consuming method in terms of experiment preparation and cannot be used with conditions of high cutting speeds or low feed rates.

The method based on material microstructure and hardness changes [7] can be used for a tool composed of high-speed steel. The structure and hardness of the cemented carbide tool is not significantly affected by heating; therefore, this method is less applicable.

The thermal indicator methods [8], among which the physical vapor deposition (PVD) film and temperature-sensitive paint methods are notable, are of particular interest. However, high-gradient temperature fields obtained by these methods present low accuracy due to the thermophysical differences between the films and the tool material. Moreover, fields with a wide temperature range and short interval isotherms are difficult to study by those methods. The tempering colors method (oxide layer method) is not suitable for quantifying temperatures.

The infrared thermometry method currently gives the most accurate results and is therefore used most extensively. However, its accuracy highly depends on the measuring accuracy of the implemented emissivity coefficient, which can change with increasing temperature and depends on the roughness and oxidation state of surface. Due to thin film interference on oxide layers, the method can result in a false shift of the measured temperature. Moreover, infrared cameras are difficult to use for studying small objects due to their relatively low spatial resolution and small achievable field of view, caused by the long wavelength of infrared radiation [9, 10]. In addition, difficulties in measuring large temperature changes and the high cost of infrared detector arrays and optical elements determine the limited application of the method.

2. Method
To improve the process of measuring the cutting tool temperature fields and overcome the disadvantages of the above-mentioned methods, we developed a method [11] based on a laser interferometry.

This method is implemented for orthogonal cutting. When a cutting tool works, it heats and expands. Shifts and shape changes of the tool side surfaces are determined by changing interference fringe patterns obtained by a Fizeau-type interferometer, of which a simplified schematic is shown in figure 1. The interferometer is formed by surface A of the tool (1) and surface B of the wedge prism (2). The laser beam hitting the wedge prism is split into two new beams. The first (reference) beam is reflected from the surface B of the wedge. The second (measurement) beam is transmitted through the wedge and is reflected from the mirror side surface A of the tool. Both reflected beams recombine and produce an interference pattern, which represents the shape of the tool surface A. A feature of the applied interferometer design [12] is the rigid fastening of the optical wedge relative to the tool, which eliminates their relative shift induced by vibration during cutting and increases the interference pattern quality.
Figure 1. Schematic of interferometer.

Since the power of heat sinks on the tool side surfaces is low, and the tool width is narrow relative to its size, temperature distribution parallel to the cutting edge direction may be regarded as uniform. Therefore, due to symmetrical expansion of the tool side surfaces while heating, a tool width change $\Delta t$ at the point of interest may be determined by:

$$\Delta t_i = \frac{\Delta m_i \cdot \lambda}{n},$$

where $\Delta m_i = m_i - m_0$ – difference of the interference fringe order at the point of interest between the heated and cold tools respectively; $\lambda$ – laser wavelength; $n$ – refractive index of the air.

Temperature change at the point of interest in the temperature field may be found by:

$$\Delta T_i = \frac{\Delta t_i}{t_0} \cdot \frac{1}{\alpha},$$

where $t_0$ – width of cold tool; $\alpha$ – mean coefficient of thermal expansion (CTE) for tool material, which can be measured by any dilatometry method or found in reference literature [13].

Temperature at the point of interest may be found by:

$$T_i = \Delta T_i + T_0,$$

where $T_0$ – temperature of a cold tool.

To obtain the temperature distribution along the rake and clearance faces, fringe points along the corresponding lines have to be analyzed. Temperature fields may be determined using either of two methods: the first method involves the analysis of every fringe point inside the region of interest (ROI). However, since there are no heat sources on the tool side surfaces in the ROI and heat sinks have a low power, the tool thermal state during the steady cutting process or for a relatively short period of time may be depicted by the two dimensional steady-state case. The second method involves the analysis of fringe pattern points on the closed boundary of the ROI (e.g. bounded by lines) and calculating the temperature at points inside the region by solving the Laplace equation:

$$\nabla^2 T = 0$$  \hspace{1cm} (1)

The equation may be solved by any computer-based numerical method. The second method is preferable due to its low sensitivity to the fringe pattern quality.

3. Experimental Rig

Figure 2 shows a schematic of the experimental rig used to test our developed method. A beam from a laser (1) passed through a beam expander (2) and a cubic beam splitter (3), strikes an interferometer, which comprised an optical wedge (4) and a cutting tool (5) with a polished side surface (6), rigidly fastened relative to one another by a tool holder (7). After interference of the reference and measurement beams, the resulting beam reflected on the beam splitter’s diagonal surface was directed to a high-speed camera (8) lens. The interference fringe patterns recorded by the camera were saved on a computer (9).

The experimental rig was mounted on a conventional lathe with an adjustable speed spindle drive (figure 3). On the cross slide of the lathe, the base table with the tool holder (1) was placed with two
aluminum rails fixed on it. A single-frequency DPSS laser (2)(LCM-S-111 (λ=532 nm)), the beam expander (3), and the rotation stage with a cubic beam splitter (4) were mounted on one rail. The second rail carried the high-speed camera (5)(Fastec HiSpec 2-HR with zoom lens (6) NAVITAR Zoom 6000). Every optical element had an antireflective coating.

![Figure 2. Schematic of experimental rig.](image)

![Figure 3. View of experimental rig.](image)

4. Experiment conditions
To confirm the efficiency of this method, we tested it with the following machining parameters: the workpiece was a 4.2-mm thick disc composed of difficult-to-cut martensitic heat-treated steel grade X13Cr11Ni2W2MoV [14], the chemical composition of which is presented in table 1. This steel is used for the production of turbine disks and blades. The steel hardness was HB 277.

![Table 1. Chemical composition of steel grade X13Cr11Ni2W2MoV.](image)

The cutting tool was composed of grade VK8 [15] cemented tungsten carbide, with 8% cobalt content by weight, and had a 0° rake angle, 8° clearance angle, and 4.6-mm width. Cutting speed $V$ and feed rate $S$ were 6 m/min and 0.14 mm/rev respectively.

5. Results and Discussion
Figure 4 shows the interference fringe patterns for a cold tool (a) with $T_0=20^\circ C$, and a heated tool (b) right after the interruption of the cutting process.
Figure 4. Interference fringe patterns for cold (a) and heated (b) tool.

To obtain the fringe order distribution plot, we generated interference pattern profiles along the rake and the clearance faces in ImageJ, and then found maxima of image intensity for the cold and heated tools. Every maximum was numbered relative to a randomly selected fringe, which had a position on both patterns that could be recognized accurately. The most convenient position for this purpose was the farthest from the heating zone fringe. The plot shows the number of profile maxima (fringe order) and their positions relative to the cutting edge. To obtain values for tool expansion caused by heating, the plots for the warm and cold tools have to be subtracted. Figure 5 shows fringe order distributions along the rake (a) and clearance (b) faces for heated and cold tools and their difference.

Figure 5. Fringe order $m$ distributions along the rake (a) and clearance (b) faces with respect to the distance $R$ from the cutting edge.

To convert fringe order distribution to temperature distribution, the CTE of the tool material [16] was used. Figure 6 shows temperature distributions along the rake (a) and clearance (b) faces. Plotting and mathematical processing was performed using MS Excel. Figure 7 shows the temperature field, which was obtained by solving the Laplace equation (1) in Cartesian coordinates via the finite difference method, computed by a specially-created program in Turbo Basic. $C$ and $C_1$ on the figure show the length of the tool in contact with the chip and the workpiece respectively.

6. Conclusion

We developed an experimental method for measuring temperature fields, which involves recording the cutting tool thermal expansion fields by laser interferometry and calculating the tool material temperatures with its CTE.

Compared to the methods employing infrared thermometry, the method developed in this study demonstrates a higher spatial resolution and a lower achievable field of view due to its use of light in the visible region. Moreover, by utilizing cheaper optical components and equipment for interference fringe pattern registration, this method is more economical.
Furthermore, since the oxidation film has a higher reflection coefficient for visible light, the proposed method is less sensitive to the thin-film interference on an oxidized tool surface than methods that employ infrared thermometry; this eliminates the false shift of the measured temperature.

Unlike the emissivity coefficient in infrared thermometry, the CTE is unaffected by changes in the surface quality and can be measured with high accuracy by modern dilatometry. Therefore, the developed method, which employs CTE to calculate the temperature, is more reliable.

References

[1] Komanduri R and Hou Z B 2001 Int. J. Mech. Sci. 43 89–107
[2] Abukhshim N A, Mativenga P T and Sheikh M A 2005 Int. J. Mach. Tool. Manu. 46 782-800
[3] Klocke F, Brockmann M, Gierlings S and Veselovac D 2015 Mech. Sci. 6 89-94
[4] Komanduri R and Hou Z B 2001 Tribol. Int. 34 653–82
[5] Davies M A, Ueda T, M’Saoubi R, Mullany B and Cooke A L 2007 CIRP Ann.-Manuf. Techn. 56 581-604
[6] Astakhov V P 1998 Metal Cutting Mechanics (Boca Raton: CRC Press) p 320
[7] Trent E M and Paul K W 2000 Metal cutting 4th ed. (Boston: Butterworth-Heinemann) p 464
[8] Longbottom J M and Lanham J D 2005 Aircr. Eng. Aerosp. Tec. 77 122-30
[9] Pujana J, del Campo L, Pérez-Sáez R B, Tello M J, Gallego I and Arrazola P J 2007 Meas. Sci. Technol. 18 3409
[10] Daniels A 2018 Field Guide to Infrared Systems, Detectors, and FPAs 3rd ed. (Bellingham: SPIE Press) p 170
[11] Efimovich I A, Zolotukhin I S and Shvetsova E I 2010 RF Patent Specification 2442967
[12] Efimovich I A 2010 RF Patent Specification 2423663
[13] James J D, Spittle J A, Brown S G R and Evans R W 2001 Meas. Sci. Technol. 12 R1–R15
[14] Russian Federation State Standard 1997 GOST 5632–72
[15] Russian Federation State Standard 1998 GOST 3882–74
[16] Efimovich I A, Zolotukhin I S and Zav’yalov E S 2019 Obrabotka metallov 21 129–40