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RESEARCH PAPER

A Novel Approach to Measure the Chip Formation Temperature Using the Implanted Thermocouple Method

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Abstract

Simultaneous measurement of the temperature in different regions during machining operations presents many limitations. Currently, only orthogonal cutting using a infrared camera allows the simultaneous measurement of temperature in different regions. Additionally, temperature measurement in certain regions is a challenge, for instance, in the chip/tool interface and inside the chip. The application of advanced sensors and the adaptation of well-established techniques in regions of difficult access, such as the chip-tool interface and the chip itself, have been the subject of research to allow the better understanding of the heat generation and temperature evolution during machining operations. This work investigates the application of the inserted thermocouple method to measure the temperature inside the chip during its formation, together with the tool-workpiece thermocouple method to compare the effect of the cutting parameters on both the chip-tool interface and chip temperature. Orthogonal cutting of AISI 1020 steel was performed using cemented tungsten carbide bits. The findings indicated that both methods were able to assess the influence of the investigated parameters and that temperature presented the same behavior, in spite of the differences in absolute values (higher temperatures were recorded using the tool-workpiece thermocouple). Temperature increased with cutting speed, decreased with the elevation of the undeformed chip thickness and was not affected by width of cut. The highest temperature (668 °C) was observed at the tool-workpiece interface using a cutting speed of 120 m/min, undeformed chip thickness of 0.1 mm and width of cut of 1.5 mm.

Keywords Implanted thermocouple · Tool-workpiece thermocouple · Chip temperature · Orthogonal cutting

Introduction

Temperature measurement methods applied to machining processes present several restrictions depending on the specific operation and region where the temperature must be measured. Therefore, there is no consensus on the choice of the best method and numerical approaches are often required to provide a more comprehensive view of the temperature distribution. Regardless of the measurement method used, it is essential to understand the heat distribution and the temperature evolution in the tool, workpiece and chip. This aspect plays a key role for improving the quality of the machined component, increasing tool life and reducing costs.

Metal cutting promotes in high strain rates, which lead to a significant increase in heat generation in the cutting region. In addition to that, plastic deformation in the primary and secondary shear zones together with friction at the chip-tool interface produce a considerable temperature increase, which negatively affects tool wear [1]. The damage caused by the conversion of electric energy into heat during cutting is a critical factor that restricts the production rate, as it drastically affects both the performance of the cutting tool and the surface integrity of the workpiece [2]. Thus, the accurate measurement and analysis of the cutting temperature allows

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estimating possible subsurface alterations in the machined component, including the residual stress profile [3].

One factor that affects the thermal behavior of the cutting tool is the presence of coatings. According to Jawahir and Van Luttervelt [4], the amount of energy transferred to the chip depends on the thermal conductivity of the tool coating. Moreover, Abukhshim et al. [5] state that the behavior of the material at the chip-tool interface is greatly influenced by heat generation and the temperature gradient in the cutting tool.

Nevertheless, the experimental determination of the maximum temperature at the tool-chip interface is a major challenge. Figueiredo et al. [6] presents a survey on the different methods employed to measure cutting temperature with their advantages and drawbacks and according to Da Silva and Wallbank [7], the practical limitations associated with the experimental methods used to determine the temperature distribution at the chip-tool interface result in obtaining the average temperature at the interface. Consequently, several authors continue to dedicate efforts to remedy the difficulties in experimentally measuring the temperature in machining.

Coelho et al. [8] found that even with an increase in cutting speed and the consequent increase in heat flux, the temperature in milling does not follow the same trend due to the reduced contact time between the tool and workpiece. A study on the temperature distribution in AISI 4340 steel conducted by Huang [9] showed that due to the continuous nature of the chip, most of the energy is converted into heat. Moreover, friction between the chip and the rake face of the tool also contributes to the temperature elevation. The use of an infrared camera provided satisfactory results in orthogonal cutting, however, this method is not applicable to measure the tool-chip interface temperature in oblique cutting or when using a cutting fluid.

The use of standard thermocouples for the measurement of temperature in machining is one of the most traditional and efficient methods owing to the possibility of performing direct temperature measurements at different regions during the operation. In addition to the low cost of standard thermocouples, Samy and Kumaran [10] state that the sensor ability to provide continuous data is a positive effect. When combined with numerical modelling and simulation methods, the implanted thermocouple can promote a substantial advance in the knowledge in this particular field.

Li et al. [11] investigated the temperature distribution when machining a titanium alloy with coated carbide inserts using thin K-type thermocouples inserted 0.1 mm below the rake face of the cutting tool. One thermocouple was located 400 µm from the cutting edge and other five at distances ranging between 200 and 300 µm from the cutting edge. This configuration was devised to measure the temperature below the rake face at distinct distances from the cutting edge and to assess the influence of the depth of cut. The results indicated temperatures ranging from 90 to 210 °C considering the thermocouples farthest and nearest the cutting edge, respectively.

Lima et al. [2] compared the temperature measured with the tool-workpiece thermocouple and embedded thermocouple methods with finite element model (FEM) simulations. The findings indicated that the tool-workpiece thermocouple and FEM methods presented consistent and converging results. Sorrentino et al. [12] measured the temperature while drilling a fiber reinforced polymeric composite using a thermocouple inserted into the cooling channel up to the clearance face of the drill and another thermocouple attached to the rake face, near the cutting edge. They noticed that temperature increased with cutting speed, though following a smoother trend in comparison with cutting of metals. Uçak and Çiçek [13] implanted several thermocouples in an Inconel 718 workpiece to measure the temperature evolution during drilling under flooding, cryogenic cooling and dry cutting. The thermocouples were implanted perpendicularly to the drill rotation axis at a distance of 0.1 mm from the hole wall. Temperatures below 0 °C were recorded when drilling using cryogenic cooling under certain cutting conditions.

Arrazola et al. [14] state that the chip-tool interface temperature is higher when measured by the tool-workpiece thermocouple in comparison with the temperature measured by infrared thermography when machining steels, however, in the case of titanium alloys, both methods provide similar results. Such behavior can be explained by the differences in the thermal diffusivity of the materials. Heigel et al. [15] and Saez-de-Buruaga et al. [16] also used infrared thermography coupled to FEM to determine the temperature in the chip-tool interface, however, while the former authors found quite satisfactory results, the latter noticed a difference of up to 21% in the temperatures at the border of the chips.

Werschmoeller and Li [17] used a thin film thermocouple to measure the temperature on the rake face of a PCBN tool and observed that this technique presents satisfactory linearity and sensitivity, together with very short response time. Saelzer et al. [18] employed a two-color fiber pyrometer to measure the temperature on the rake face of the tool and noticed that the texture of the rake face affects the temperature in the chip-tool interface. Storchak et al. [19] also used an infrared pyrometer to measure the temperature on the rake and clearance faces together with FEM and noted that the temperature on the clearance face is affected by cutting speed.

Experimental methods are quite useful, either for directly obtaining the temperature of interest, or for feeding analytical/numerical models. Young and Chou [20] developed an analytical model to determine the temperature distribution at the chip-tool interface and reported a large temperature gradient along the flow zone. Korkut et al. [21] measured the chip temperature employing using an inserted thermocouple and found that it increases with the elevation of cutting speed, feed rate and depth of cut.

Jaspers and Dautzenberg [22] investigated the behavior of the strain rate and temperature during orthogonal cutting and reported that cutting speed and feed rate present a marginal influence on the temperature of the primary shear zone. Cotterell et al. [23] compared the chip temperature obtained through experimental (infrared thermography) and bidimensional models and found a satisfactory agreement between the two approaches. Dhananchezian [24] carried out an experimental work to measure the chip temperature when machining Inconel 600 and found that the temperature increased slightly with cutting speed. Afrasiabi et al. [25] measured the temperature on the rake face of the tool and on the free surface of the chip using infrared thermography and an optical fiber sensor. Such approach was used to overcome the difficulties associated with the measurement of the temperature at the chip-tool interface. Yang et al. [26] analyzed temperature distribution models in grinding, while Yang et al. [27] studied the atomization mechanism of nano fluid aerosol refrigerants and also developed a method to measure the convective heat transfer coefficient.

Hamm et al. [28] proposed an innovative experimental approach to measure heat partition in orthogonal cutting of a titanium alloy. The novelty resides on the use of a miniaturized thermocouple to measure the temperature in the primary shear zone. The results showed that less than 15% of the total cutting power is transferred to the machined surface using a fresh tool and this amount decreases with the reduction of the rake angle.

The main goal of this work is to fill a gap concerned with the use of the implanted thermocouple and tool-workpiece thermocouple methods to measure the cutting temperature when machining with rotary tools. To achieve this goal, two novel approaches are proposed to experimentally measure the cutting temperature. The first approach consists on implanting a standard thermocouple in the region of the workpiece where the chip will be formed to measure the chip formation temperature and the second approach is a modification of the tool-workpiece thermocouple method to measure the temperature in orthogonal cutting with a rotary tool. In addition to that, the influence of the cutting parameters on the chip formation temperature is investigated.

Materials and Methods

AISI 1020 steel was selected as the work material owing to its elementary composition and to the fact that it has been extensively investigated. Orthogonal cutting tests were carried out in a machining center (power of 11 kW and maximum speed of 7500 rpm) in view of the configuration of the workpiece, designed in such manner that the cut occurs during half of a revolution. Thus, in the other half of the revolution, the tool is stopped and prepared for the next cut. Tungsten carbide bits ISO grade K30 with dimensions 10 × 10 × 50 mm, approach angle of 90°, rake angle of 5º and clearance angle of 6º were mounted on a tool holder adapted for orthogonal cutting. Figure 1 shows the experimental setup for temperature measurement using the tool-workpiece thermocouple.

In order to close the electric circuit between the rotary cutter and the workpiece, one end of a copper wire was attached to the cutter, while the other end was free and

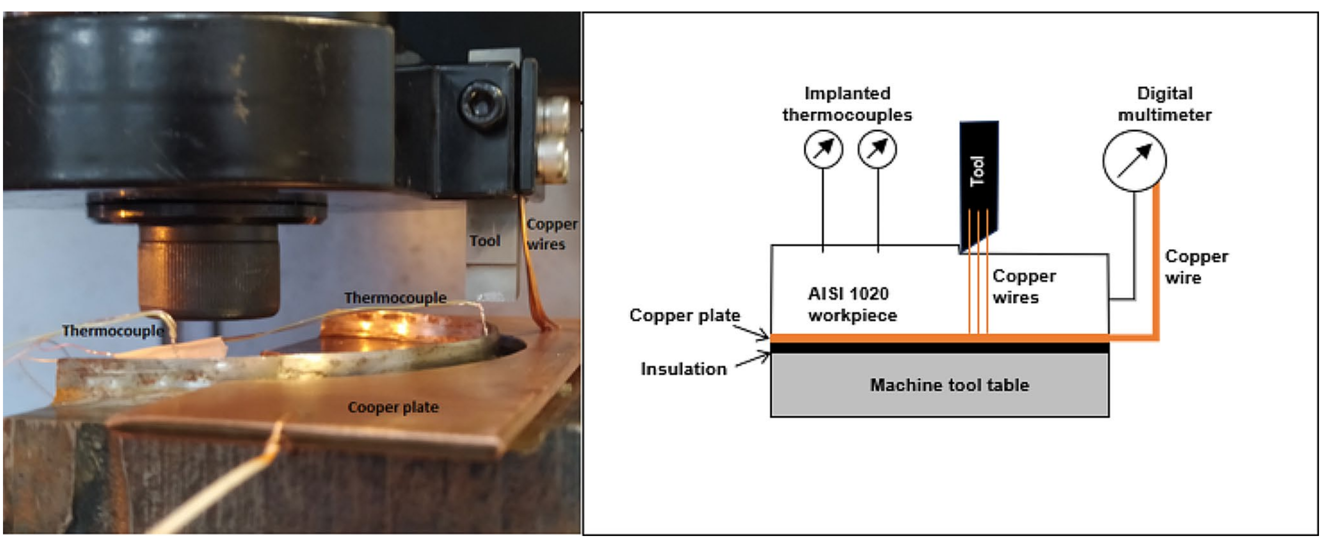


Fig. 1 Experimental setup for chip temperature measurement during orthogonal cutting

Table 1 Orthogonal cutting parameters

Cutting speed v_c (m/min)	Undeformed chip thickness h (mm)	Width of cut b (mm)
15	0.1	1.5–2.5
30	0.1–0.2–0.3	1.5
15–30– 60–120	0.1	1.5

touched a copper plate fixed on the workpiece (insulated from the machine tool table) during the cutting period, see Fig. 1.

For temperature measurement during chip formation, holes with a diameter of 0.3 mm and 0.5 mm deep were drilled for thermocouple implanting in the region which will become the chip. The thermocouples were attached to the bottom of the hole using a capacitor bank and an Instrutherm model FA-3050 power supply. Type K thermocouples (TFCY-005 Chromega wire and TFAL-005 Alomega wire) with a diameter of 0.127 mm were chosen for providing the required features and response times for orthogonal cutting. Thus, at the highest cutting speed (120 m/min), the operating time is 180 ms (acquisition rate of 14.3 Hz). Temperature and e.m.f data were recorded with a Keysight Technologies® model 34970 A acquisition system and Agilent BenchLink Data Logger Pro software. Table 1 presents the cutting parameters tested, where it can be seen that one factor was varied at a time.

Tool-Workpiece Thermocouple Calibration

Figure 3 shows the calibration procedure for the tool-workpiece thermocouple. A pointed rod made of the same material used as cutting tool (ISO grade K30 tungsten carbide) was attached to the milling shank and pressed against the workpiece. Copper wires were used to connect both the pointed rod and workpiece to the multimeter and the electric circuit was closed (the workpiece and rod were insulated

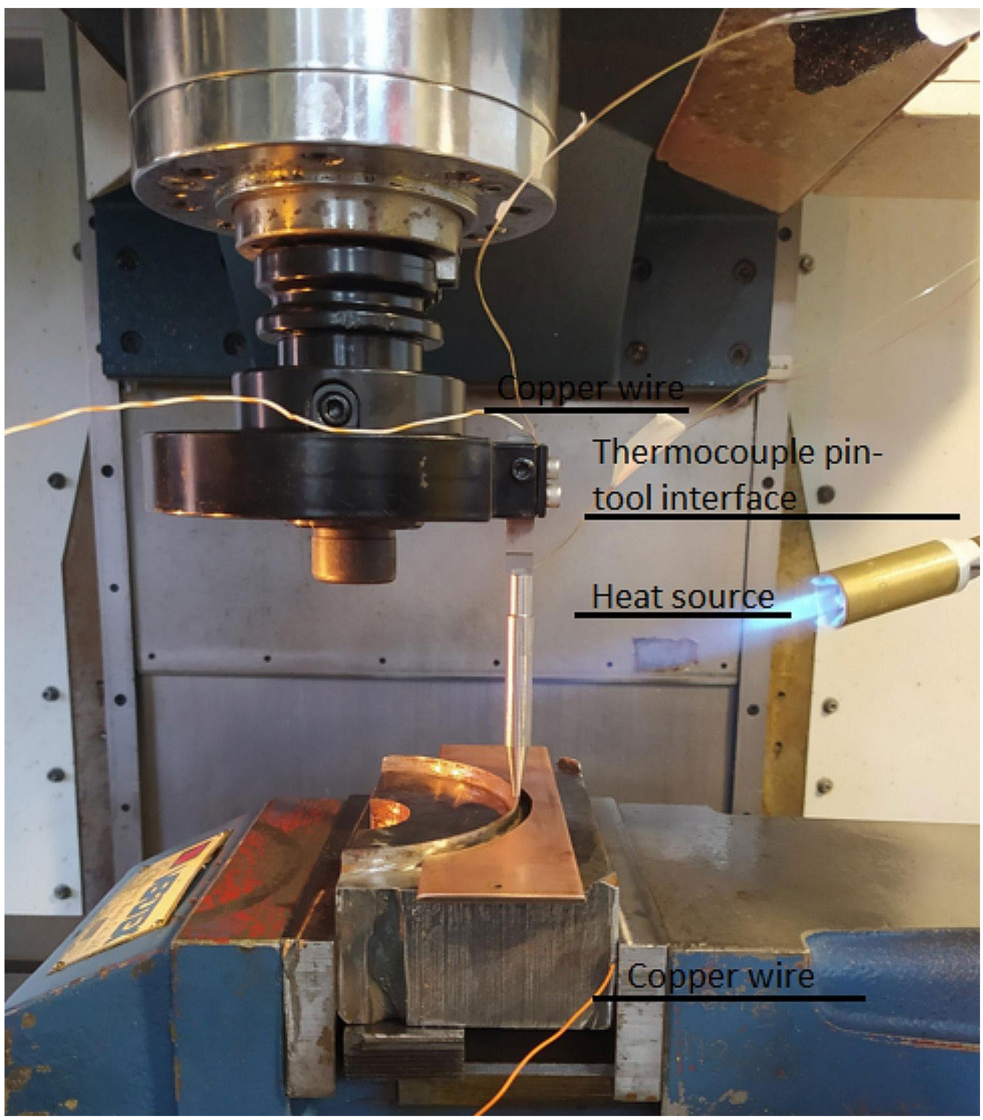


Fig. 2 Calibration setup for the tool-workpiece thermocouple

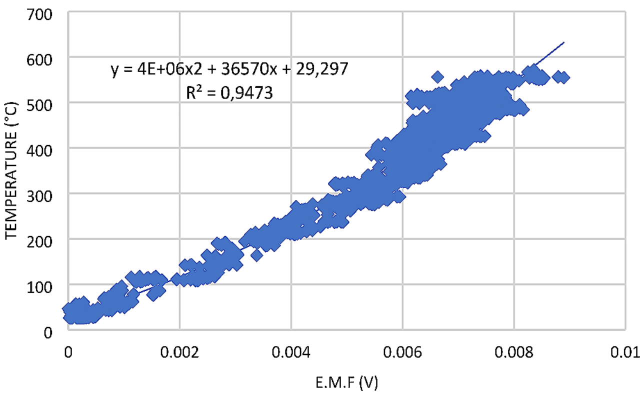


Fig. 3 Calibration curve for the tool-workpiece thermocouple

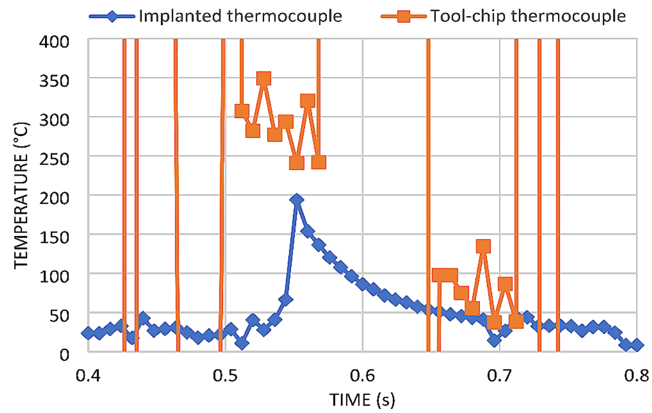


Fig. 5 Temperature evolution along cutting time for the implanted and tool-workpiece thermocouples for v_c = 15 m/min, h=0.1 mm and b=1.5 mm

from the machine tool using, respectively, electrical tape and epoxy paint). A type K thermocouple was employed to measure the temperature in the tool-workpiece interface and a welding torch was used as heat source, while the corresponding electromotive force (e.m.f.) was recorded by the multimeter.

Figure 3 presents the calibration curve for the tool-workpiece thermocouple and the corresponding quadratic regression for temperature (y) as a function of e.m.f. (x) with a coefficient of determination of 0.9473. It can be noted that the higher the temperature, the larger the scatter in the voltage values.

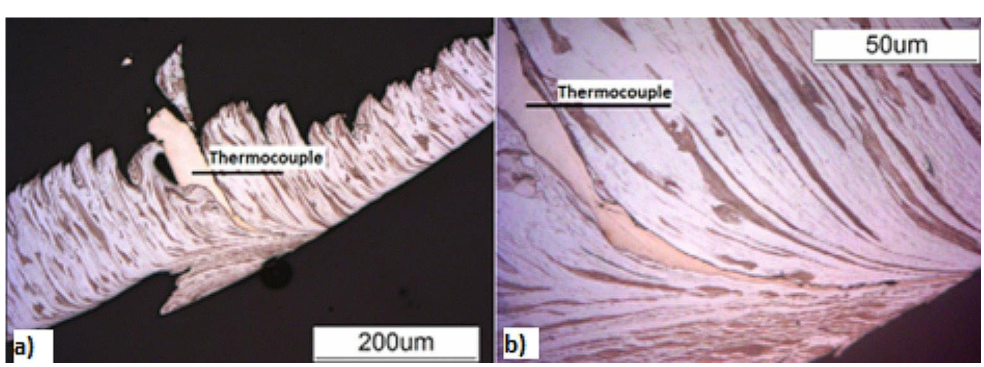
Results and Discussion

The micrograph presented in Fig. 4(a) shows the thermocouple wire implanted in a chip, together with the microstructure of AISI 1020 (ferrite and pearlite). The sample was etched with Nital at a concentration of 2%. Figure 4(b) shows that the thermocouple hot junction is extended throughout the entire thickness of the chip, reaching the chip-tool interface. However, despite being a positive result, one cannot assert that the hot junction reached the tool-chip interface, since it was probably sheared in the flow zone. Consequently, the recorded temperature is considered the average temperature at the primary shear plane.

Figure 5 presents the temperature as a function of time for both the implanted thermocouple and tool-workpiece thermocouple. Due to the fact that the cutting time is rather short (70 ms), only a few temperature values are recoded during the process. In the particular case of the implanted thermocouple, the chip reaches its maximum temperature (195 °C) almost instantaneously and loses heat to the environment a little more gradually, but still within a short period of time. The curve in Fig. 5 suggests an exponential cooling rate after the chip is formed. The set of results for the temperature measured by the chip-tool thermocouple method showed on the left gives an average temperature of 300 °C. This can be the average temperature at the chip-tool interface. The set of data obtained with the chip-tool thermocouple showed on the right represents the temperature when the tool is sliding against the machined surface without cutting. This temperature is associated with the heat generated in the tertiary shear zone, or the contact between the tool flank face and workpiece and can be used to help estimating the heat generated in this zone. Hamm et al. [28] measured the chip temperature with a method similar to that used in this work and found an identical behavior of the chip temperature.

Figure 6 shows the effect of the cutting speed on the temperature at the tool-workpiece interface and in the chip. As

Fig. 4 (**a**) Micrograph of the AISI 1020 chip with implanted thermocouple and (**b**) detail of (**a**), v_c = 30 m/min, h=0.1 mm and b = 1.5 mm



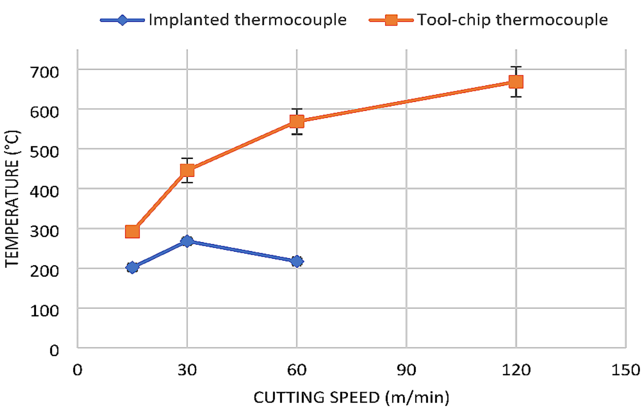


Fig. 6 Effect of the cutting speed on the temperature measured using the tool-workpiece thermocouple and the implanted thermocouple

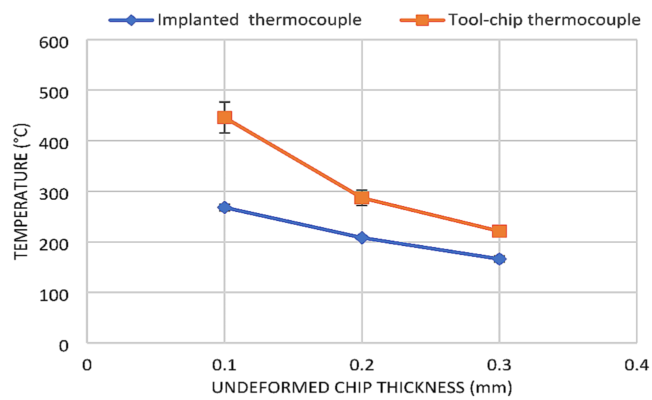


Fig. 7 Effect of the undeformed chip thickness on the temperature measured using the tool-workpiece thermocouple and the implanted thermocouple

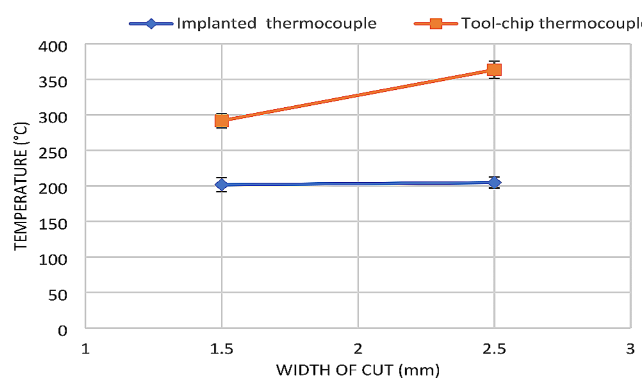


Fig. 8 Effect of the width of cut on the temperature measured using the tool-workpiece thermocouple and the implanted thermocouple

expected, the temperature in the tool-chip interface increases with cutting speed because more heat is being generated at the chip tool interface. Nevertheless, the temperature inside the chip does not follow the same trend because it is associated with the heat generated in the primary shear zone. Unfortunately, it was not possible to measure the temperature of the chip at a cutting speed of 120 m/min due to the difficulty to keep the thermocouple implanted during the chip formation process. The results suggest that cutting speed possesses a negligible influence on the temperature in the workpiece for cutting speeds below 60 m/min. When the thermocouple deforms (reaches the primary shear plane), the average temperature in a larger zone is recorded. As the cutting speed increases, the time available to measure this temperature decreases and the response time of the thermocouple has a great effect on the result. It can be noted that the higher the cutting speed, the larger the difference between the temperatures measured using both methods.

According to Stephenson [29], the tool work thermocouple measures the average thermo-electric e.m.f. at the interface between the tool and the chip. Based on the calibration curve shown in Fig. 3, the e.m.f. represents the average temperature, as the thermo-electric e.m.f. varies linearly with temperature [7].

Abouridouane et al. [30] measured the interface temperature in orthogonal cutting of AISI 1045 steel using thermography and recorded a maximum temperature of 600 °C for a cutting speed of 150 m/min, undeformed chip thickness of 0.5 mm and width of cut of 3.5 mm. Saelzer et al. [18] used a two-color pyrometer to measure the temperature in the chip and on the tool rake surface. For the experimental procedure, AISI 1045 steel was machined at a cutting speed of 60 m/min. Temperatures of approximately 310 and 500 °C were obtained in the chip and on tool, respectively. In the above-mentioned works, the cutting conditions were close to those employed in the present work, thus validating of the proposed approaches.

The influence of the undeformed chip thickness on the temperature measured employing both methods is given in Fig. 7. Despite the differences in terms of absolute values, the same trend showing a reduction in temperature with the elevation of the undeformed chip thickness can be seen in both cases. As the undeformed chip thickness increased from 0.1 to 0.2 and to 0.3 mm, the differences between the two methods were, respectively, 178, 79 and 55 °C. This reduction in temperature is associated with the fact that the heat generated is distributed over a larger area, decreasing the maximum temperature in the tool and in the chip. The steep decrease in the temperature measured by the tool-workpiece thermocouple (225 °C when h was elevated from 0.1 to 0.3 mm) shows how sensitive this method is to changes in the contact area between the tool and workpiece.

The result for the effect of feed rate on the temperature at the chip tool interface is different from the effect of cutting speed. This result can be explained by the presence of the built-up edge (BUE). If BUE is formed, it increases with feed rate and the secondary shear plane will be shifted from the rake face. The size effect means that the specific cutting energy required to remove material increases as the chip size decreases, as shown by [31]. This increase can be the responsible to the higher temperatures at lower undeformed chip thickness.

Saelzer et al. [18] and Korkut et al. [21] evaluated the influence of the cutting speed and undeformed chip thickness on the chip temperature. The former authors noticed that the chip temperature was not subjected to significant changes as the investigated parameters were altered, whereas latter showed that chip temperature was not affected by cutting speed, but increased with the elevation of the undeformed chip thickness.

The width of cut presents a marginal influence on the tool-chip interface temperature and does not seem to affect the temperature of the chip within the investigated range, as shown in Fig. 8. Korkut et al. [21] assessed the influence of the width of cut on the temperature measured in the chip and reported that this influence increase with feed rate. They found a temperature of approximately 180 °C with a cutting speed of 50 m/min, feed rate of 0.1 mm/rev and a width of cut 2 mm. These results converge with those shown in Fig. 8. As the width increases the heat generation also increases, but the area and volume to dissipate the heat also increase. Additionally, it is difficult to state that the width of cut statically affects the temperature measured by the tool-chip thermocouple. For a width of 1.5 mm, the temperature is close to 300ºC, while for 2.5 mm it is close to 360ºC. The repeatability associated to the method is estimated to be 25 ºC.

Conclusion

In this work, two techniques were employed to measure the temperature during orthogonal cutting of AISI 1020 steel: the implanted thermocouple method was used to record the chip formation temperature and the tool-workpiece thermocouple was used to measure the temperature at tool-chip interface.

Implanting the thermocouple into the cutting region was effective and the chip images show that the thermocouple hot junction was present throughout the entire thickness of the chip. Despite the limitations that the acquisition system and the thermocouple diameter imposed on the data acquisition rate, it was possible to obtain the maximum temperature and the chip cooling profile.

When comparing the results of the implanted thermocouple and the tool-workpiece thermocouple with the published literature, it is possible to state that the adaptation of the inserted thermocouple technique for measuring the temperature of the chip was effective and the temperature behavior was consistent.

Concerning the results themselves, the behavior of the chip temperature curve a steep elevation through the primary shear zone, but the following temperature reduction is gradual over time. At the chip-tool interface, it is possible to observe the temperature behavior during chip formation and sliding (friction between the tool flank face and workpiece) in the second half of the revolution of the tool.

Considering the implanted thermocouple method, the chip temperature is not directly influenced by cutting speed within the studied range, the same can be said of the width of cut. However, the undeformed chip thickness presents an inverse influence on the chip temperature, i.e., the larger the undeformed thickness, the lower the temperature. The temperature at the tool-chip interface increased with cutting speed, however, it decreased with the increase in the undeformed chip thickness and this result was not expected. Nevertheless, it can be explained by the formation of a built-up-edge and the consequent increase in the distance between the thermocouple hot junction and the primary shear zone.

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Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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