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Research Paper

Determining tool/chip temperatures from thermography measurements in metal cutting

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HIGHLIGHTS

- Calculated tool/chip temperatures up to 75% greater than measurements in tool side.
- Calculation of tool/chip temperatures reliable to discern the influence of material.
- Tool/chip temperatures are reliable to analyse the influence of cutting conditions.
- Tool/chip temperatures in ferrite-pearlite grades are linked to perlite content.
- Deviation less than 12% between FEM and calculated tool/chip temperatures.

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ABSTRACT

Temperature measurement in metal cutting is of central importance as tool wear and surface integrity have been demonstrated to be temperature dependent. In this context, infrared thermography is presented as a reliable technique to determine tool temperatures and thermal fields at near real-time. However, a constraint of this technique is that temperatures are measured on the tool side faces normal to the cutting edge but offset from the tool/chip contact. In the present research, tool/chip contact temperatures were calculated from the tool side based on analytical theories of heating and the principles of heat generation in cutting processes. The required inputs were commonly measurable variables (cutting and feed forces, chip thickness and tool/chip contact length). The proposed approach was combined with a new calibration method in which a calibration curve that directly relates real and radiated temperatures is obtained, instead of measuring the emissivity of the radiating surface.

As a case study, the research was conducted on a set of four ferrite-pearlite steels (16MnCr5, 27MnCr, C45 and C60). The results demonstrated the effectiveness of the method to establish the real influence of the cutting conditions (cutting speed and feed) and to distinguish the effect that different work material microstructures have in tool/chip temperature. Furthermore, the results showed a high degree of accuracy and less than 12% deviation from the trends when compared with 2D cutting simulations.

1. Introduction

The experimental investigation of heat generation occurring in metal cutting has received much attention in recent decades [1], as it is well established that tool-chip interface temperatures have significant influence on machining performance. Problems such as tool wear are commonly linked to activation temperatures above which diffusive mechanisms cause exponential reduction of tool life [2]. Even the surface integrity of machined components is affected by the temperatures reached during processing [3]. Basically, these cutting temperatures are an indirect measurement of heat produced due to the high plastic deformation of the material, and tool/chip and tool/workpiece friction [4].

Temperature measurement techniques can be mostly divided into direct and indirect methods. Indirect techniques have the drawback of only giving post-process information of the maximum temperatures reached during cutting [5,6]. The most extensively used direct method is the tool/work thermocouple. However, it has limited transient response, does not effectively obtain accurate temperature gradients and interferes with heat flow [7,8].

Another direct method is infrared thermography (IR), which has become a matured and widely accepted condition monitoring tool

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where the temperature is measured in a non-contact manner [9]. This non intrusive technology has the benefit of not interfering with heat flow as other methods such as thermocouples do, and also enables the direct determination of temperature fields in near real-time. However, it has some drawbacks such as difficulties in measuring temperatures when the presence of dust or water vapor is found in the environment, as these absorb the emitted radiation of the object. In fact, due to the difficulty of using IR techniques for measuring temperature with lubricants [10], dry orthogonal cutting is the only choice considered in nearly all research works. Another drawback is the establishment of an appropriate methodology to obtain accurate measurements [11,12], and the cost of the equipment.

The accuracy of all known infrared techniques depends on the calibration technique employed, which essentially is linked to the estimation of the emissivity [13]. The emissivity of an object depends on factors such as temperature, measuring angle, geometry of the surface and constitution of the surface (polished, oxidized, rough, sandblasted). Therefore, this is commonly the major uncertainty source [12] in IR measurements. To solve this problem, researchers have developed calibration methods in which real temperature values from camera response are directly obtained without the need for emissivity correction [14].

Most research works focus their analysis on the measurement of tool temperatures, although researchers have also attempted to measure those of the chip/workpiece [15]. However, the curl occurring in the chip and the swelling of the chip and workpiece as a consequence of thermal expansion, leads to a lack of control of the topology of the measured surface. Thus, measuring radiation on non-flat surfaces may lead to considerable uncertainties on given temperatures.

When focusing on tool temperature measurements, the major challenge is to estimate those occurring in the tool/chip or tool/workpiece contact area. During cutting, the chip obstructs a clear view of the tool, which is reported as one of the principal disadvantages of IR techniques to measure tool/chip interface temperatures [16,17]. In order to prevent this problem three alternatives can be found in the literature, (i) modify tools by drilling holes to allow partial vision of the tool-chip interface [18], (ii) place the camera orthogonally to the chip flow, allowing the measurement of the temperature on a side face of the tool [19,20] or (iii) use transparent tools [21,22]. Although the knowledge acquired in these studies is valuable, the fact that the materials and geometry of the tools employed do not correspond to those of real cutting operations, may lead to significant changes in the thermal fields.

Another option is that published by [23], who developed a methodology to directly record rake face temperatures when orthogonal cutting a Ti-alloy and AISI 4140 steel. However, as reported by [14], the observed tool temperatures did not correspond exactly to those that occur during the cutting operation, as cooling occurs when the chip moves away and the rake face becomes visible. The authors thus assumed that temperatures during the cut would be at least 150–200 °C greater than those measured, and the location of the measured maximum temperature might not correspond with the real location when cutting.

The researchers of [24] proposed an alternative to calculate tool/chip contact temperatures from measured tool side temperatures, in which the camera was placed orthogonally to the chip flow. Based on classical theories of heating, they developed an equation to calculate the temperature increase depending on the distance from the contact to the tool side (overhang distance). The authors demonstrated the technical feasibility of the developed methodology, as the temperature rises corresponded to previously developed tests of their own property. However, in spite of the reliability of the results, the main inputs required for the calculations such as the heat flux produced by friction effects or even the heat partition between tool and workpiece were roughly estimated.

Taking into account that the studies in the literature still have certain weaknesses, a new approach was developed in this research for the establishment of tool/chip contact temperatures. The first step was to experimentally measure IR temperatures in the tool side, following the studies of [11], as the direct measurement of the temperatures on the rake face presented some uncertainties due to cooling/quenching effects. The real tool side temperatures were obtained from radiation temperatures based on the method proposed by [14]. In this method, a calibration curve that relates real and radiated temperatures is obtained, which eliminates the need for calculating the emissivity of the radiating surface.

The main innovation of the present research occurs in the second step. In this step, tool side temperatures are transferred to those of the tool/chip contact, combining the theory proposed by [24] with the shear plane model of [25] for the calculation of heat fluxes generated when cutting.

The study was conducted on four different ferrite-pearlite steels: 16MnCr5, 27MnCr5, C45 and C60. These work materials were selected to cover a wide range of microstructure variants of commonly employed steels in the development of automotive products such as camshafts, gear wheels and pinions. In the manufacturing route of these components, machining processes such as turning, broaching and drilling are commonly employed operations. The goal was to determine to what extent the improvement of the methodology proposed in this paper distinguished the influence of microstructure in the tool/chip contact temperature.

The contribution of the proposed methodology is that it determines the real influence of cutting conditions on cutting temperatures, which then permit a reliable comparison between all the tested steels. In addition, the accuracy of the method was also compared with a set of 2D cutting simulations, where calculated and simulated tool/chip contact temperatures obtained a low degree of deviation and the same trends.

This article is structured as follows: first the description of the materials, the experimental and calibration procedures and the analytical theories to transfer tool side to tool/chip contact temperatures is presented in the methodology section. Then, the main results are presented, in which tool side and tool/chip contact temperatures are analyzed. In the next section, the compliance of the results with those of literature and simulations are discussed and finally, the main conclusions from the research work are presented.

2. Methodology

2.1. Workpiece materials

Four different ferrite-pearlite steel grades were selected to develop this research: 16MnCr5, 27MnCr5, C45 and C60. These were selected to cover a wide range of microstructure variants. All the grades were processed by isothermal annealing, in order to obtain a ferrite-pearlite structure as homogeneous as possible. The chemical composition of the different grades is summarized in Table 1.

Microstructure data and mechanical properties are given in Table 2. The ferritic and pearlitic grain sizes were qualitatively measured following the standard ASTM E112-13 by means of the intercept method. Tensile and hardness tests were carried out to determine the mechanical properties.

Table 1
Chemical composition of steel grades.

Grade	C	Si	Mn	S	P	Ni	Cr	Mo	Cu	Al
16MnCr5	0.19	0.17	1.23	0.028	0.016	0.19	1.03	0.07	0.17	0.020
27MnCr5	0.25	0.24	1.19	0.033	0.009	0.09	1.06	0.04	0.11	0.032
C45	0.45	0.33	0.78	0.025	0.014	0.09	0.12	0.02	0.11	0.007
C60	0.61	0.28	0.65	0.027	0.016	0.14	0.11	0.04	0.24	0.005