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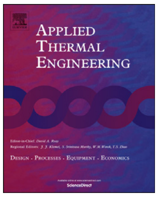

Extended infrared thermography applied to orthogonal cutting: Mechanical and thermal aspects

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HIGHLIGHTS

- An infrared thermography workbench is presented to investigate orthogonal cutting.
- A lot of mechanical and thermal data are acquired and processed.
- The reliability of usual assumptions is challenged through the experimental setup.
- A tool–chip contact length determination technique is tested.
- Global and local results are compared with previous works when possible.

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ABSTRACT

The temperature knowledge is essential to understand and model the phenomena involved in metal cutting. A global measured value can only provide a clue of the heat generation during the process; however the deep understanding of the thermal aspects of cutting requires temperature field measurement. This paper focuses on infrared thermography applied to orthogonal cutting and enlightens an original experimental setup. A lot of information were directly measured or post-processed. These were mainly focused on the geometrical or thermo mechanical aspects of chip formation, i.e. tool–chip contact length, chip thickness, primary shear angle, heat flux generated in the shear or friction zones, and tool–chip interface temperature distribution. This paper proposes an experimental setup and post-processing techniques enabling to provide numerous, fundamental and original information about the metal cutting process. Some comparisons between collected data and previous experimental or theoretical results were made.

1. Introduction

Heat generation in cutting was always a main topic studied in machining. The principal causes of heat generation during cutting are 1 – the plastic deformation in the different shear zones, 2 – the friction at the tool–chip interface and also at the tool–workpiece interface [1], Fig. 1. The generated temperatures have a significant influence on the friction conditions at the tool–chip and the tool–workpiece interfaces. Therefore, they have a consequence on the level of cutting forces. An increase of the workpiece temperature softens the material, thereby decreasing cutting forces and energy to cause further shear. The tool–chip contact temperature affects the seizure and the sliding conditions at this interface. They play an important role on the tool wear and then on the limitation of tool life. High temperatures at the tool–workpiece interface accelerate the flank wear mechanisms and promote plastic deformation on the machined surface. That leads to a significant thermal load of the subsurface which may induce phase transformation, generate surface alterations and produce high tensile residual stresses which have a negative effect on the machined parts fatigue life.

It is possible to estimate the heat generated if the temperature may be measured; however, such a measurement is difficult [2]. The shear zones are extremely narrow; the temperatures as well as the gradients may reach high values. The chip prevents a direct observation of the tool rake face; two different bodies, i.e. chip and

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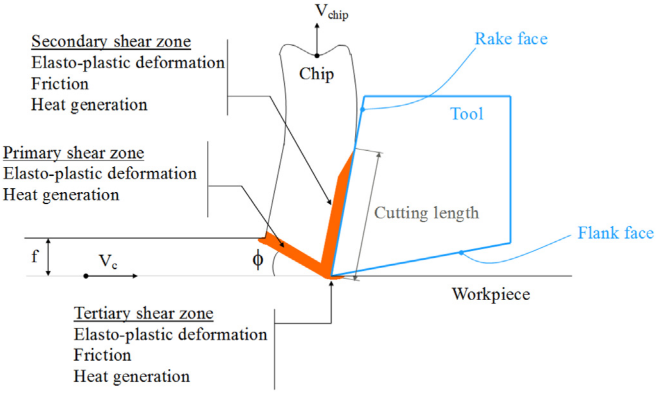

Fig. 1. Heat sources in the orthogonal cutting process.

tool, are in sliding contact in a continuous or intermittent way [2]. Several techniques have been developed during the last 80 years in order to measure the temperature in various machining processes. They mainly use thermocouples (the embedded, dynamic or the chip–tool thermocouples), pyrometers and infrared thermography cameras. Komanduri and Hou [3], Abukhshim et al. [2], and Davies et al. [4] reviewed previous works using these different measuring techniques. According to Abukhshim et al. [2], the infrared thermography appears to be the most suitable in high speed machining applications. Main advantages are a fast response, no adverse effects on measured temperatures, no physical contact, and allowing measurements on objects, such as chips, which are difficult to access. As pointed out, a special care has to be taken regarding the measurement position to avoid chip obstruction. In addition the surface emissivity or at least the relation between measured digital level and the temperature should be known to perform accurate temperature measurements [5]. The surface emissivity depends on the material composition and may vary with surface oxidation and roughness [6]. In the following, previous works using IR camera during different machining processes (orthogonal cutting, milling and drilling) are briefly presented.

Thermographic techniques were mainly used to measure temperature distribution during orthogonal cutting experiments [7]. Nevertheless, some researchers proposed measurement in complex machining operations such as milling [8] and even drilling [9].

Attention is here focused on the orthogonal cutting experiments. Young [10] used Infrared camera to measure the chip back temperature during orthogonal cutting of AISI 1045 steel. This author investigated the distribution of the temperature along the chip flow direction. Kwon et al. [11] investigated the rake face temperature distribution of the cutting tool inserts, after the feed was stopped; and an inverse estimation scheme was used to calculate temperature profiles. Usui et al. [12] examined the influence of tool flank wear on the whole temperature distribution within the cutting zone. Dinc et al. [13] used IR camera to measure the temperature distribution in the tool and valid prediction model.

Different cameras were employed. Some researchers used CCD cameras developed for the visible range, [13,14]. In comparison with the classical IR cameras, the cost of CCD cameras is lower but they only operate in the short wave infrared range; and they may only measure high temperatures. The proper measurement of the whole temperature range occurring in metal cutting needs a camera specifically developed for infrared observations [15].

This paper presents an experimental device using an IR camera and exposes an original experimental procedure for studying both the thermal and mechanical aspects of orthogonal cutting. It is thus shown how infrared thermography associated with the measurement of cutting forces can completely characterize an orthogonal cutting operation.

The measurements performed during the cutting tests, for various cutting conditions, were used to examine the validity of previous cutting models and provide the necessary elements for a new modeling approach, subject to further work. It is also shown that the device and the proposed procedure can be used to experimentally characterize the machinability of a material or the tool performance.

2. Experimental procedure

2.1. Experimental setup and IR camera

Orthogonal cutting tests of medium carbon steel AISI 1055 were carried out; Table 1 gives some of the main characteristics of the work material. The tool was a Sandvik Coromant TPUN 160308 coated carbide mounted on the tool holder TFPR 1603. The carbide grade was the referenced GC235 one, which heat capacity and thermal conductivity are given in Table 1. The values of rake angle and relief angle were, respectively, 6° and 5°.

The experimental samples involved a tubular part with an outer diameter of 58 mm. The samples were integrated into the tool holder of the machine spindle; orthogonal cutting conditions were obtained by removing the end of the tubular part of the samples with a tool attached, through a special fixture, to a dynamometric table Kistler 9257A fixed on the machine table (Fig. 2). Lateral view of the cutting process (in a plane perpendicular to the cutting edge) was recorded with an infrared camera. This camera was adapted into CNC machine through a special device screwed on the machine table. In order to obtain thermal maps of the cutting tool and the chip and to observe the tool–chip interface, the tool insert was ground in a plane normal to the cutting edge. With this experimental setup and during cutting tests, both forces and temperature fields were measured.

The IR camera used in the experiments was an FLIR SC7000 equipped with a G3 lens. With this equipment, the full screen frame rate was up to 100 Hz, the field of view was about 9.5 mm × 7.5 mm, and the array size was 640 × 512 pixels providing a spatial resolution of about 15 μm × 15 μm/pixel. The focal distance was very short (i.e. 30 mm) thereby the camera was placed very close to the observed cutting zone, Fig. 2. The temperature distribution commonly observed in metal cutting requires a large measuring range, i.e. from 0 °C to 1500 °C; then two configurations of the camera were used: the first one to measure the low temperature values from 0 °C to 300 °C, and the second one for higher temperature values from 300 °C to 1500 °C (this configuration consisted in the use of a spectral filter and with a 3.97–4.01 μm wavelength pass band filter at 60% transmission ratio). The Noise Equivalent Temperature Difference (NETD) was less than 25 mK for a black body at 25 °C.

Table 1
Material characteristics.

	AISI 1055	Tool
Young's modulus E (GPa)	210	
Yield stress (MPa)	370	
Tensile strength (MPa)	700	
Density (kg/m^3)	7850	11,100
Thermal conductivity k (W/m K)	55	37.7
Heat capacity c_p (J/kg K)	460	276
Hardness HV$_{30}$	200	