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Measurement and finite element simulation of micro-cutting temperatures of tool tip and workpiece

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ABSTRACT

Temperature generates in micro-scale cutting process has a great effect on cutting performance due to centralized heat generation. In this study, a set of micro-cutting experiments (8 μm/r ≤ f ≤ 50 μm/r) were carried out to measure temperatures in micro-cutting process with high accuracy. A fast-response thermocouple with a property of self-renewing was installed in a cylinder workpiece to measure the temperatures of workpiece and tool tip simultaneously. In each test, temperature of the workpiece surface is obtained just before the hot junction of thermocouple is machined. When the hot junction is machined, the tested maximum temperature is recognized as the temperature of tool tip. In parallel, an energy density-based ductile failure material model is developed to simulate the micro-cutting process by finite element method. In simulation, when mesh distribution is changed, the predicted forces with same energy density G_ε are closer to the forces at original mesh distribution than those predicted by same energy G_f. Consequently, the energy density-based ductile failure material model can reduce mesh dependence in different mesh distribution conditions. Under new mesh distribution, Temperatures of the workpiece surface and tool tip are identified in the predicted micro-cutting temperature field. The predicted micro-cutting temperatures of workpiece surface and tool tip are very close to the experimental results. Further, the variation of temperature and its relationship with chip curling are also discussed.

1. Introduction

In the past decade, the need for high-accuracy and miniaturized components in fields of aerospace, electronics, optics, biomedical, communication, and avionics has increased greatly. Developments in these fields have drawn the attention of many researchers to micro-machining processing and mechanism, including material properties, specific cutting energy and surface generation at the micron and sub-micron level [1–3]. Thermal field and temperature in metal cutting have been considered as the major factor that affects tool wear, surface integrity and machining precision [4]. In micro-cutting process, thermal field plays a key role in affecting machining performance because high temperature concentrates in a small area near the micro-cutter. The effect of heat generation needs to be concerned especially when high machining accuracy is required [5].

Measurement of cutting temperature in the area around tool-chip interface is technically difficult, especially for micro-cutting process. Accurate temperature measurement needs to be further developed [6]. For macro scale machining, many measurement techniques have been established in previous experimental works, including tool-work thermocouples [7,8], embedded thermocouples [9], single wire thermocouples [10], thin-film thermocouples [11,12], radiation pyrometers [13], infrared cameras [4], etc. These techniques have been reviewed by Davies et al. [14], Abukhshim et al. [15], Longbottom et al. [6] and Komanduri et al. [16]. According to their studies, these measurements have their advantages and limitations: (1) the tool-work thermocouple is a relatively simple method for measuring cutting temperatures. However, the measured value represents the mean temperature over the entire tool-work contact area, and the local temperature at a specific point on this interface cannot be measured; (2) the embedded thermocouples can accurately measure the temperature at a given point. However, the response time is limited due to their mass, and they normally cannot measure the tool-work contact area. (3) the single wire thermocouple method is proper to measure local high temperatures, such as the temperature of tool edge (or grinding wheel) in milling/grinding process, but the workpiece has to be partitioned to install the thermocouple wire using this method; (4) other non-intrusive/contact measuring methods are easily to obtain temperature without disturbing the heat distribution in cutting zone, however, infrared thermometer method cannot be used in coolant condition and infrared camera

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method is limited because the camera only see the workpiece end on [6]. To acquire cutting temperature of tool and workpiece with high accuracy, new measurements need further research. Due to the difficulty of temperature measurement in machining, very few measurements have been proposed to determine temperature in micro-machining, especially for measurement with high accuracy. Moriwaki et al. [17] applied copper-constantan thermocouples to measure the temperature rise of workpiece in orthogonal micro-machining; the measured temperature of test point that is far from cutting point was compared with simulation results by finite element (FE) model. Yang et al. [4] measured the cutting temperature near tool tip by an infrared thermal imaging system and investigated the tool edge effect on Al2024-T6 alloy micro-milling process. The dimension of critical heat generation zone near tool-chip interface is less than 200 μm in micro-machining [18,19]. Therefore, to acquire accurate temperature in micro-cutting edge, machined surface or subsurface, temperature measurements in micro-machining require higher precision and faster response than those in macro-machining.

To overcome the difficulty of temperature measurements, finite element method (FEM) has been widely used to investigate heat generation in cutting process. It is convenient to obtain the transient cutting temperature at given points by the thermal-mechanical FE analysis. Yang et al. [4] developed a three-dimensional micro-milling FE model to predict the effect of edge radius on milling temperature. Liu and Melkote [1] proposed a strain gradient plasticity based FE model to investigate the size effect in aluminum alloy micro-cutting process and found that temperature dependent flow stress can predict specific cutting energy more accurately than temperature independent model at a cutting speed of 200 m/min. Kim et al. [20] studied the stress and temperature distribution in micro-machining of OFHC copper by FEM. It is found that temperature has a great effect on flow stress, which will lead to the variation of predicted forces. Consequently, the temperature effect is very important for micro-machining process.

In this work, micro-cutting experiments were carried out to measure temperatures of the micro-cutter and workpiece by a fast-response and self-renewing thermocouple which was installed to a specific cylinder workpiece. In addition, an energy density-based ductile failure material model is proposed and applied in FE model to predict the micro-cutting temperature distribution. The measured temperatures are compared with the simulation results. Temperatures of tool tip and workpiece surface are analyzed according to experimental and simulation results.

2. Micro-cutting experimental procedure

2.1. Description of micro-cutting experimental setup

Micro-cutting experiments were performed on a vertical machining center NEXUS 410B –HS. Workpiece material is 2A12-T4 aluminum alloy, its component is similar with 2024-T351, as shown in Table 1. Cutting forces were monitored using a piezoelectric force dynamometer (Kistler 9257A) and a charge amplifier type 5070A. To measure cutting temperature, a fast-response thermocouple (NANMAC™, type E12) was installed to a specific cylinder workpiece (with 8 mm height, 4 mm thickness and 11 mm outer radius) as shown in Fig. 1. The output voltage of thermocouple was amplified by a signal conditioning extension (ESC-TC02) with cold junction compensation. The sampling frequency was set as 10 kHz. Both of cutting force and temperature were collected by a data acquisition device (NI-USB 6215). To conduct the force and temperature measurement, the milling tool holder and inserts are used to accomplish a turning process. In addition, two different tool inserts were installed in a revolving tool holder: one is the polycrystalline diamond (PCD) insert which was used as machining insert; another smaller one is installed to balance the machine tool system. Tool holder rotates with a constant speed and feeds along the symmetry axis of the cylinder specimen to accomplish the machining process.

To measure temperatures of tool tip and workpiece simultaneously, a specific fast-response thermocouple was applied in the experiments. The sensing tip (hot junction) is on the top of the thermocouple as shown in Fig. 1(a). Because the sensing tip is

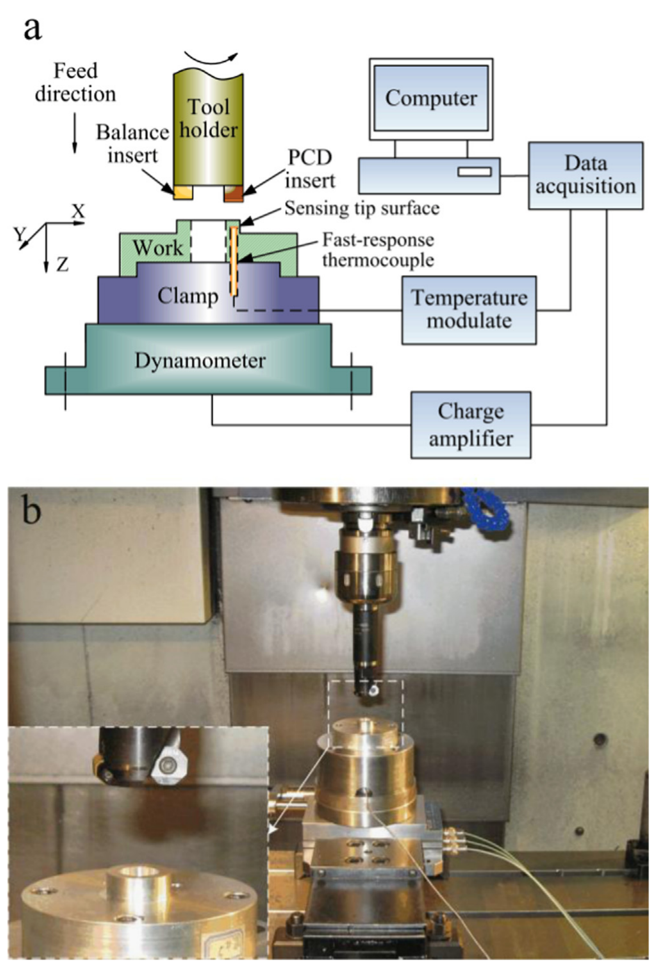

Fig. 1. Micro-cutting experimental setup (a) schematic diagram and (b) experimental photograph.

Table 1
Chemical composition of aluminum alloys 2A12 and 2024 (%) [21].

	Al	Cu	Mn	Mg	Si	Fe	Ni	Cr	Zn	Ti	Other	
											Individual	Total
2A12	Balance	3.8–4.9	0.3–0.9	1.2–1.8	0.50	0.50	0.10	–	0.30	0.15	0.05	0.10
2024	Balance	3.8–4.9	0.3–0.9	1.2–1.8	0.50	0.50	–	0.10	0.25	0.15	0.05	0.15