A Method for In-Process Cutting Force and Temperature Monitoring Using Cutting Tool Itself in Ultra-Precision Machining

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In-process monitoring of cutting force and temperature in micro-nano scale cutting zones of ultra-precision machining play an important role in evaluating machined surface quality and optimizing machining process. However, the traditional sensors for measuring cutting temperature and cutting force are discrete from the tool, making it challenging to meet the requirements of ultra-precision machining attributing to the low measurement accuracy, slow response time, and low spatial resolution. In this work, a high-spatial resolution, high-sensitivity smart tool system was developed, containing a cutting force measurement module for three-axis cutting force measurements and a boron-doped diamond tool functional of temperature sensing, thereby realizing the integration of ultra-precision machining and in-process monitoring. A solution for multi-channel measurement of pico-coulomb weak charge and microvolt weak voltage signals was proposed, to shorten the signal transmission chain and enable high-precision monitoring of cutting force and temperature. Subsequently, in-process monitoring of cutting force and temperature experiments were conducted during ultra-precision machining of acrylic glass, copper, and single-crystal silicon under various process parameters, in which the advancements of the smart tool setup was validated, compared with those of traditional cutting force and cutting temperature sensors. It is of significant importance for achieving high-consistency machining of large-scale and micro-structure functional surfaces.

1. Introduction

Ultra-precision cutting technology is a key approach to manufacture micro-structured or freeform surfaces, and it is widely used in fields such as aerospace, semiconductor manufacturing, nuclear engineering, and infrared detection[1]. The cutting process involves complex thermo-mechanical coupling[2], and the in-process monitoring of cutting force and temperature in the micro/nano-scale cutting zone plays a crucial role in assessing the surface quality and optimizing the machining process[3]. However, existing sensors for measuring cutting temperature and force, such as commercial dynamometers[4] and thin-film thermocouples[5], are almost always separate from the tool. Due to the certain distance between the measurement point of the sensor and the cutting point of the tool, the measurement sensitivity and accuracy are insufficient to meet the requirements for in-process monitoring of force and temperature in ultra-precision machining.

In our previous work, a piezoelectric three-dimensional force measurement mechanism[6] was proposed with a flexible hinge symmetrical layout, which achieved sub-milliNewton-level cutting force measurement for ultra-precision machining. However, this three-dimensional force measurement mechanism had limited interference resistance and required additional signal processing instruments, which restricted its application. In terms of temperature measurement, a novel cutting temperature measurement method based on functionalized temperature-sensing diamonds[7] was proposed, enabling cutting temperature measurement at the nano-scale for ultra-precision machining. The combination of these two methods makes synchronous in-process monitoring of cutting force and temperature in ultra-precision machining possible.

In this paper, based on the temperature-sensing diamond and the three-dimensional force measurement mechanism we developed, we present a smart tool system for ultra-precision machining processes with high spatial resolution and high sensitivity for simultaneous measurement of cutting temperature and force. A high-precision signal-acquisition module for pico-coulomb-level charge and micro-ampere-level voltage was proposed to ensure the performance of the tool system. Experiments were carried out to demonstrate its effectiveness in cutting force and temperature measurement for ultra-precision machining process.

2. Cutting Force and Temperature Measurement Tool System

The cutting force and temperature measurement tool system consists of four main components: a temperature-sensing diamond tool, a three-dimensional force measurement mechanism, a signal acquisition module, and a steel tool holder. Figure 1 shows the structure of the tool system. The temperature-sensing diamond tool is mounted at the front end of the three-dimensional force measurement mechanism. Output signals from the diamond tool and the force measurement mechanism's are connected to the signal acquisition module via fine silver wires, and all components are integrated into the tool holder.

As shown in Figure 1(a), the signal acquisition module comprises three parts: a signal pre-processing circuit, a signal acquisition circuit, and a power circuit. The power circuit supplies power to the signal acquisition module and provides a reference voltage. The entire circuit is powered by a 1300mAh lithium battery. The weak signals from the three-dimensional force measurement mechanism and the temperature-sensing diamond tool are converted and amplified by the signal pre-processing circuit, then connected to the signal acquisition circuit. After being converted into digital signals by the analog-to-digital conversion circuit, these signals are received by the STM32 processor and transmitted to the PC via RS485. The maximum sampling frequency of the circuit module was 5 kHz. Compared to traditional external charge amplifiers, this integrated module significantly shortens the path from the sensor to the amplifier from approximately 1m to about 0.04m, reducing environmental interference and improving data accuracy.

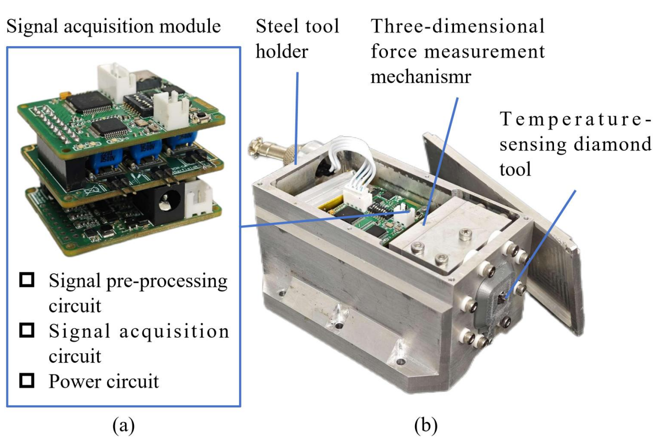

Fig. 1 Structure of the Cutting Force and Temperature Measurement Tool System

The signal pre-processing circuit is the core of the entire signal acquisition module and includes five micro-charge amplifiers, one micro-voltage amplifier, and one micro-ampere constant current source. The latter two components are based on our previous designs[7] used for processing signals from the temperature-sensing diamond tool, and their performance has been validated. The micro-charge amplifier is used to convert the picocoulomb-level(10^{-12}) charge signals output by the force measurement mechanism into measurable voltage signals. Due to the extremely weak nature of the charge signals, they are highly susceptible to interference by environmental factors such as electromagnetic waves, airflow, and temperature changes, with electromagnetic interference being particularly significant. The micro-charge amplifier is designed based on the LMP7721 precision amplifier with a femtoampere-level low input bias current. The solder mask on the PCB in the input stage circuit has been removed to reduce charge accumulation. The feedback circuit utilizes a parallel structure comprising a 500 pF silver mica capacitor and a 100 MΩ metal film resistor.

The three-dimensional force measurement mechanism itself is equipped with a shielding layer, but due to the presence of multiple openings, the shielding effectiveness is limited. The steel tool holder, serving as a second layer of shielding, can effectively enhance the overall shielding performance[8]. To ensure insulation between the tool holder and the force measurement mechanism, high-rigidity ceramic spacers are used to prevent direct contact between the two. Due to usage and installation requirements, there are inevitable seams and openings on the tool holder, which can reduce electromagnetic shielding effectiveness. To address this, foam-copper gasket is used at the seams between the tool holder's cover and base to maintain the continuity of the shielding layer. The diameter of the mounting holes at the front end of the tool holder is smaller than the wall thickness, and the rear-end opening is designed with a boss structure. These openings can be regarded as waveguide structures, which help to ensure the effectiveness of the tool holder's shielding.

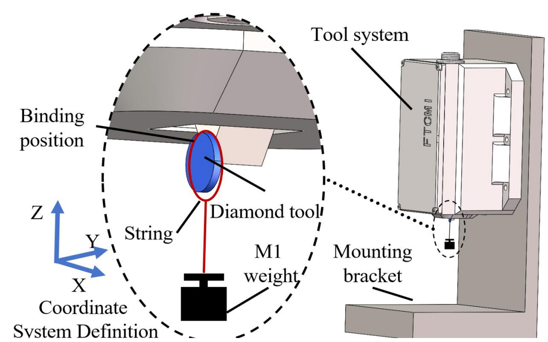

Fig. 2 The Calibration Setup of Z-direction Sensitivity

Due to the use of piezoelectric ceramics as the force sensor in the three-dimensional force measurement mechanism, the resolution and sensitivity of the tool system are largely dependent on the data acquisition module. Therefore, it is necessary to calibrate and test the relevant performance of the force measurement component of the cutting force and temperature measurement tool system, while the parameters related to temperature measurement still follow the results of our previous work[7]. Figure 2 shows a schematic diagram of the sensitivity test process in the Z direction. The tool system is mounted on an "L"-shaped bracket, with the Z direction of the tool coordinate system parallel to the direction of gravitational acceleration. A M1-class weight is suspended from one end of a fine string, with the other end tied to the tool tip. Since the diamond tool can be regarded as a rigid body, the variation in the binding position of the string at the tool tip has a negligible impact on the experimental results.

Weights of 1g, 2g, 5g, 10g, 20g, 50g and 100g were used respectively. The experimental results are shown in Figure 3(a), with a Z-direction sensitivity of 0.27 mN/mV. Due to charge leakage in the acquisition of the output signal from the piezoelectric ceramics, a charge leakage compensation algorithm was used in the data processing[9]. The linearity of the V-F curve was approximately 0.8% over the full test range. Figure 3(b) shows the resolution test results of the tool system of Z direction, which indicates that the tool system is capable of clearly distinguishing a weak cutting force signal of 0.3 mN.

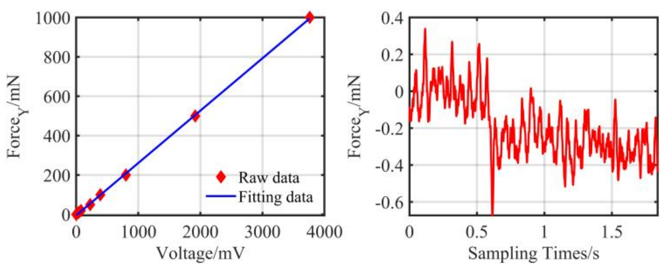

Fig. 3 The Calibration Setup of Z-direction Sensitivity

The resolution and sensitivity tests for the X and Y directions of the tool system follow the same procedure, with only the tool's mounting direction changed. The experimental results indicate that the sensitivity of the tool system in the X and Y directions is 0.26 mN/mV and 0.25 mN/mV, respectively, with a resolution better than 0.3 mN in both directions. Additionally, stability tests were conducted on the tool system, and the results show that the signal zero drift in the Z direction was less than 1 mN within 2 hours, while the signal zero drift in the X and Y directions was less than 0.5 mN.

3. Cutting Force and Temperature Measurement in Ultra-precision Machining Process

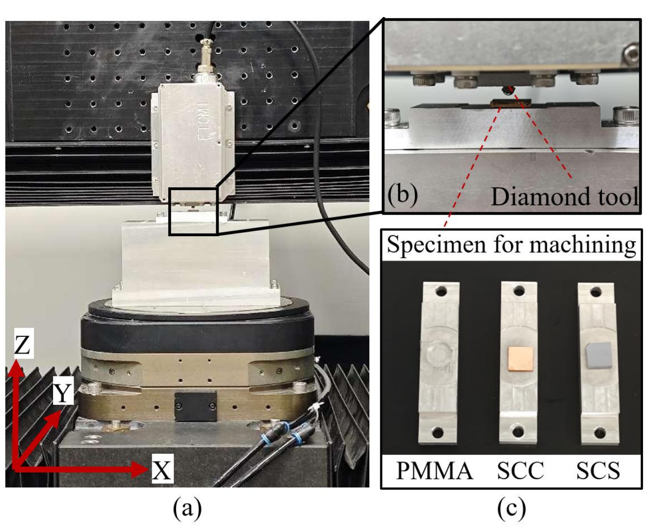

Fig. 4 Experimental setup on a four-axis precision machine

To verify the performance of the cutting force and temperature measurement, the tool system was installed on a four-axis precision machine for carrying out microstructure machining experiments, as shown in Figure 4(a). This machine tool can provide a positioning accuracy of ±20 nm. Figure 4(c) shows the Polymethyl methacrylate (PMMA), single-crystal copper(SCC), and single-crystal silicon(SCS) samples used in the experiment. During the experiment, the X-axis of the machine tool remained stationary, while the Y and Z axes followed a half-sine wave trajectory, with the Y-axis speed set to a constant value of 50 μm/s.

Figures 5(a) and 5(d) show the cutting force measurement results for SCC and PMMA samples, respectively. The periodic spikes observed are caused by environmental interference. Figure 5(c) shows the surface morphology of the PMMA sample measured by a white light interferometer after machining, with the cross-sectional shape shown in Figure 5(b). Figure 5(e) shows the surface morphology of the SCC sample after machining, with the cross-sectional shape shown in Figure 5(f). Since there was no movement in the X direction, the cutting force was almost zero and is not displayed. The experimental results indicate that as the cutting depth increases, the cutting force required to remove material also increases. When the maximum cutting depth (approximately 150 nm) is reached, the cutting force in the Y and Z directions also reaches its maximum value, with the cutting force in the Z direction for SCC reaching 14mN. Due to the higher hardness of copper, the cutting force for copper is greater than that for PMMA at the same cutting depth.

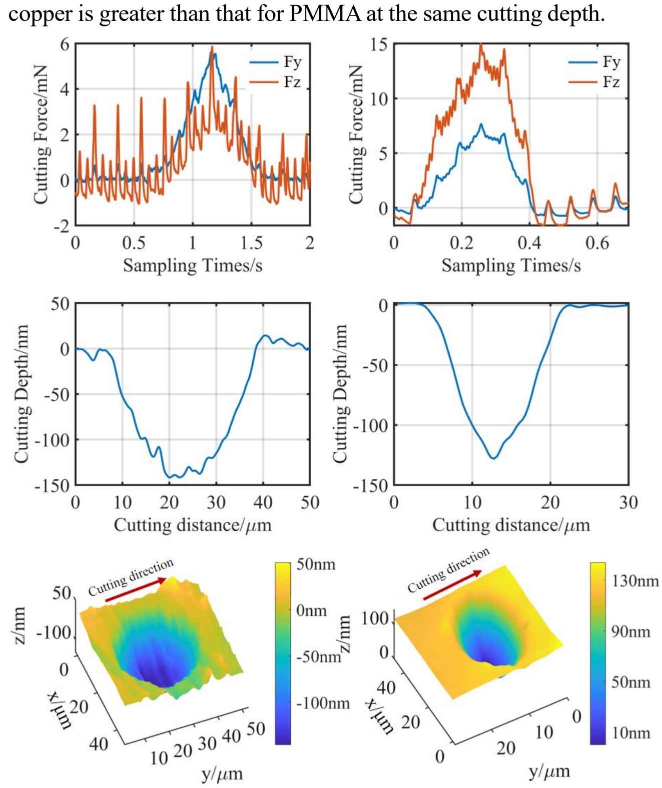

Fig. 5 Cutting force measurement during PMMA and SCC machining process.

Figures 6(a) and 6(b) show the synchronous measurement results of cutting force and temperature for the SCS sample. Figure 6(d) presents the surface morphology measured by a white light interferometer after machining, with the cross-sectional shape shown in Figure 6(c). The maximum cutting depth was approximately 190 nm. Due to the higher hardness of single-crystal silicon, a greater cutting force was observed at the same cutting depth, with the maximum cutting force in the Z direction reaching about 40 mN. The cutting temperature exhibited the same variation pattern as the cutting force, with the tool tip temperature increasing by approximately 0.5°C during the entire machining process. However, there was some lag in the temperature signal, which is due to the heat conduction process involved in temperature measurement. The actual machined morphology deviated from the preset machining trajectory, with an approximately 25μm near-horizontal segment appearing in the middle section of the microstructure. This error was clearly reflected in the data from the cutting force and temperature measurement tool system, without the need for other surface measurement methods. This demonstrates the system's potential and superiority in in-process monitoring for ultra-precision machining.

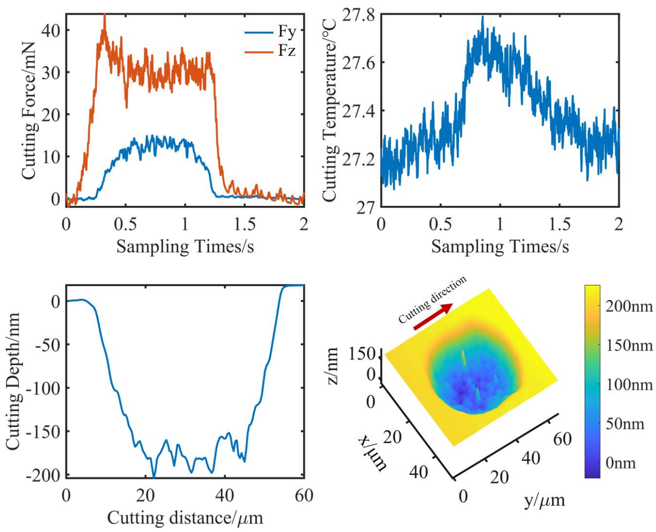

Fig. 6 Synchronous measurement of cutting force and temperature during SCS machining process.

4. Conclusions

This paper reports a tool system applicable for the synchronous measurement of cutting force and temperature during ultra-precision machining processes, integrating machining and measurement to achieve in-process monitoring of the cutting force and temperature. The tool system integrates a signal acquisition module, shortening the signal transmission chain of weak force and temperature and ensuring the measurement performance of the tool system. The sensitivity of the three-axis force measurement is 0.26 mN/mV (X), 0.25 mN/mV (Y), and 0.27 mN/mV (Z), respectively, with a resolution better than 0.3mN.

Experiments of in-process cutting force monitoring on SCC and PMMA samples, as well as the synchronous in-process monitoring experiment of cutting force and temperature on SCS, validated the performance of the tool system. This tool system is capable of sensitively measuring the cutting force and temperature during the ultra-precision machining process and has potential applications in the in-process monitoring of machined surface morphology. In future work, we will further study the correlation between cutting force, temperature, and machined surface morphology, thereby exploring the further application of the force and temperature measurement tool system in the field of ultra-precision machining.

ACKNOWLEDGEMENT

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