Development of a smart cutting tool with cutting force sensing and monitoring for ultraprecision machining

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Abstract

In this paper, a smart cutting tool developed by the authors is presented to address the demand of smart adaptive machining, which can real-time monitor cutting forces in a plug-and-produce manner without additional equipment; easy to use and minimum modification of the cutting tool; employed at low cost and adequate accuracy and sensitivity. The smart cutting tool has integrated efficient sensors combination using piezoelectric films to directly measure the 3 dimensional cutting forces real-time in ultraprecision machining. Piezoelectric film sensors combination generates electrical signals under cutting forces acting at the nose tip of the diamond cutting tool. The four output electrical signals can be acquired, amplified, and processed with decoupling so as to measure 3 dimensional cutting forces with adequate accuracy.

1 Introduction

With the development and requirement of adaptive smart machining, the self-sensing, monitoring and control of machining processes are becoming increasingly important particularly in ultra-precision machining [1], where there is sometimes the need to sense the micro cutting forces in-process in relation to tool wear and consequent surfaces generated. The most effective method to monitor cutting tool conditions is to sense the cutting force in the process [2]. At present, the major challenge in the process monitoring is lack of robust in-process cutting force sensors, which can self-sense cutting forces in real-time and be placed at the point of interest on the cutting tool to keep clarity of measurement accuracy and higher sensitivity [3, 4]. Therefore, it has been highly desired to develop a smart cutting tool and the associated cutting force-based sensing/monitoring systems for smart ultraprecision machining.

This paper presents a smart cutting tool with cutting force self-sensing ability, which has employed piezoelectric films to directly measure the 3 dimensional cutting forces.

Piezoelectric films are packaged in a suitable housing which is arranged onto the head of diamond tool shank with four cavity structures accommodating four piezoelectric sensors combinations. When subject to small cutting forces acting at the nose of the diamond cutting tool, Piezoelectric sensors combination generates four electrical signals according to the transverse piezoelectric effect, which can be acquired, amplified, and processed with decoupling so as to measure 3 dimensional cutting forces (*Fx*, *Fy*, *Fz*) with adequate accuracy.

2 Design of the smart cutting tool and its configuration

As shown in Figure1, the smart cutting tool developed mainly includes a special tool shank configuration, diamond tool, four pieces of piezoelectric film sensors (PZT4) with the dimensions of 8mm×5mm×1mm and four protective covers to seal the smart cutting tool, and a plug for charges interface to transmit cutting force signal.

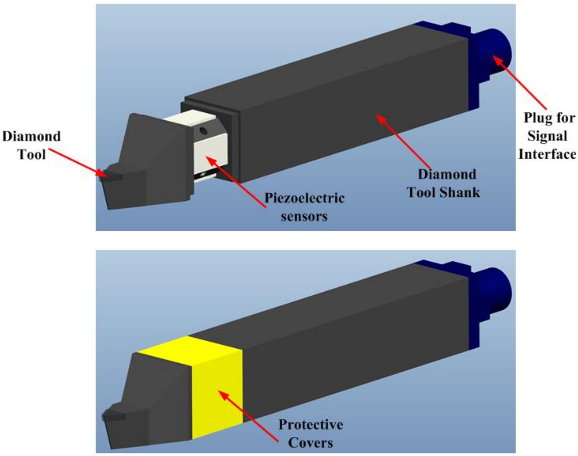

Figure 1: Schematic of the structure of the smart cutting tool

The nose of diamond tool is on the centre of the transverse tool shank. Piezoelectric sensors are glued at the surface of four cavity structures respectively, to accommodate piezoelectric sensors combination. A wire is soldered onto the Ag metal film that functions as the output electrode of the piezoelectric sensor.

3 Cutting forces measurement strategy

Due to the cutting forces acting at the tool nose during the machining process, the piezoelectric sensors (*P1*,*P2*,*P3*,*P4*) integrated into the smart cutting tool shank will generate electrical signals (*Q1,Q2,Q3,Q4*) according to the transverse piezoelectric effect (*d31* piezoelectric effect) when subject to small strain of strain cavities ahead of the tool shank. The transverse of the strain cavities is illustrated in Figure 2.

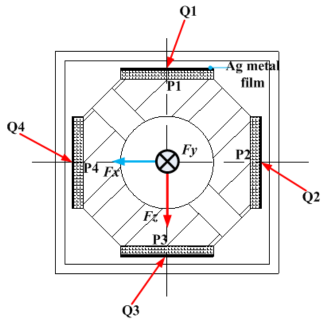

Figure 2: The transverse Schematic of the strain cavities of the smart cutting tool

The cutting force can be decomposed into three cutting forces of *Fx*, *Fy*, and *Fz*. According to the tool shank structure relationship based on flexibility, dielectric and piezoelectric effect within piezoelectric crystal elastic limits, the relationship between cutting forces and four charges can be decoupled and given by Eq. (1).

$$\begin{aligned} Fx &= K_1(Q2 - Q4) \\ Fy &= K_2(Q1 + Q2 + Q3 + Q4) \\ Fz &= K_3(Q1 - Q3) \end{aligned} \quad (1)$$

K_1, K_2, K_3 are constant dependent on the size and property of the smart cutting tool.

4 Testing on the smart cutting tool

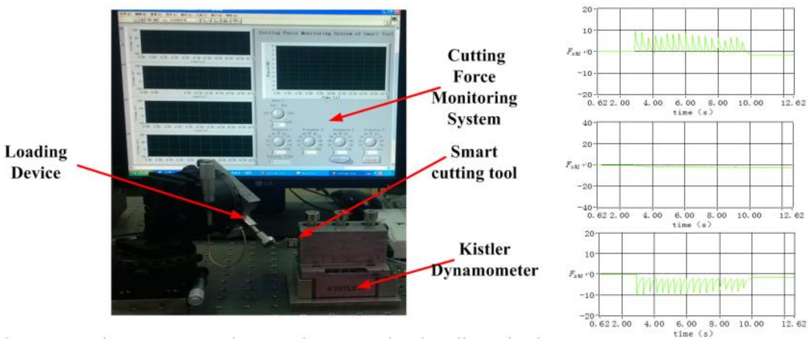

Figure 3: The smart cutting tool testing setup with a dynamic loading device for 3 dimensional cutting forces monitoring in real time

To verify the smart cutting tool concept and feasibility, the prototype of the smart cutting tool is developed and a dynamic loading device is set up with a PI actuator operating in 0~3,972Hz frequency range. The testing system can exert dynamic forces (emulating cutting forces real time) and be bulit with the labview programme to acquire, processes and decouple the four output electrical signals. In order to make a further calibration, the smart cutting tool is mounted on the Kistler dynamometer 9256C2 as showen in Figure 3, and the test results illustrate that ability to real time measure the small 3 dimensional cutting forces down to 1N and low variations in the 0.1N, and verified the decoupling measurement strategy.

5 Conclusions

A smart cutting tool is designed and developed, which integrates four pieces of piezoelectric film sensors and specially designed tool shank configuration for monitoring real-time cutting force in ultra-precision cutting. Based on transverse piezoelectric effect, the cutting forces measurement algorithm is deduced and the relationship between cutting forces (*Fx, Fy, Fz*) and four electric charges (*Q1,Q2,Q3,Q4*) is established, which enable the sensing and monitoring of the cutting forces in real time. In addition to the advantages of the smart cutting tool: no additional measure equipment; simple structure and minimum modification of entirely shape and size of the tool; easy to install and employ; low cost and reliably potential employed in adaptive smart machining.

References:

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