Research of a smart cutting tool based on MEMS strain gauge

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Abstract. Cutting force is an important factor that affects machining accuracy, cutting vibration and tool wear. Machining condition monitoring by cutting force measurement is a key technology for intelligent manufacture. Current cutting force sensors exist problems of large volume, complex structure and poor compatibility in practical application, for these problems, a smart cutting tool is proposed in this paper for cutting force measurement. Commercial MEMS (Micro-Electro-Mechanical System) strain gauges with high sensitivity and small size are adopted as transducing element of the smart tool, and a structure optimized cutting tool is fabricated for MEMS strain gauge bonding. Static calibration results show that the developed smart cutting tool is able to measure cutting forces in both X and Y directions, and the cross-interference error is within 3%. Its general accuracy is 3.35% and 3.27% in X and Y directions, and sensitivity is 0.1 mV/N, which is very suitable for measuring small cutting forces in high speed and precision machining. The smart cutting tool is portable and reliable for practical application in CNC machine tool.

1. Introduction
Cutting force is generated between workpiece and cutting tool during machining process, it is closely associated with cutting heat, cutting vibration and tool wear. Cutting force is a key factor that affects machining smooth, tool life and energy consumption [1]. Any tiny variation of cutting status can be reflected by cutting force. Thus, measuring cutting force is useful for monitoring machining status, improving accuracy and forecasting failure [2], which is of great importance for intelligent machining. Cutting force dynamometer is an effective tool for cutting force measurement.

So far, many kinds of cutting force dynamometer based on different principles have been developed [3,4]. Among them, strain gauge and piezoelectric cutting force dynamometers are widely used because of high accuracy and good reliability. For example, Kistler Company (Switzerland) is a famous piezoelectric sensor manufacturer [5], its piezoelectric cutting force dynamometer is qualified with large rigidity (2 × 10^9 N/m) and low cross-interference error (≤2%), which is a main supplier of cutting force dynamometer around the world. YDC series piezoelectric cutting force dynamometers developed by Dalian University of Technology possesses satisfying resolution (1N) and high natural frequency (≥4kHz), it is very suitable for dynamic cutting force measurement [6,7]. Strain gauge cutting force dynamometer developed by TeLC Company (Germany) is able to measure and analyze cutting forces [13], its DKM type cutting force dynamometer can match with different types of cutting insert for variable application occasions. Xi’an jiaotong University has proposed a strain gauge cutting force dynamometer based on octagonal ring structure, the developed dynamometer owns high accuracy (≤0.84%) and high natural frequency (≥1122Hz)[8,9].
However, strain gauge and piezoelectric cutting force dynamometer usually own comprehensive structure and heavy weight, which is incompatible with CNC lathe for installation. In recent 5 years, researchers have focused on smart cutting tool research by integrating force measurement unit on the cutting tool to measure cutting forces. For example, Harbin Institute of Technology has developed a smart cutting tool by embedding a tiny triaxial force measurement system into a structure optimized cutting tool [10]; North University of China developed a micro-sensor for cutting force measurement based on Ni-Cr alloy[17]; University of Birmingham proposed a smart cutting tool based on piezoelectric film[18]. As the research of smart cutting tool is still in its infancy, there are a lot of work worth exploring. This paper proposes a smart cutting tool based on Micro-Electro-Mechanical System (MEMS) strain gauge. Its structure composite, working principle and performance test are introduced in following sections.

2. Materials and Methods

2.1. Structure design

According to problems of present cutting force dynamometers that have been mentioned above, and taking the requirement of cutting force measurement in intelligent machining, a smart cutting tool for cutting force measurement should fulfill following principles: ① good compatibility, the developed smart cutting tool can be easily installed on CNC lathe without affecting its machining performance; ② fine portability, the smart cutting tool should be structure simple and potable for application; ③ high accuracy, it needs high accuracy and good sensitivity for monitoring small cutting force variation.

Figure 1 depicts a schematic view of the designed smart cutting tool, it is basically the same with an ordinary cutting tool except that there are four strain gauge bonding slots distributed in the front of tool shaft. MEMS strain gauges are packaged in the strain gauge bonding slots and are organized into Wheatstone bridges for measuring cutting forces in X and Y directions. A signal cable channel is designed for placing power and signal wires. A shielded cable is adopted for signal transmitting in order to avoid electromagnetic interference.

![Smart cutting tool structure](image)

**Figure 1.** Smart cutting tool structure

2.2. MEMS strain gauge

The strain gauge used in this research is fabricated by MEMS technique, because MEMS strain gauge possesses the advantages of small size, large resistance, high sensitivity and batch manufacturing, which is good for improving the integration degree and measuring accuracy of smart cutting tool.

The MEMS strain gauge used in this paper is a commercial product of Anhui Tianguang Sensor Co. Ltd., Bengbu, China, as shown in figure 2. The strain gauge looks like a sandwich, its top and bottom layers are polyimide insulation, and the middle layer is MEMS strain gauge devices, including piezoresistor, gold wire, metal pad and metal pin. The MEMS strain gauge’s resistance, sensitive coefficient and size are 1000Ω, 150±5% and 3×0.20×0.04mm³, respectively. Figure 2 also illustrates
fabrication process of the strain gauge: ① boron ions are implanted into single crystal silicon bar in order to form p-type piezoresistor material; ② p-type piezoresistor material is cut into small slices; ③ small pieces of piezoresistor material is ground for next step; ④ the ground piece of silicon material is cut into smaller slices as a single resistor; ⑤ each resistor is etched to appropriate size and a gold layer is patterned to form the contact area; ⑥ the resistor is bonded between two pieces of polyimide film and the resistor is linked to metal pad by gold wire, two pins are finally bonded to the metal pad.

**Figure 2.** Schematic view of MEMS strain gauge and its fabrication process

2.3. **MEMS strain gauge bonding and Wheatstone bridge organization**

When X (or Y) direction cutting force component is applied to the tool tip, each two symmetrical slots of the 4 strain gauge bonding slots receive opposite surface stress. According to this principle, Wheatstone bridge circuit is adopted for cutting force measurement in order to improve sensitivity. Eight pieces of MEMS strain gauge are packaged symmetrically in bonding slots and two groups of Wheatstone bridge are organized for cutting force measurement in X and Y directions, as shown in figure 3. A layer of silica gel is coated on top of each MEMS strain gauge in order to isolate it from steam and other corrosive substances. Power and signal cable for Wheatstone bridge is collected into the signal cable channel, and then it is connected to data acquisition equipment by shield cable.

**Figure 3.** Strain gauge location and Wheatstone bridge organization method
It is important to note that: (1) all strain gauge should be placed symmetrically in the packaging slot, which is helpful for reducing measurement accuracy that caused by positioning error; (2) each strain gauge should be placed as close as possible to the slot’s symmetrical axis in order to make it stay on the neutral layer of surface stress under the effect of cross force, which can reduce cross-interference error.

2.4. Static calibration test

Static calibration test was carried out to verify practical performance of the developed smart cutting tool and to obtain its static characteristic indexes. Figure 4 depicts the experiment setup for static calibration. During the test, the smart cutting tool was fixed on the base of an electro-mechanical universal testing machine (EMUTM, type UTM6104) and was powered by 5 V DC. The EMUTM was pre-set to apply standard-static force on the tool tip in X and Y directions, respectively. Each calibration cycle includes a loading process and an unloading process. During loading process, the standard-static force applied to the tool tip rises from 0 N to 260 N with an integral of 20 N in each step; then it falls from 260 N to 0 N by 20 N in each step during unloading process. At least 3 cycles of calibration test were needed for each direction, and the test results were averaged for eliminating random error. The output of two Wheatstone bridges were recorded by two sets of precision digital multimeter (type FLUKE 8846A).

3. Results and Discussion

Figure 5 depicts the output voltage signal versus the input force signal of the smart cutting tool in X and Y directions’ calibration test, respectively. It is apparent that the developed smart cutting tool possesses fabulous linear property and desirable cross-interference error. After further data processing, main static characteristic indexes are obtained and listed in table 1.

The developed smart cutting tool owns satisfying static properties, its sensitivity is 0.1 mV/N, which means it is sensitive to small variation of cutting force and is suitable for cutting force measurement in high speed or precision machining. The cross-interference error are 1.97% and 3.03% in X and Y directions, respectively. Thus, each measuring circuit is able to measure a single direction’s cutting force component while hardly disturbed by cutting force component in another direction. Furthermore, its linearity error (0.87%, 1.21%) and hysteresis error (1.08%, 1.31%) are acceptable except repeatability error. The repeatability error may be affected by bonding material’s stability, which can be reduced by optimizing MEMS strain gauge bonding process.
4. Conclusion
This paper proposes a smart cutting tool based on MEMS strain gauge, which has fully considered the compatibility and reliability of its installation on CNC machine. MEMS strain gauges are bonded in the specially designed slots and are organized into Wheatstone bridge for cutting force measurement. Static calibration test proves that:

1. The smart cutting tool possesses favorable sensitivity (0.1 mV/N), which is capable of measuring small cutting force in high speed and precision machining process;
2. Its accuracy error is around 3%, which is promising to be reduced by optimizing MEMS strain gauge bonding process.
3. Cross-interference (1.97% and 3.03%) is acceptable for application, the developed smart cutting tool is able to measurement cutting force components in X and Y direction respectively while hardly interfering each other.

5. Acknowledgments
You Zhao designed the sensor and analyzed the data, Yulong Zhao Contributed guidance for sensor design and experiment, Yiwei Shao, Tengjiang Hu, Qizhang and Xiaohui Ge performed the experiment. In addition, this research is supported by the National Natural Science Foundation of China (Grant No. 51705408), the Fundamental Research Funds for the Central Universities (xjj2017017), and the Changjiang Scholars and Innovative Research Team in University of China (No. IRT_14R45), the National Science Fund for Distinguished Young Scholars (Grant No. 51325503), the National Natural Science Foundation of China (Grant No. 51421004).

References
[1] Teti R, Jemielniak K and O'Donnell G 2010 CIRP. Ann. Manuf. Tech. 59 717-39
[2] Jain R, Rathore J and Gorana V 2016 Proc. Int. Conf. on CARs & FoF (Kolaghat, West Bengal India) 13-21
[3] Rehorn AG, Jiang J, and Orban PE 2005 Int. J. Adv. Manu. Tech. 26 693-10
[4] Audy J 2006 J. Zhejiang Uni. Sci. 7 1781-89
[5] Information on https://www.kistler.com
[6] Ren Z, Zhang J and Jia Z 2014 Adv. Mater. Res. 945 2191-94
[7] Bingyao Cheng. Development of tool changeable piezoelectric dynamometer on turning, master’s degree thesis of Dalian University of Technology. 2013
[8] You Z, Yulong Z and Chaohui Wang 2016 Sen. Act. A. Phys. 237 119-27
[9] You Z, Yulong Z and Songbo L 2015 Sen. 15 7969-84
[10] Xiao CW, Ding H and Li WD 2012 Proc. Preci. Engi. Nano. (Aspen, Colorado, USA) 516 373-77