An investigation on the development of a smart cutting tool for precision machining using SAW-based force measurement

Chao Wang*, Kai Cheng*, Richard Rakowski, Xun Chen and Mingyi Zheng

Advanced Manufacturing and Enterprise Engineering (AMEE) Department, School of Engineering and Design, Brunel University, Uxbridge UB8 3PH, UK

** Corresponding authors: chao.wang@brunel.ac.uk and kai.cheng@brunel.ac.uk*

Abstract

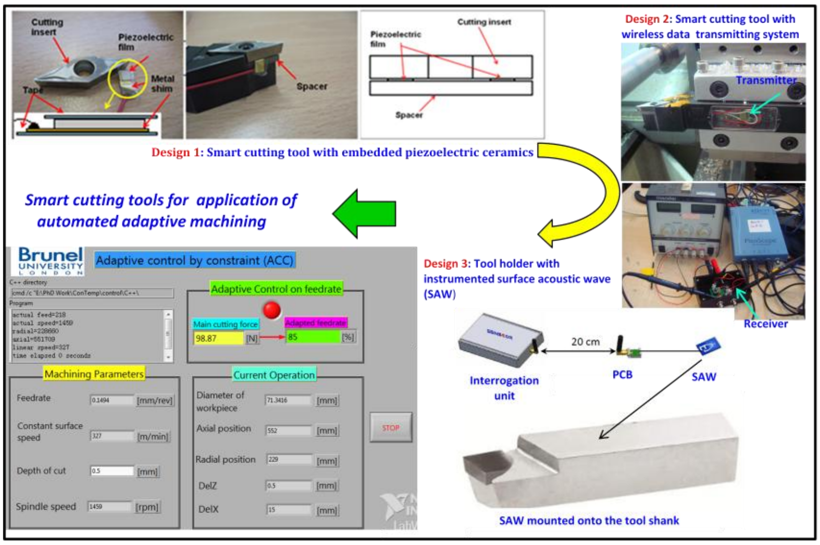
With the rapid development of high precision machining, there is a need to monitor certain parameters in the machining processes so as to detect tool wear, to optimize cutting parameters, and to render the machining process some level of smartness and intelligence. Over the last decade or so, sensors based on surface acoustic waves (SAW) form an important part of the sensor family, these have seen diverse applications ranging from gas and vapour detection to strain measurement. In this paper, the use of SAW sensors for potential application to precision machining processes is presented. The working principle for such an application has been demonstrated through FEA simulation in order to detect its modal frequency and modal shape by modal analysis. For the experimental implementation, two SAW strain sensors are mounted onto two Al plates bolted on top and bottom of the cutting tool shank respectively. Moreover, the two SAW sensors are formed into a half-bridge measurement configuration in order to minimise any environmental perturbations caused by temperature effects, the torque effect, and the RF telemetry link. Furthermore, the two SAW sensors have been calibrated to measure the cutting force in a real machining environment.

1 Introduction

In modern day manufacturing it is essential to monitor cutting forces with high precision, because a change in the cutting force is directly related to the cutting conditions and thus have a direct effect on the machining outcome [1 and 2]. Wear and breakage of the cutting inserts can increase the cutting forces and vibrations of the tool holder, resulting in poor surface finish and loss of dimensional accuracy of the machined work piece [3]. This paper will investigate the potential application of SAW sensors to detect cutting forces based on the indirect force measurement principle. Previous research using the piezoelectric materials as the force sensing transducer suffered from the pyroelelctric effect, which affected the linearity and accuracy of cutting force measurement. The location of the SAW sensors is critical and in this application they are positioned away from the cutting insert onto the tool shank, at a point where maximum strain occurs. The tool shank is fixed at one end and acts like a cantilever, and will experience strain under a static cutting force generated from the turning process. As long as the relationship between the force and the strain is established, the SAW sensors are able to measure the cutting forces. The advantages of using SAW in machining applications are: (1) suitable for wireless data transmission, (2) batteryless, (3) high sensitivity, (4) high frequency response, (5) plug and play sensor connectivity and installation, and (6) low cost. These advantages have the potential for SAW sensors to function as a smart cutting tool for tool wear and force detection in smart machining applications.

2 Design and development approach for the smart cutting tools

The smart cutting tool should a plug-and-produce tooling device including the tool hardware, plug-and-play algorithms and interfacing/wireless communication protocols compatible with the machining system – CNC control system in particular. Bear the above smart cutting tool characterizations in mind, recent machining innovations have cutting tools with integrated thin film sensors designed to detect tool wear. Also, to reduce temperature at the cutting tool tip with internal coolant, cutting inserts have been developed with micro-channels [4]. This trend for additional smart features in cutting inserts has led to a cutting tool embedded with a single-layer piezoelectric film to measure the orthogonal cutting force. *Design 1* (in Fig. 1) shows one type of configuration using a piezoelectric ceramic d_{33}-typ sensor 'sandwiched' between the cutting insert and the spacer. This type of configuration employs a force shunt measurement method to measure the orthogonal cutting force acting on the tool tip [5]. *Design 2* (in Fig. 1) also employs a piezoelectric ceramic d_{31}-type sensor that is mounted onto the tool shank to measure the orthogonal cutting force, based on an indirect force measurement method. A wireless data transmitting system has been employed to transmit the signal to the measuring system interrogation unit. The transmitter is embedded inside the modified tool shank and the receiver is connected with the data acquisition system. *Design 3* (in Fig. 1) shows the SAW-based smart cutting tool schematic, which needs to be mounted onto the tool shank, in order to detect the cutting force.



C++ directory: cmd /c "E:\PhD Work\ConTemp\control\C++\

Program

```
actual feed=218
actual speed=1459
radial=228660
axial=551708
linear speed=327
time elapsed 0 seconds
```

Main cutting force 98.87 [N]
Adapted feedrate 85 [%]

Feedrate 0.1494 [mm/rev]
Constant surface speed 327 [m/min]
Depth of cut 0.5 [mm]
Spindle speed 1459 [rpm]

Diameter of workpiece 71.3416 [mm]
Axial position 552 [mm]
Radial position 229 [mm]
DelZ 0.5 [mm]
DelX 15 [mm]

Figure 1: Design and development of smart cutting tools for smart precision machining

3 SAW-based force sensoring and FEA simulation

Surface acoustic waves are ultrasonic waves propagating along the surface of solids and the transmit and receive principle is based on piezoelectric transducers. SAW sensors often consist of hundred of electrodes, namely interdigital transducers (IDTs), fabricated like comb-shapes on the top surface of piezoelectric substrate materials like quartz and lithium-niobate. The function of IDT is to convert electrical energy into mechanical energy, and vice versa, for generating and detecting the SAW. If an AC voltage with a certain frequency is applied to the electrodes, the dynamic strain in the substrate can be introduced. An FEA simulation has been carried out to investigate a variety of proposed structures, set with accurate boundary conditions, in order to gain a better understanding the SAW strain performance as a machining force sensor. The SAW strain sensor substrate is made of quartz with a STX cut and the electrodes are made of Al. Rayleigh waves can be generated using quartz-STX with velocity of 3158 m/s, moreover, the energy of the Rayleigh wave is confined close to the surface and dies out within two or three wavelengths in depth from the surface. The resonant frequency of the SAW is chosen to be 433 MHz. Based on the resonant frequency (fr) and the velocity (V), the elastic wavelength (λ) can be determined by

$$\lambda = \frac{V}{fr} = \frac{3158\ m/s}{433\ MHz} = 7.29\ \mu m$$

The distance between successive ITD electrodes P is 3.645 µm, which is half of the elastic wavelength. The geometries of the SAW structure used in the simulation are listed in Table 1.

Table 1: Geometries of SAW substrate and IDT

Substrate thickness	15 µm
Periodicity of electrode	7.29 µm
Width of electrode	1 µm
AL electrode thickness	0.2 µm

In order to simulate the SAW strain sensor, the boundary conditions for the FEA simulation, Fig.2, need to be defined accurately as well as the material properties for both the piezoelectric substrate and the Al electrodes. There are three matrices required to be input into the FEA simulation, these are the stiffness matrix, the piezoelectric matrix, and the permittivity matrix. Young's modulus, the Poisson's ratio and the density are also needed for the Al electrodes. The modal analysis has been studied to detect the modal frequencies and the corresponding mode shapes in order to choose the proper propagation wave mode travelling along the substrate. The modal analysis was performed to show several mode shapes and modal frequencies. The 8th mode shape and its corresponding modal frequency of 465 MHz were found to be the preferred propagation wave mode, as shown in Fig. 3 [6], because the wave only propagates near the surface and maximally penetrates about 1.2 λ below the surface, which agrees with the theory of Rayleigh waves.

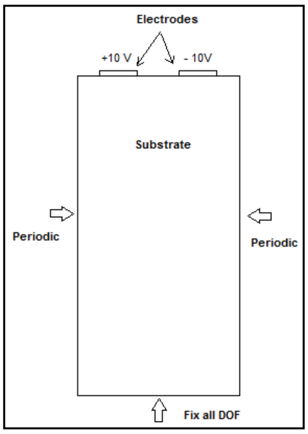
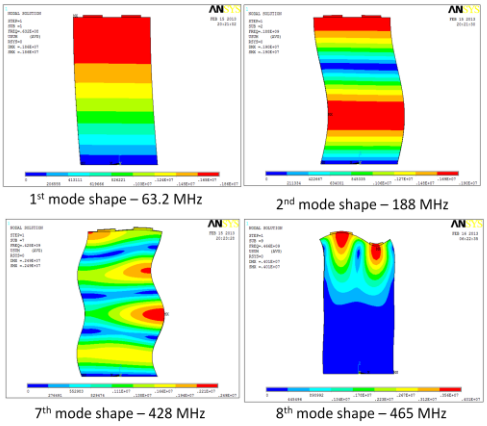


Figure 2: Boundary conditions defined for the FEA simulation


1st mode shape – 63.2 MHz

2nd mode shape – 188 MHz

7th mode shape – 428 MHz

8th mode shape – 465 MHz

Figure 3: Modal shape at 465 MHz for SAW propagation

4 Design implementation perspectives

4.1 Experimental implementation with SAW strain sensor

The two SAW strain sensors were mounted onto two Al plates firmly bolted on the top and bottom surface of the tool shank, as shown in Fig.4. The advantage of this design allows for the re-use of the SAW sensors and reduces the amount of heat generated from the cutting insert reaching the SAW sensor, which could cause failure. Moreover, the proposed half bridge configuration can produce theoretical characteristics useful for temperature compensation, traction compression compensation and additionally torque has no effect given gauges orientation. In order to use the SAW-smart cutting tool device for force measurement in real machining, calibration was carried out to find the factor between strain and force. A known static force, reading from a force gauge FT 200, is applied on the tool tip in order to produce a corresponding strain measured by the SAW. Fig. 5 shows a linear relationship between the force and the strain output within the range from 0 to 120 N, which is due to the tool shank deforming in the elastic region [7]. Curve fitting has shown the exact equation for describing the relationship between the force and the strain, with a considerably high R-squared value of 0.9962.

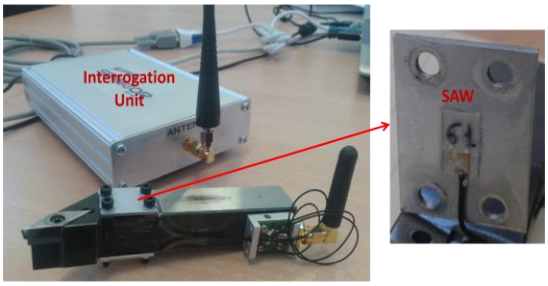


Figure 4: SAW strain sensor instrumented onto the cutting tool shank

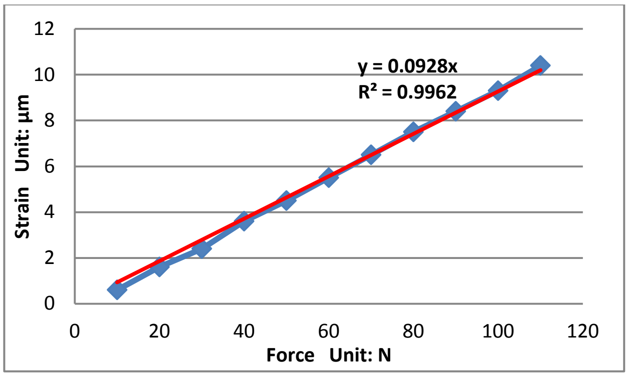
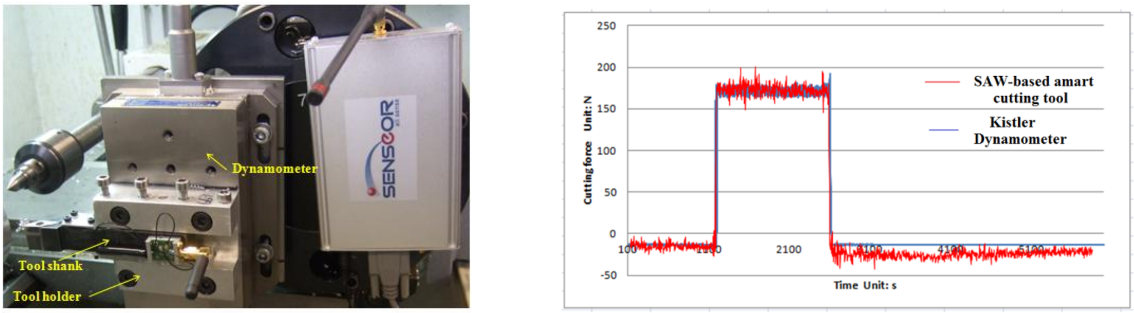


Figure 5: Linear relationship between static force and strain

4.2 Preliminary machining trial based on proposed SAW strain sensor

The SAW sensors were used to indicate the cutting force in a dry turning process with a 1mm depth of cut, a constant feed rate of 0.2 mm/rev, and a spindle speed of 900 RPM. Fig.6 (a) shows the experimental setup of the instrumented tool shank mounted onto the Kistler dynamometer and the interrogation unit communication with the SAW sensors. Fig.6 (b) shows the comparison on the cutting force measurement between the SAW-based smart cutting tool and the Kistler dynamometer; the signal pattern captured by the SAW-based smart cutting tool shows good correlation with the Kistler dynamometer signal.



(a) (b)

Figure 6: (a) Experimental setup; (b) Cutting forces measured by the SAW-based force sensoring and the Kistler dynamometer.

5 Concluding remarks

The FEA modal analysis shows the mode shape of the SAW sensor when an excitation frequency of 465 MHz is applied. Based on this analysis, a better understanding of the working principle of the SAW sensor helped to optimize the practical design using these devices. The experimental results from real machining trials provide close agreement between the Kistler dynamometer and the SAW-based smart cutting tool as to the main cutting force measurement. Further research is underway to use the SAW sensors for force measurement in adaptive machining applications.

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