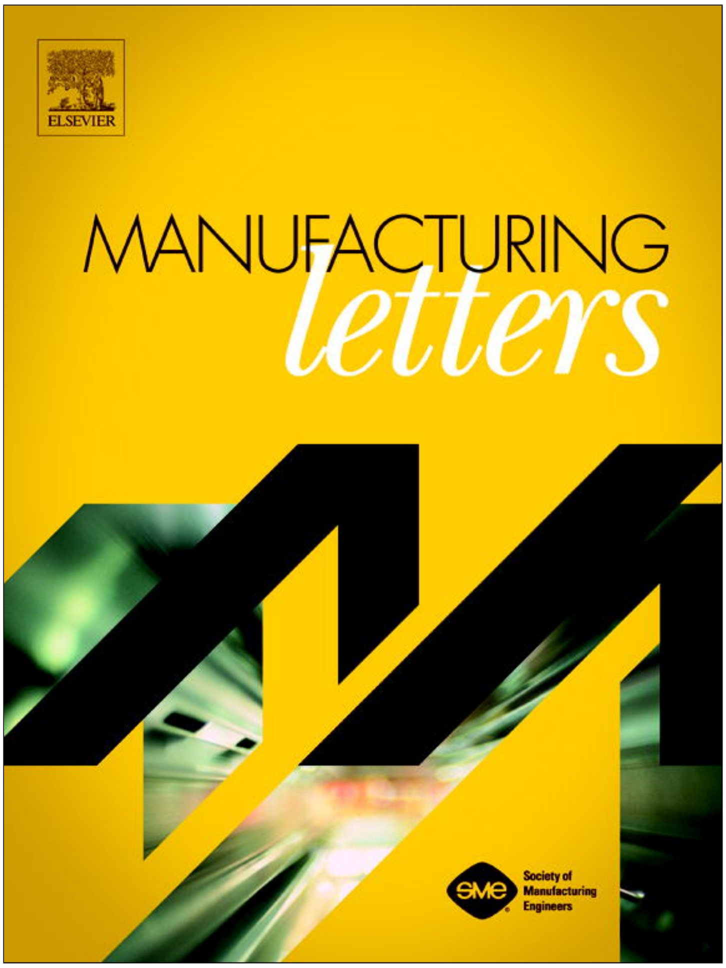
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Design of a smart turning tool with application to in-process cutting force measurement in ultraprecision and micro cutting

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Abstract

In modern micromachining, there is a need to measure and monitor certain machining process parameters in process so as to detect tool wear in real time, to optimize the process parameters setup, and to render the machining process some level of smartness and intelligence. This paper presents the innovative design of a smart turning tool using two pieces of piezoelectric films to measure cutting and feed force in real time. The tool was tested on its performance through the calibration and cutting trials against the commercial dynamometer. The results show the smart turning tool has achieved the performance as designed.

Keywords: Smart turning tool; Micro cutting; Cutting force measurement; Piezoelectric films

In modern manufacturing it is essential to monitor the cutting process, particularly for machining high value added components with an ever higher dimensional accuracy and finer surface roughness. With increasingly stringent requirements on surface quality, some indirect condition monitoring methods have been proposed to specially monitor cutting forces with high precision, since a variation in cutting forces is directly related to the cutting/tooling conditions and thus will have a direct effect on the machining outcome [1,2]. Furthermore, cutting forces measurement in real time machining processes is essential and much needed in machining hard-to-machine materials such as single crystal silicon and silicon carbide because of the tool wear and its correlation with cutting forces.

There are many researchers who have developed a number of ways of monitoring cutting conditions, covering cutting force monitoring, cutting temperature monitoring, acoustic emissions, vibrations signature, and use of miscellaneous sensors. The techniques all are in common to some extent, i.e. using advanced fault detection, check and safeguard of the process stability, and the machine or tool damage avoidance system [1]. Various devices have been designed and applied for this purpose, they are typically dynamometers as developed by the industry specially for measuring and monitoring cutting forces. However, there are some limitations in their usage, such as being unsuitable for industrial environment, expensive and even more limited for ultraprecision and micro machining [3]. In this paper, the development of a cutting force based smart turning tool is presented, which is built with embedded piezoelectric film sensors into a refitted tool holder so as to measure both cutting forces in the cutting process. The smart turning tool can measure the cutting force and feed force with a resolution of 0.1 N in the force measurement range up to 10 N. The assessment on both the static and dynamics performances of the tool are carried out on the test-bench and with cutting trials.

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1. Design of the cutting force based smart turning tool

1.1. The tool design configuration

The proposed design configuration for the smart turning tool is shown in Figure 1, which comprises of a diamond cutting insert, a refitted tool holder and two single layer piezoelectric film sensors. The tool holder was made from two separate parts, i.e. the upper part and base part, which are firmly bolted together with two screws (M3). The piezoelectric film sensor has dimensions of $3 \times 3 \times 0.26$ mm. One piezoelectric film, namely sensor 1, is embedded between the upper part and base part and placed 15 mm away from the cutting tip, in order to measure the cutting force. A slot of thickness of 0.35 mm was machined on the upper part as shown in Figure 1, to embed the other piezoelectric film named as sensor 2, in order to measure the feed force. Two pieces of insulation tape stick are placed on top of the piezoelectric film sensor and the bottom of the metal shim respectively, as applied to insulate and fix the piezoelectric film into a position. A connection wire is soldered onto the metal shim that functions as the electrode extension of the piezoelectric film sensor and renders voltage output generated from the sensor.

The pre-stress imposed by pre-stress screws can reduce the unwanted hysteresis effect, which can provide a better linear relationship between an applied force and the sensor voltage output as it enhances the piezoelectric film sensor performance through a much improved surface contact. At this smart turning tool, two strews (M5) are applied for pre-stressing the piezoelectric film in the cutting force direction, and one strew (M3) is used for pre-stressing the piezoelectric film in feed force direction.

The Kistler charge amplifier 5015 is employed to convert the piezoelectric charge into an equivalent voltage by taking account of the transducer sensitivity and transducer scale. The LabVIEW programme is developed to acquisite voltage outputs through the NI DAQ 9434 acquisition card.

1.2. The piezoelectric film sensors and outputs

The piezoelectric film is used as the sensing element in this research and development, which is capable of generating electric charge signals only when it experiences a change in the force applied. Under a static force load condition, the charges generated by the piezoelectric film migrate towards the dipoles, neutralizing the charges on the dipoles. As a result, there is no any output signal. In practice, in order to use the piezoelectric film for measuring dynamic charge signals corresponding to the dynamic micro cutting forces typically encountered in ultraprecision and micro turning, it is essential to use a multi-channel charge amplifier to prevent any charge leakages [5,6].

1.3. Cutting forces measurement

A force can be generally measured by three methods, i.e. using force shunt, direct and indirect force measurement. The proposed smart turning tool has employed the force

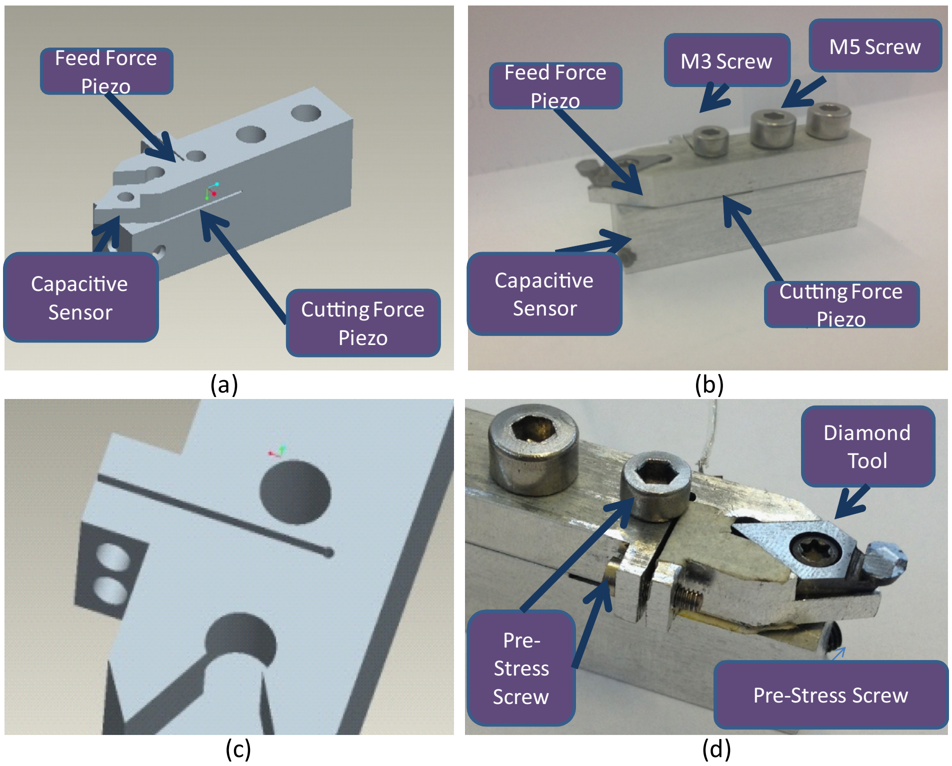

Figure 1. The design configuration of the smart turning tool: (a) 3D model; (b) Prototype; (c) Detail view of 3D model; (d) Detail view of real tool.

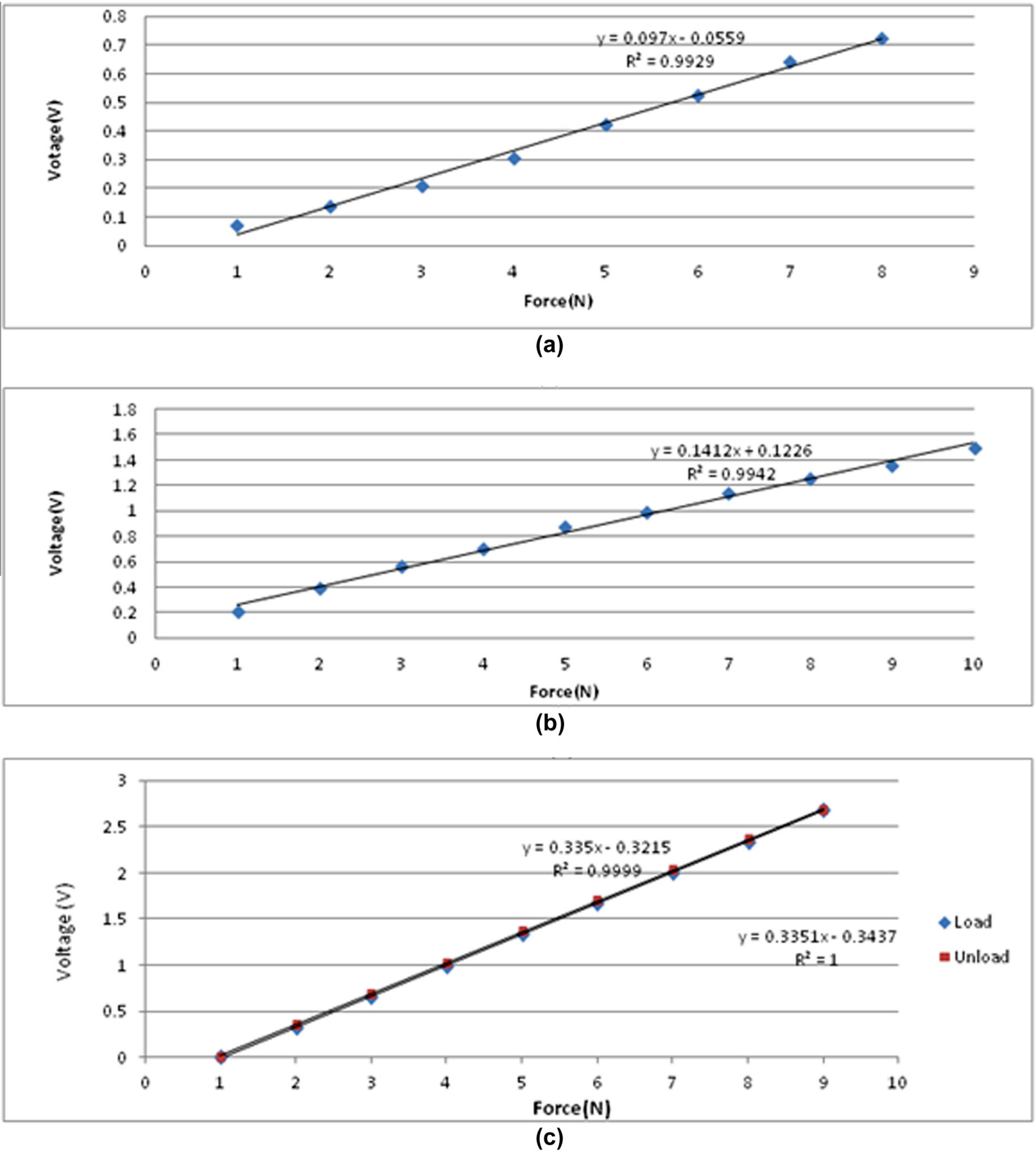

Figure 2. (a) Linear relationship between the emulated cutting force and the sensor 1 voltage output; (b) Linear relationship between the emulated feed force and the sensor 2 voltage output; (c) Hysteresis at the sensor 1 with loading and unloading test.

shunt for cutting forces measurement by taking account the tool design and refitted tool configuration. For the direct force measurement, it is difficult to mount a sensor fully in line with the force path which may result in the piezoelectric film element to fracture. With the indirect method, the measured strain may only represent a small proportion of the cutting force and the measurement sensitivity may well be limited [4]. To achieve a high resolution in measuring the cutting forces in process, the piezoelectric ceramic films are applied with direct force measurement method. The film sensor is secured onto a metal shim between the slots on the tool shank and being pre-stressed to enhance its measurement sensitivity.

2. Assessment of the smart turning tool

2.1. Static performance of the tool

Cutting forces generated in the turning process include static and dynamic components. The static force component can be used to investigate the cutting process performance and cutting tool condition to some extent. In

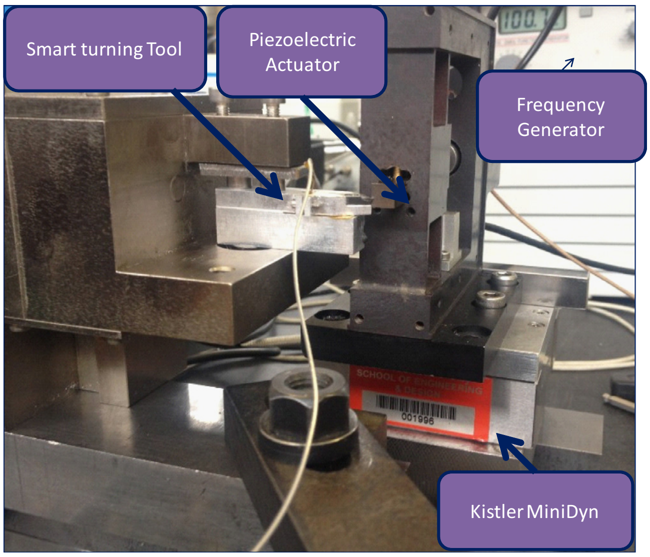

Figure 3. Dynamic performance assessment of the smart turning tool on a testing bench.

order to use the smart turning tool as a device for cutting force measurement in process, the tool calibration is carried out to find out the correlation factor between the sensor output voltage and cutting force. A known static force loading from 1 to 10 N, in steps of 1 N, is applied on the tool tip in order to produce an equivalent voltage output representing the force measurement by the proposed smart turning tool. The known force loading is applied on the tool tip for a few seconds and then removed. This procedure produced a voltage output step due to the corresponding force loading. Figure 2(a) and (b) show a linear relationship between the force loading and the voltage output within the range of 0–8 N for the sensor 1 and sensor 2 respectively, which confirms that the tool holder is deforming in the elastic region [7]. Curve fitting has shown the exact equation for describing the relationship between the loading force and the voltage output for each sensor, with a considerably high R-squared value of 0.993 and 0.994, respectively.

The capacitive displacement sensor is integrated onto the tool holder to measure the hysteresis at the sensor 1. The hysteresis is 1.6% as calculated based on the two

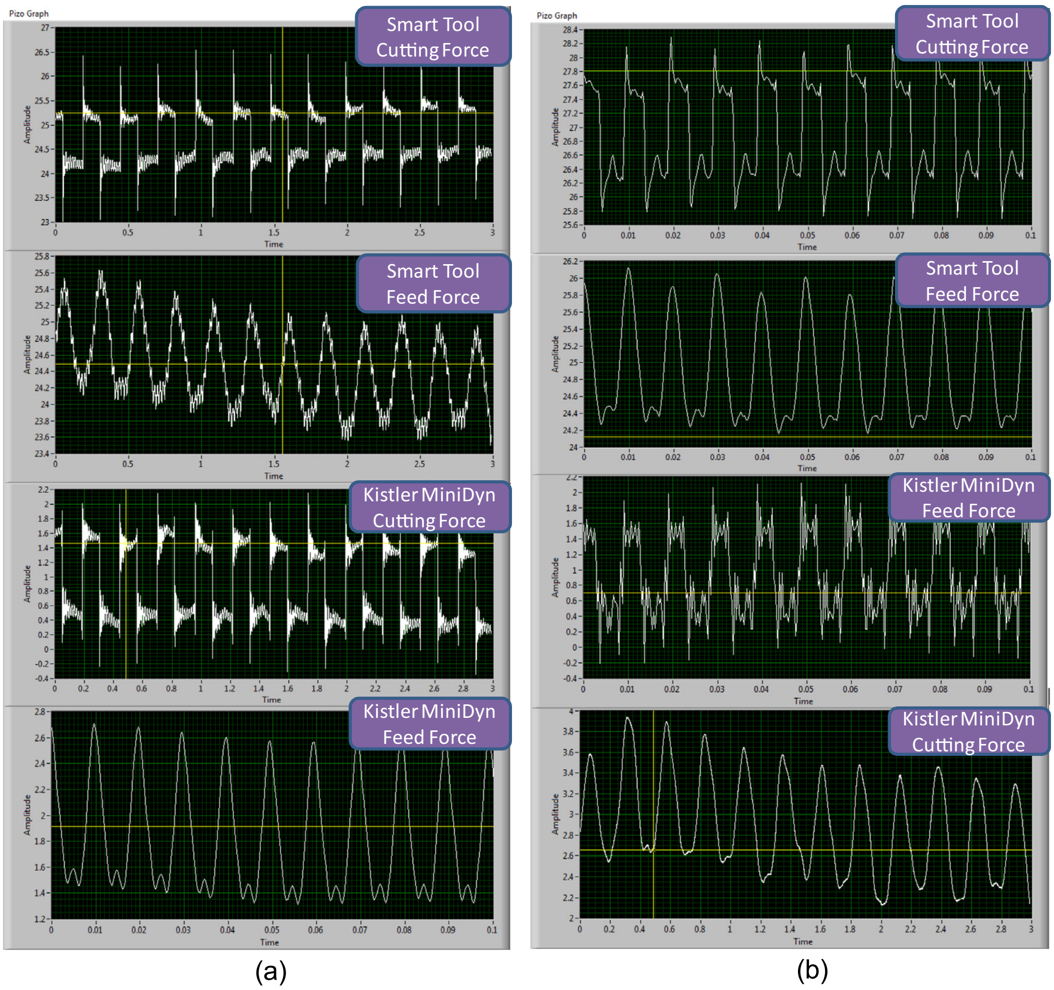

Figure 4. Dynamic response to the square and sinusoidal force modes by the smart turning tool and Kistler MiniDyn dynamometer respectively: (a) at the low frequency of 4 Hz and; (b) at the high frequency of 100 Hz.

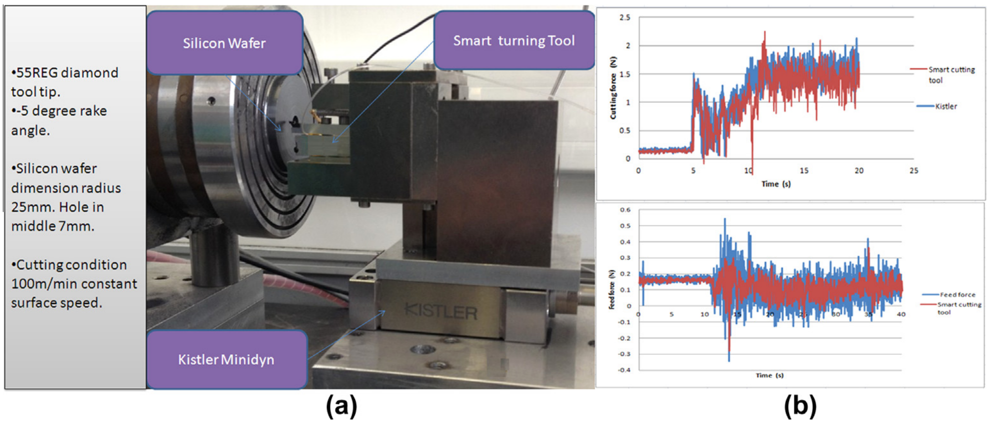

Figure 5. (a) Cutting trials setup with the smart turning tool; (b) Comparison of cutting forces and feed force measured by the smart turning tool and Kistler MiniDyn dynamometer.

displayed equations as shown in Figure 2(c), which is in light of the loading and unloading tests on the tool shank over the full range of up to 10 N.

2.2. Dynamic performance of the tool

The dynamic cutting force is normally indicating the varied conditions of the cutting tool when progressive wear increasingly occurs or the tool damage takes place [8,9]. The on-bench experiments are carried out to assess the dynamic performance of the sensors, using the fast tool servo (FTS) as a driving unit to apply the emulated dynamic cutting forces but under offline 'cutting' conditions. Figure 3 shows that the smart turning tool is firmly clamped onto a fixture at a solid testing bench and the FTS was mounted on top of the Kistler MiniDyn dynamometer. A gauge block fixed onto the FTS is used in contact with the cutting tool tip. The FTS is driven by a DC voltage of 100 V to ensure that a solid contact is constantly maintained between the cutting tool tip and the front surface of the gauge block. Moreover, the FTS is also driven by an AC voltage of 50 V with a certain frequency to generate the dynamic movement to test the dynamic response of the sensors. The MiniDyn dynamometer is used to measure the corresponding force acting at the cutting tool tip with dynamic movement; its measured results are instantaneously compared with the measurement outputs from the smart turning tool.

Figure 4 shows the dynamic response of the smart turning tool at the low and high frequencies of 4 Hz and 100 Hz respectively. There are cutting force signal drifting in the force measurement during the experiment period. The Kistler dynamometer (Minidyn) is more stable in terms of the drifting compared with the proposed smart turning tool. However, considering the relative magnitudes of force measurement, the measurement results by the proposed smart turning tool illustrate the same amplitude accuracy level as the dynamometer as shown in Figure 4. Therefore, the comparisons results are in good correlation on dynamic response at the low and high frequency for both the square and sinusoidal force modes, which are particularly used to examine the dynamic response of the smart turning tool developed.

3. Cutting trials with the smart turning tool, results and discussion

The cutting trials with the smart turning tool are carried out on a 3 axis diamond turning machine in dry cut conditions. The smart turning tool is placed on top of the Kistler MiniDyn and the workpiece material is single-crystal silicon wafer, 50 mm in diameter and 10 mm in thickness, firmly vacuum chucked on the air bearing spindle, as shown in Figure 5(a). The rake angle of the diamond tool is 0 degree. In order to avoid cutting the centre of the workpiece where the cutting speed approaches to zero, the centre area of the wafer is pre-drilled a hole with a diameter of $\phi = 7$ mm. The machining parameters selected in cutting trials are: depth of cut (a_p) = 10 μm, feed (f) = 5 mm/mins, and cutting speed (Vc) = 100 m/mins.

Figure 5(b) illustrates the comparison on the cutting force and feed force measured by the smart turning tool and the Kistler Minidyn respectively. The cutting force signal patterns captured by the smart turning tool show in good agreement with those simultaneously captured by the Kistler Minidyn dynamometer.

4. Conclusions

This paper presents an innovative development of a refitted smart turning tool, using piezoelectric film sensors as sensing elements integrated within the tool shank, to measure cutting force and feed force in process with a high resolution and accuracy. The experimental testing and cutting trials are performed to assess the smart turning tool, which show the tool can measure the cutting forces in process with 0.1 N resolution within the range of 10 N. The smart turning tool has great potential for ultraprecision and micro cutting purposes particularly in machining high value difficult-to-machine materials. Currently, the authors are further developing the wireless transmission capability integrated with the tool, which will be reported separately in the near future.

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