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Acoustic emission based tool contact detection for ultra-precision machining

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ABSTRACT

Precise tool length measurement and work coordinate setup have been challenging tasks in ultra-precision machining. An acoustic emission (AE) sensor can be used to do both tasks at the same time based on AE generated on contact. First, a parametric study was conducted to identify the relationship between damage on the workpiece and key parameters. Second, two approaches, continuous and incremental, were proposed to minimize the potential damage to the workpiece surface. The incremental method produced much smaller damage while the continuous method minimized the setup time. Proper selection of either method depending on the application would improve the precision of tool length and work coordinate setup.

1. Introduction

Many machine manufacturers have introduced various configurations of multi-axes machines with one nanometer or one angstrom command resolution for the table movement. While machine capability advances, peripheral technologies critical to achieve integrity of form accuracy and surface quality are not quite able to match the level of precision of such machines [1]. For example, fabrication of precision lens molds requires precise tool and work setting. However, accuracy of commercially available tool setters is on the order of 100 s of nanometers at best and work setting needs to be done separately at the micron level. If on-machine measurement is not available, additional tool setting is required for compensation cutting, which makes the whole process much more difficult and time consuming. Hence, referencing the tool tip position to the workpiece becomes a big challenge to guarantee required form accuracy.

To address this challenge, research work has been conducted by several researchers following diverse approaches, differing in their sensor principle and functionality (Fig. 1). Liang [2] developed a system for tool length determination using a laser beam. A photo detector measures the amount of light emitted by a laser source. A decrease in photocurrent indicates a blockage of the beam by the tool and thus, its position can be determined. Popov et al. [3] proposed a combination of laser-based tool length measurement and conductivity-based contact detection. Compared to the only laser-based solution, this approach has an advantage of determining the actual contact to the workpiece instead of only measuring the tool length. However, due to the need for conductivity of the workpiece material, this technology is restricted to conductive materials only.

Min et al. [4] proposed the possibility of using an acoustic emission (AE) sensor for tool length determination of end mills, by vertically approaching the workpiece in incremental steps of 0.1 μm with the rotating tool while monitoring the signal generated by an AE sensor mounted to the workpiece. Bourne et al. [5] introduced an analytical model predicting the surface damage caused by an acoustic emission-based contact detection process depending on material, surface and process parameters.

At the level of ultra-precision, tool and work setting requires an easy setup without removing the tool, high sensitivity of the sensor being used, and automatic offset setting in the controller. In this study, an acoustic emission sensor was chosen to meet all the requirements mentioned above. The challenge of using the AE sensor for the tool contact detection is to reduce any resulting surface damage to less than the required tolerance of surface quality and form accuracy while generating contact signals distinguishable from noise.

2. Surface damage and signal sensitivity

The strength of the AE signals depends on the media where elastic energy is released generating elastic waves which propagate to the surface. Therefore, the larger the instantaneous impact exerted during contact the stronger the AE signals are. The amount of the instantaneous impact is influenced by tool diameter, spindle speed, feed, etc. The modulus of elasticity influences the signal strength of the AE sensor at the contact as well. Previous research proved that stainless steel produced clearer signals and thus less surface damage at the contact than aluminum [4].

First, surface damage and signal strength at the contact were investigated for varying spindle speeds. The stainless steel 304 for the workpiece and two-flute tungsten carbide endmills with diameters of 127, 254, and 508 μm were used for the experiments. A block of the workpiece is mounted on the spring loaded AE sensor unit (PZT-type). The feed in *z*-direction was manually applied at 0.1 μm increments.

Fig. 2 shows the surface damage and threshold crossing voltages for the 508 μm, 254 μm and 128 μm diameter endmills where the threshold values are set to 200 mV, 35 mV and 35 mV,

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Direct Methods (tools as reference standard)				Indirect Methods (separate reference standard)
Laser	Acoustic emission	Vision	Conductivity	Tactile touch probe

Fig. 1. Methods for tool length measurement and tool–workpiece contact detection.

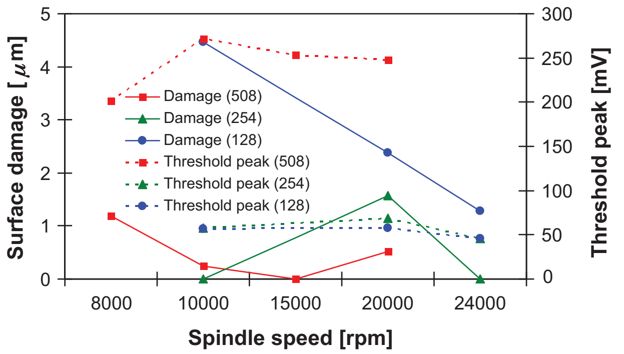

Fig. 2. Surface damage and threshold peak amplitude vs. spindle speed (input gains: 50 dB for 508 μm and 40 dB for both 254 μm and 128 μm).

respectively. A Wyko NT3300 white light interferometer was used to evaluate the surface damage for this and subsequent tests. For the two larger diameter tools (508 and 254 μm), the surface damage was under 1.6 μm regardless of the spindle speed, which is within the surface roughness tolerance. On the other hand, it showed a strong dependency on the spindle speed for the 128 μm diameter tool. For the larger tools, when the interaction during the contact emits a strong enough signal to cross the threshold value, the surface damage resides within the irregularity of the surface. However, for the smaller tool, the system requires stronger signals by increasing either incremental feed or spindle speed in order to exceed the threshold value. Otherwise, the damage becomes inversely proportional to those parameters until acoustic energy reaches a proper level.

3. Automated touch detection

3.1. Two methods for tool approach

For the practical use of AE sensor-based contact detection, automatic offset setting on the controller of the machine was applied. The generated AE signals were monitored through a LabView program running on a computer and trigger values were adjusted to generate the required signal to the controller. Therefore, the time delay from contact to the G-code stop on the controller results in further damage on the workpiece after the contact is detected. This delay depends on the signal processing equipment, signal conditioning methods, monitoring program interference, and reaction time of the automated control loop. Typically the reaction time of the automated control loop is predefined and can be compensated for. With this setup, data acquisition and processing had reaction time of 40–60 ms each, respectively. It is obvious that an approach at even a slow constant feed rate would lead to significant surface damage. For example, at a feed rate of 3 mm/min, a delay of 50 ms recording and 50 ms processing time would imply a damage of 5 μm without

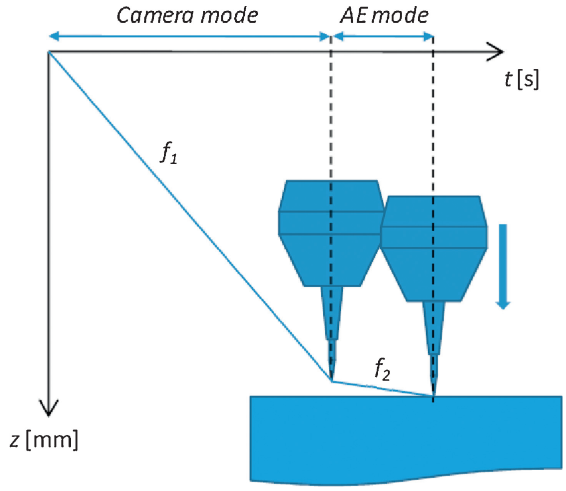

Fig. 4. Schematic illustration of two-stage feed approach.

considering feedback time delay. This delay can be minimized by handling all the processes and programs in a digital signal processor (DSP). But uncertainty still exists.

Therefore, two approaches, the incremental method and the continuous method, are proposed. The incremental method lets the rotating tool progress downward at an increment of 1 μm, stopping for 200 ms at every step allowing for sufficient signal processing time, which results in an equivalent feed rate of approximately 0.3 mm/min (Fig. 3 (left)). The CNC program is interrupted once the preset condition is met (i.e. threshold excess) and the 200 ms accounts for total system delay.

For the continuous method the tool moves downward at a feed rate of 1 mm/min with a high frequency (2 MHz) monitoring cycle (Fig. 3 (right)). When the unfiltered signal exceeds the threshold, feed motion stops and signals are monitored at 100 KHz with a filter to identify actual contact. If the triggering was due to noise, the tool continues to move until the actual contact is detected. This method will reduce the setup time even though larger damage is expected.

It takes about 3 min for the incremental method and 1 min for the continuous method to travel a 1 mm distance from the workpiece. If the increment was reduced to the machine command resolution (0.1 μm in this experiment), it would take 30 min with the incremental method for a 1 mm travel. Therefore, a two-stage feed approach was applied to both methods to reduce unnecessary travel time before contact (Fig. 4).

A compact microscope is used to monitor the position of the tool tip relative to its surroundings. Through image processing, the distance between the tool tip and its reflection on the workpiece surface can be measured. If the material is not reflective, then another reference image can be substituted. It takes about 125 ms per frame for image acquisition and distance processing. During the evaluation test, an initial approaching feed rate, f_1, was 10 mm/min, resulting in a distance of 20.8 μm travelled during one cycle. The microscope was adjusted to a scale of 14 μm/pixel and a skip signal is generated to the machine to switch to the slower AE-mode feed rate, f_2, when reaching a distance of 10 pixel which is equivalent to a distance of 140 μm between the tool and its reflection, resulting in a height of about 70 μm above the workpiece surface.

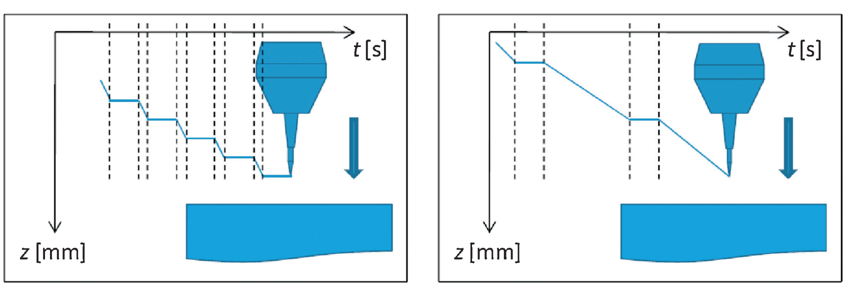

Fig. 3. Schematic illustration of incremental approach method (left) and continuous approach method (right).

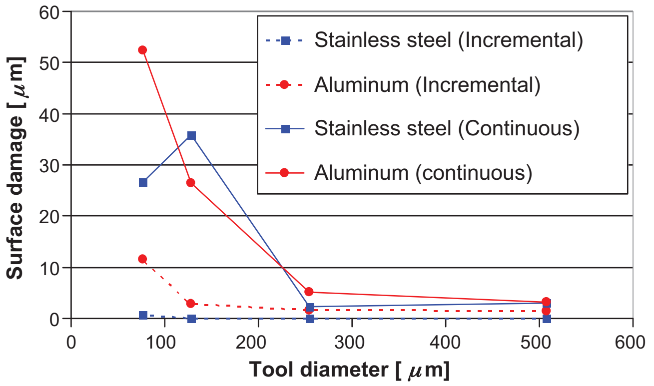

Fig. 5. Surface damage vs. tool diameter (incremental step height: 1 μm, feed rate: 1 mm/min, spindle speed: 24,000 rpm).

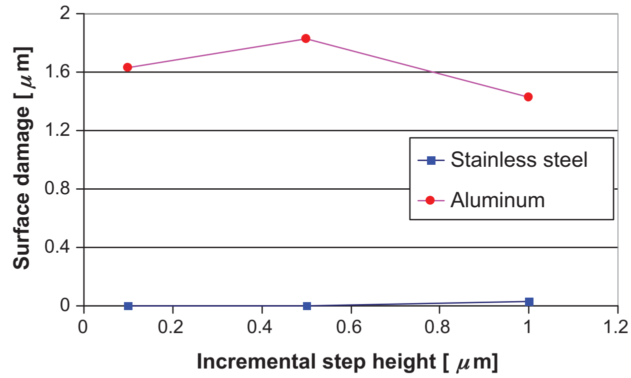

Fig. 7. Surface damage vs. incremental step height for incremental method (tool diameter: 508 μm, feed rate: 1 mm/min, spindle speed: 24000 rpm).

3.2. Experimental results

The complete setup was tested on a Mori Seiki NV1500DCG machining center (table command resolution of 0.1 μm and maximum spindle speed of 24,000 rpm) with two workpiece materials, stainless steel 304 and aluminum 6061-T6511, and two-flute endmills with diameters of 508, 254, 128, and 77 μm for the two AE approach methods (incremental and continuous). Furthermore, the approach speed was varied for the continuous method and the incremental step size was varied for the incremental method.

Three repetitions were conducted for every parameter set. A Wyko NT3300 white light interferometer was used to evaluate the surface damage as before. Sample workpieces of 6 mm thickness were milled and fly cut to a surface roughness of Ra 0.20 μm for aluminum and Ra 0.29 μm for stainless steel. An AE sensor holder was designed which could be integrated into a clamp for the spring loaded sensor against the bottom surface of the work piece. A steel bearing ball with a diameter of 3 mm was glued to the membrane of the AE sensor for optimal contact between the sensor and workpiece. The sensor amplifier was operated in RMS mode with a time constant of 0.02 ms. The experimental conditions and results are summarized in Table 1.

Figs. 5 and 6 show surface damage over the tool diameter variations for both methods. Overall, the continuous method produced more damage due to the time delay to send a skip signal to the controller when the tool contacted the work surface. If the required surface quality or form accuracy is given, with a proper selection of feed rate, threshold value, and sample rates this method can be applied with increased productivity due to reduced setup time.

For both methods, the damage increases as the tool diameter decreases due to the reduced interaction between the tool and the workpiece. The acoustic energy generated by the interaction decreases as the tool diameter becomes smaller. Therefore, either higher feed rate or faster spindle speed is required to generate the minimum required AE signal and reduce damage to the workpiece. Further investigation will be conducted with higher spindle speeds and smaller incremental steps.

Due to a higher modulus of elasticity, stainless steel shows less damage than aluminum without exhibiting any dependency on the tool diameter. Therefore, instead of using minimum incremental step height which is determined by the machine specification, a larger step height can be used to shorten the setup time.

The incremental step height significantly influences the total setup time and defines an interaction envelop between the tool and the workpiece which influences the acoustic energy during the

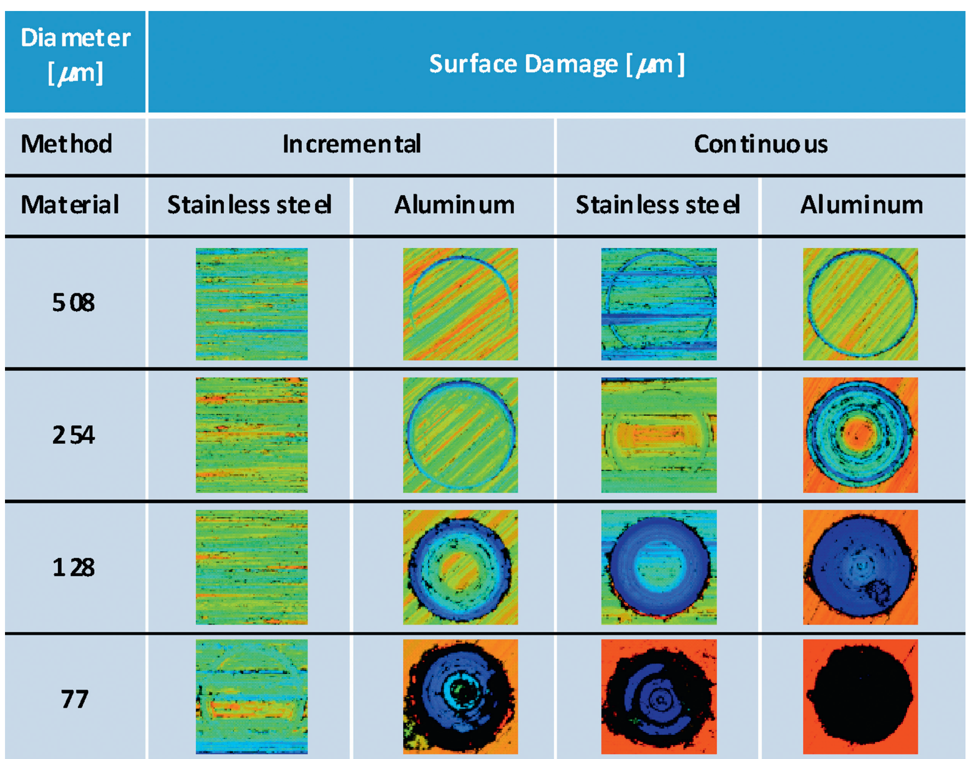

Fig. 6. Wyko images of the surface damage for varying tool diameter (incremental step height: 1 μm, feed rate: 1 mm/min, spindle speed: 24,000 rpm).

Table 1
Experimental conditions and surface damage.

Method	Diameter [μm]	Spindle speed [rpm]	Material	Feed rate [mm/min]	Step height [μm]	Surface damage [μm]	Standard deviation [μm]
Incremental	508	24,000	Stainless	1	1	0.03	0.06
					0.5	0.00	0.00
					0.1	0.00	0.00
			Aluminum	1	1	1.43	0.35
					0.5	1.83	0.40
					0.1	1.63	0.40
		20,000	Stainless	1	1	0.00	0.00
			Aluminum	1	1	1.93	0.90
		16,000	Stainless	1	1	0.00	0.00
			Aluminum	1	1	2.30	1.01
	254	24,000	Stainless	1	1	0.00	0.00
			Aluminum	1	1	1.53	0.35
	128	24,000	Stainless	1	1	0.00	0.00
			Aluminum	1	1	2.77	1.46
	77	24000	Stainless	1	1	0.7	0.00
			Aluminum	1	1	11.60	2.40
Continuous	508	24,000	Stainless	1		2.93	3.09
				3		7.20	3.99
			Aluminum	1		3.23	0.38
				3		6.43	0.45
	254	24,000	Stainless	1		2.23	0.76
			Aluminum	1		5.17	2.47
	128	24,000	Stainless	1		35.80	33.20
			Aluminum	1		26.47	25.34
	77	24,000	Stainless	1		26.63	20.85
			Aluminum	1		52.40	34.31

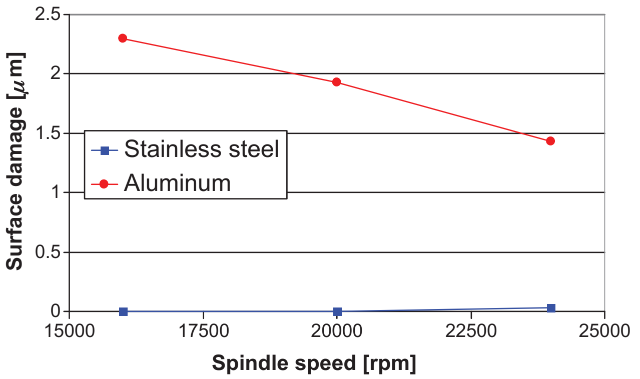

Fig. 8. Surface damage vs. spindle speed for incremental method (incremental step height: 1 μm, tool diameter: 508 μm, feed rate: 1 mm/min, spindle speed: 24,000 rpm).

contact. A minimum degree of interaction between the tool and surface is necessary to exceed the AE signal threshold. Stainless steel emitted enough signal at contact for all incremental steps and visible damage was hard to observe. Aluminum required much higher engagement with the workpiece and minimum penetration for this experimental setting was about 1.5 μm (Fig. 7).

A clear influence of the spindle speed on surface damage was observed for aluminum in the incremental method when large engagement of the tool to the workpiece is required (Fig. 8). This corresponds to the linear relation between cutting speed and the AE signal root mean square value [6]. Therefore, for materials with a relatively low modulus of elasticity, the optimal cutting speed should be sought to minimize damage to the workpiece.

4. Conclusion

For ultra-precision machining, automated tool/work setting is critical to reduce setup error and time. A reliable tool/work setting method enables flexible tool changes and possibly an ATC (automatic tool changer) for ultra-precision application. The AE sensor is a feasible approach for high precision tool contact detection, even with some damage on the work surface that can be minimized within the pre-conditioned surface roughness. A reliable and fully automated contact detection methodology was developed and setup time was remarkably reduced with the help of camera-based image processing to allow accelerated approach feed rates before slowing the approach speed for contact at a reduced distance from the workpiece.

Two methods for final approach to contact were proposed. The incremental method, which aims at delay time compensation through sufficient dwell time at each increment, has proven to be the more accurate method for contact detection. Although the reaction time caused by filtering was compensated for by a dwell time of 200 ms at each incremental step, the contact surface of the aluminum 6061 workpiece still featured a relatively large amount of cutting damage. Increasing spindle speed can reduce the damage for materials with a smaller modulus of elasticity but this is limited to the machine capacity. The continuous method was designed for better productivity but it generally creates relatively larger damage due to the continuous tool movement. Both methods can be applied to set work coordinates and tool offsets in X and Y directions and this will be investigated in the future.

As a further improvement, adaptive digital filters or digital signal processing (DSP) could be used for the band pass filtering or faster signal processing to decrease the complexity of the contact detection setup. Reducing the time needed for signal processing would allow a faster feed rate for the incremental method.

Further decrease in signal noise could reduce the requirement for filtering and decrease the possible detectable tool diameter. Instead of the camera used here, a commercially available, vision-based tool length and condition monitoring system could be applied to measure the tool length within a specific uncertainty. This way the machine tool could travel to a certain distance above the workpiece in rapid traverse before switching to the slower AE-based feed movement.

References

[1] Dornfeld DA, Min S, Takeuchi Y (2006) Recent Advances in Mechanical Micromachining. *Annals of the CIRP* 55(2):745–768.
[2] Liang SY (2006) Mechanical Machining and Metrology at Micro/Nano Scale. *Proceedings of SPIE* 6280.
[3] Popov K, Dimov S, Ivanov A, Pham DT, Gandarias E (2010) New Tool–Workpiece Setting Up Technology for Micro-milling. *International Journal of Advances in Manufacturing Technology* 47(1-4):21–27.
[4] Min S, Sangermann H, Mertens C, Dornfeld DA (2008) A Study on Initial Contact Detection for Precision Micro-mold and Surface Generation of Vertical Side Walls in Micromachining. *Annals of the CIRP* 57(1):109–112.
[5] Bourne KA, Jun MBG, Kapoor SG, DeVor RE (2008) An Acoustic Emission-based Method for Determining Contact between a Tool and Workpiece at the Microscale. *Journal of Manufacturing Science and Engineering Transactions of ASME* 130(3). 031101-1–031101-8.
[6] Kannatey-Asibu E, Dornfeld DA (1981) Quantitative Relationships for Acoustic Emission from Orthogonal Metal Cutting. *Journal of Engineering for Industry* 103(3):330–340.