

Precision Force Measurement and Control in Micro Ultrasonic Machining

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Abstract: Micro ultrasonic machining (Micro-USM) is a process with a great capability to generate micro features in hard and brittle materials. Despite some developments in micro-USM process, issues such as precision measurement and control of the machining force, which is crucial for stable machining conditions, need further investigations. In this paper, the precision measurement and control of the machining force is studied using a newly-developed force measurement configuration. The results of the force measurement for different levels of static force, abrasive particle size and amplitude of vibration demonstrated that the variation of measured machining force increases at higher static forces. Furthermore, a better control over the static load was acquired when feeding the abrasive slurry with particle size of 0.37 μm as compared to 1 μm and 3 μm particles leading to more stable machining conditions in micro-USM process. Finally, applying lower levels of vibration amplitude to the workpiece resulted in more stable machining conditions and lower static load errors.

Keywords: Machining force, Measurement and control, Micro ultrasonic machining, Static force

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1 INTRODUCTION

Research advancement in the field of micro-manufacturing is encouraged by the rising demand on miniaturized features, components and products as well as promising developments in adoption of various existing macro-manufacturing techniques for micro-scale manufacturing. One such technique is ultrasonic machining (USM), in which the potential of the abrasive particles within a fluid is exploited for material removal of hard and brittle materials with no thermal damage induced into machined surfaces and no direct contact between tool and workpiece. As such, micro-USM turned to be a niche micromachining process to make micro components and micro features from hard and brittle materials such as silicon, glass, and ceramics in a cost-effective way [1], [2]. Also, this technique has revealed to be a competitive alternative for micromachining processes such as diamond micro grinding and micro laser beam machining (micro-LBM) [2-4]. It is postulated that micro-USM is capable of providing practical solutions towards the realization of large MEMS structures as well as packaging for both prototype and production in silicon, glass and ceramic materials [5].

Since the first attempt to realize the micro-USM process, there have been some improvements in design and configuration of micro-USM system [2], [6], [7]. While these advances have resulted in enhancement of the process efficiency and accuracy, some technical issues such as repeatability, accuracy, and controllability need to be addressed in order to introduce micro-USM as a reliable micromachining process for commercial use [2], [8]. One of the major issues affecting the accuracy of the micro-USM system is the precision measurement and control of the machining force. During the process, the micro-tool has to progress towards the workpiece and maintain a constant gap to achieve continuous material removal and stable machining conditions. A machining gap larger than optimum level causes the particles to lose their effective kinetic energy before striking the workpiece surface. On the other hand, if the gap is too small the particles would be suppressed by micro-tool and would not have sufficient energy to impact on the workpiece surface.

In both conditions, the material removal rate is low or even nearly zero. The optimum machining gap is achieved via precise measurement and control of the machining force during the process. Furthermore, downscaling from macro-USM to micro-USM necessitates a reliable force measurement and control system to obtain a stable micromachining process and to protect the tiny tool from breakage. Mismatched tool-workpiece interactions not only affect the stability of the micro-USM process but also cause the breakage

of micro-tools [9]. It has been reported that around 60% of micro tool breakages are caused by mishandling of initial engagement of tool-workpiece [9]. Furthermore, after the onset of machining, the interface between tool and workpiece is changing continually and thus it is hard to guarantee the repeatability of the machining quality [2], [4], [10]. Due to these issues, a sensing and monitoring system is essential to control the condition of the machining gap.

Moronuki and Brinksmeier successfully applied the acoustic emission (AE) technique in micro-USM process [2]. They used AE sensor to detect the initial tool-workpiece contact which resulted in reduction of the probability of tool breakage. Also, real-time compensation of tool wear was realized by detection of drop in AE output signal as an indication of tool wear which results in a smaller depth of machined feature compared to the set depth of cut. Consequently, the Z-axis infeed is given to the tool until the output of AE signal reaches the set value again. Nevertheless, it has been reported by Zhang et al., [9] that the AE output signal is affected by the position of the workpiece mounted on the work table. Furthermore, they identified that the positional dependence of AE output signal, intrinsically depends on the employed ultrasonic vibration generator.

Other methods have been proposed for measuring the machining force in micro-USM. A digital balance with resolution of 10 mg and response time of 10 millisecond was proposed in [1]. Also, an electronic balance with a minimum index of 1 mg was installed in a micro-USM experimental setup acting as the sensor for feedback control [3] and a holder for ultrasonic transducer was placed on the balance. This method was used in other micro-USM research works [8], [11], [12]. However, it was reported in [8] that low frequency and small sampling rate are the major limitations of the electronic balance used as the load sensor hampering the realization of a high-performance static load control.

In another study, Kuriyagawa et al. [13] developed a micro ultrasonic abrasive machining where a small piezoelectric dynamometer with maximum allowable load of 50 N was employed to control the machining forces of 100 mN or larger. However, they reported that accurate measurement by piezoelectric dynamometer was not possible at set machining forces less than 100 mN due to drift and noise. Therefore, a double-beam strain gauge dynamometer with a maximum allowable load of 1.2 N was used instead. It is important to note that employing the dynamometer with such small working range is feasible in the case of micro-USM with tool vibration method rather than workpiece vibration approach. On the other hand, the combination of both oscillation and rotation of the micro-tool in micro-USM by tool vibration method

could result in a complex layout for spindle and tooling system. A precision position measurement and force measurement were developed and reported in [14] enabling the control and measurement of forces in the low mN range. However, the force measurement in this system is more accurate when it is used horizontally rather than vertically and it may not be appropriate for ultrasonic machining process [14].

In this paper, the precision measurement and control of the machining force exerted on the micro-tool during the micro-USM process, is studied using a newly-developed force measurement configuration. The results of the force measurement for various machining conditions are presented to investigate the stability and performance of the proposed technique. The results indicate that the force measurement and control system is capable of measuring the minute forces and stabilizing the static load with a rapid response through a reliable control of the tool infeed. It is expected that these characteristics would lead to solve some issues in previous works mentioned earlier in this section.

2 EXPERIMENTAL METHODS AND PROCEDURES

2.1. Experimental setup

The experimental setup, shown in figure 1, consists of an in-house built micro-USM system based on workpiece vibration method which is an effective and well-proved approach due to advantages such as simplicity of the spindle system, high accuracy of the tooling system, and effective agitation of the abrasive slurry giving rise to facilitating the debris removal as compared to micro-USM with the method of tool vibration [3], [15].

The developed micro-USM system consists of six main units: power generator and ultrasonic stack (transducer, booster and horn), motion control system, force measurement and control, tooling system, workpiece vacuum clamping, and slurry delivery system. The ultrasonic vibration with the frequency of 50 kHz is generated in two stages: first, the conversion of low-frequency signal to high frequency electric voltage by power generator; second, conversion of electrical energy into mechanical vibrations via ultrasonic transducer. The ultrasonic vibration is transmitted to the workpiece through booster and horn.

The system is capable of providing vibration amplitudes ranging from 0.8 to 5 μm . The workpiece is held on the face of ultrasonic horn using a vacuum clamping system consisting of vacuum pump, liquid separator and flexible tubes. The slurry delivery system consists of magnetic stirrer, peristaltic pump, and flexible tubing, and supplies the fresh abrasive particles and flushes, the debris and crushed particles from the

machining zone. The abrasive slurry needs to be agitated well to prevent the particles from settling down and to provide a homogenous suspension of the particles in water. Therefore, a magnetic stirrer is used to stir the slurry with a certain concentration before feeding into the system. A peristaltic pump with flexible tubing delivers the slurry into the machining zone with a controlled flow rate.

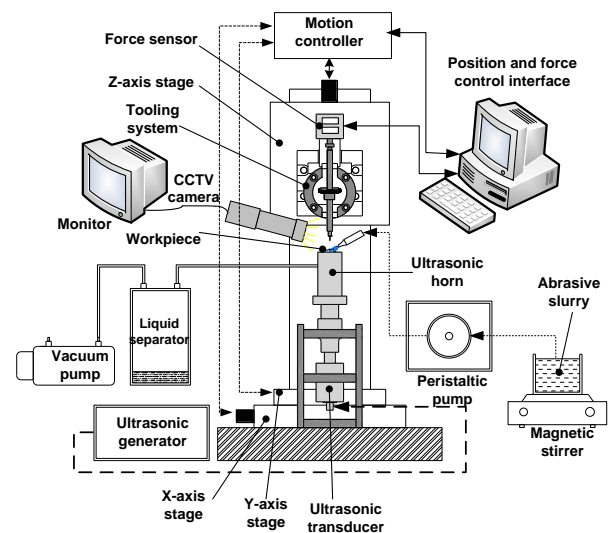


Fig. 1 Schematic of the developed micro-USM system

The micro-tooling system entails a precision mandrel on which cylindrical micro-tools with diameter of 60 up to 300 μm can be mounted and rotated with a controllable rotational speed. A three-axis stage is used for tool positioning. Machining gap is controlled by using a piezo-motor with driver and receiving the CNC commands from the computer for tool positioning and control in z-axis with steps of 30 nm.

2.2. Force measurement and control system

Figure 2 depicts the configuration of the force measurement system using a load cell which acts as a precision force sensor. It is integrated with the tooling system through a precision steel ball to facilitate the accurate rotation of the micro-tool.

Unlike methods such as using dynamometer or digital balance whereby the force measurement component is introduced in workpiece side, in the proposed configuration the sensor is introduced in tool side resulting in elimination of some errors caused by the noise and vibration of ultrasonic horn, dead weight of the ultrasonic stack and fixture, and weight variations of the slurry during the process. The sensor can be used for both tensile and compressive forces enabling the precision measurement of variations in contact force between tool and workpiece. Also, the system has a built-in overload protection feature.

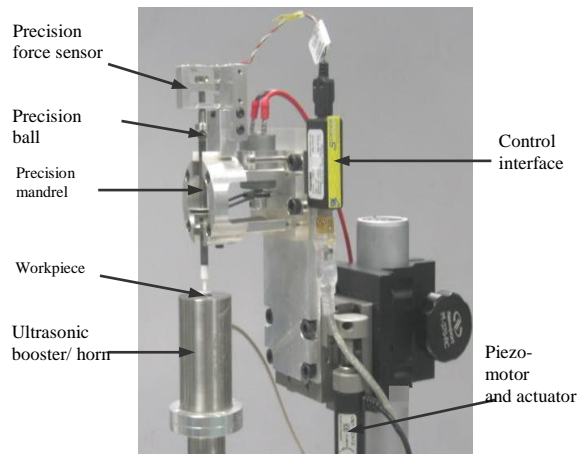


Fig. 2 Configuration of the developed force measurement system

The feedback for control the tool vertical position comes from the precision force sensor and control interface. The system can accommodate a large range of forces up to 4000 millinewtons. Also, it is capable of measuring the machining force with a high sampling rate and frequency response of 1 kHz which is suitable for micro-USM process and such an application has not been reported in literature.

2.3. Experimental design and parameters

Machining force was measured and controlled for various machining conditions by setting the process parameters (factors) at different levels. The experiments were conducted with the purpose of studying the stability and performance of the proposed force measurement technique. Three series of experiments were conducted using “one-factor-at-a-time” (OFAT) method. In each set of the experiments, the level of one factor was changed while keeping the rest of the parameters at their respective fixed values. The layout of experimental design including various factor levels and fixed values are presented in table 1. The levels were chosen based on literature as well as results from a series of preliminary machining experiments with tentative factor levels using the developed Micro-USM system.

Table 1 Factor levels and fixed values for experiments

Process parameter	Unit	levels	Fixed value
Static load	mN	10, 20, 30, 40	20
Vibration amplitude	μm	0.8, 2, 4	2
Abrasive particles size	μm	0.37, 1, 3	1

2.4. Micro-USM experiments and employed materials

Micro-USM experiments were conducted using the developed machine system. The workpiece is clamped by the vacuum chuck and it is vibrated by ultrasonic horn. The frequency of vibration is fixed at 50 kHz and the amplitude of vibration is adjusted at the desired level by varying input voltage to the ultrasonic transducer. A Polytec™ laser scanning vibrometer was employed to ensure that the vibration frequency and amplitude of the workpiece remain at desired levels during the machining process.

The workpieces used in experiments were $9.5 \times 9.5 \text{ mm}^2$ in size and were obtained by dicing from a polished silicon wafer with diameter and thickness of 100 mm and 0.525 mm respectively. Cylindrical bars from tungsten with length of 80 mm were employed as micro tools. The tool tip was ground and inspected after every single experimental run using a test stand equipped with microscope to ensure that the tool face is flat with a burr-free edge. If the tool face is uneven with any pitting remained from previous experiments, it may affect the contact conditions of the micro tool with workpiece surface. Also, the straightness as well as run-out of the micro tool was tested to prevent an uneven contact between the micro tool face and workpiece surface leading to reduction of errors in measurement of the machining force. This is also effective in achieving uniformly distributed layers of abrasive particles in the machining gap especially at the start of the machining process. Deionized water is used as the fluid for abrasive slurry. The slurry is agitated using an ultrasonic cleaning bath for 15 to 20 min immediately before feeding into the slurry delivery system. This could help to wet the particles thoroughly and to avoid the agglomeration of the particles. The summary of experimental parameters and conditions are presented in table 2.

Table 2 Experimental parameters and conditions

Process Parameter	Setting
Vibration frequency	50 kHz
Tool material	Pure tungsten
Too diameter	300 μm
Workpiece material	Silicon <100>
Abrasive particles	Polycrystalline diamond (PCD)
Slurry medium	Deionized water
Slurry concentration	1% wt

Before the onset of the machining process, abrasive slurry is supplied into the gap between the micro tool and workpiece. Then the rotated micro tool is brought close to the workpiece by moving down the z-direction stage with a minimum speed of 40 nm/sec. When the micro tool contacts with abrasive slurry and a contact

force of 1.5 to 2 mN is obtained, the z-axis is stopped. This force value could establish an effective initial static load to start the machining process and to stabilize the machining conditions based on a series of preliminary experiments. Following that, the static load is zeroed through the force measurement interface software and machining process starts subsequently by infeed of the micro tool. From then on, the static load is regulated at the set value (desired level) via a close-loop position control of z-axis with minimum incremental motion of 30 nm and with force feedback. The measured force values are recorded via the force measurement interface during the micro-USM process to monitor the machining force and to calculate the deviations from the set value of static load. Abrasive slurry is supplied continuously into machining zone with flow rate of 55 ml/min and it plays a significant part in achieving stable machining conditions.

3 FORCE MEASUREMENT RESULTS AND DISCUSSION

3.1. Force measurement for various levels of static force

The machining force values are recorded in a data file during the micro-USM process, and its average is calculated to be the static load. The results of the force measurement for different force levels using the developed force measurement and control system are presented graphically in figure 3.

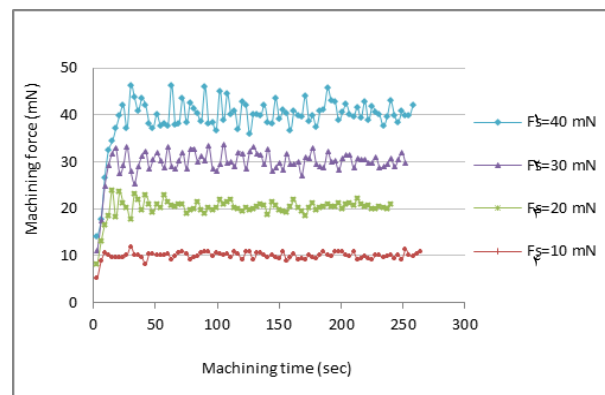


Fig. 3 Signal of machining force for various levels of static load

As illustrated, the variation of measured machining force increases with an increase of force level. Also, the average value and standard deviation of the measured machining force for various force levels are presented in table 3. The maximum static load error is 1.2 % which corresponds to set static load of 40 mN. These results indicate that the condition of the machining gap is more stable when applying smaller

static forces. Also, the proposed force measurement and control system is capable of maintaining the static force (average value) at a certain level especially in lower range.

Table 3 Measured machining forces for various levels of static load

Static load level (mN)	10	20	30	40
Average machining force (mN)	9.9	20.2	29.8	39.5
Standard deviation - mN	0.82	2.01	3.05	4.74
Static load error (%)	1	1	0.7	1.2

3.2. Force measurement for various particle sizes

Figure 4 illustrates the machining force signal during micro-USM using particle sizes of 0.37, 1 and 3 μm and set static load of 20 mN.

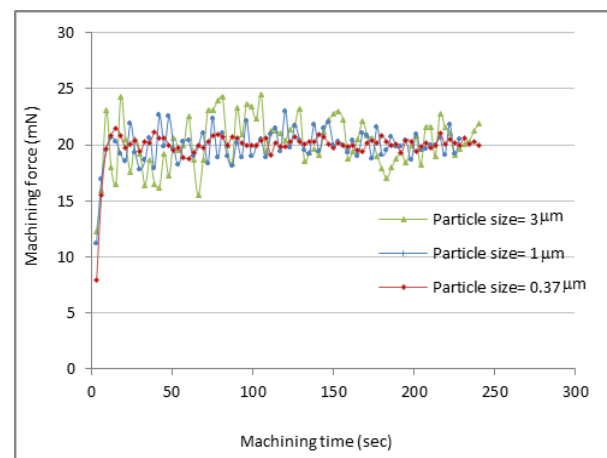


Fig. 4 Signal of machining force for various particle sizes

It is clear that the proposed force measurement and control system provide a better control over the machining gap and hence the machining force when using the particle size of 0.37 μm as compared to particle size of 1 μm and 3 μm . Therefore, applying the abrasive slurry with smaller particles size could give rise to a more stable micro-USM process. As can be seen from the results in table 4, using abrasive particles with size of 0.37 μm results in a static load error as small as 0.35 % whereas using abrasives with particle size of 3 μm , the deviation from set value of the static load reaches up to 1%.

Table 4 Measured machining forces for various levels of particle size

Particle size (μm)	0.37	1	3
Average machining force (mN)	19.93	19.90	20.20
Standard deviation (mN)	1.54	1.6	2.34
Static load error (%)	0.35	0.5	1

*static load level=20 mN

3.3. Force measurement in different levels of vibration amplitude

Figure 5 shows the experimental results of the machining force measurement in micro-USM with vibration amplitudes of 0.8, 2 and 4 μm . The force variation rises as higher amplitudes of vibration are applied to the workpiece. Also, it can be seen that at the early stage of the machining process, the variation in measured machining force is high for all particle sizes and it declines over the time. As the machining process progresses further, the conditions of the machining gap stabilize giving rise to smaller variations in machining force. The values of maximum static load error for amplitudes of 0.8, 2 and 4 μm are 0.7 %, 1.5 % and 3.75 % respectively.

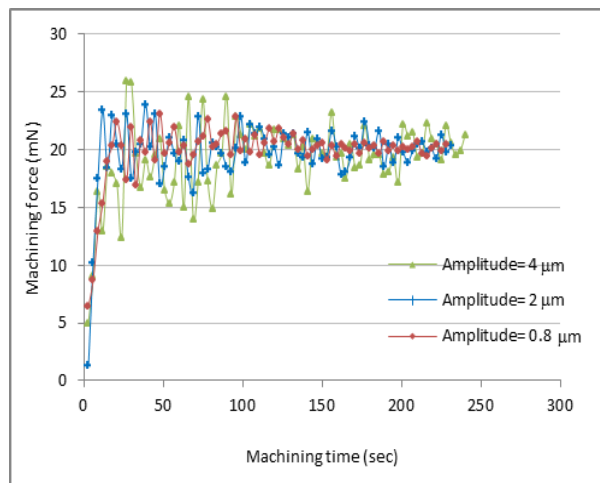


Fig. 5 Signal of machining force for various levels of vibration amplitude

4 CONCLUSIONS

The precision force measurement and control in micro-ultrasonic machining process was investigated using an in-house developed micro-USM system which is based on the workpiece vibration method and utilizes a new configuration for force measurement in which a precision load cell is integrated with tooling system. The proposed system is capable of accurate measurement of the machining force within the range of tens of millinewtons with a high sampling rate and frequency response of 1 kHz which suits the application for micro-USM process.

The results of the force measurement for different levels of static force, abrasive particle size and amplitude of vibration were presented. It was observed that the variation of measured machining force increases with an increase of the force level. Furthermore, a better control over the static load was acquired when feeding the abrasive slurry with particle

size of 0.37 μm as compared to 1 μm and 3 μm particles leading to more stable machining conditions in micro-USM process. Finally, applying lower levels of vibration amplitude to the workpiece resulted in more stable machining conditions and lower static load error.

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