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ORIGINAL ARTICLE

A new approach for force measurement and workpiece clamping in micro-ultrasonic machining

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Abstract Micro-ultrasonic machining (micro-USM) is a promising micromachining technique to meet the increasing demands of high accuracy in processing the micro-components of hard and brittle materials. Unlike the well-established conventional USM, micro-USM still lacks in its commercial viability. The major concerns in micro-USM process are the accuracy of the setup and dynamic behavior of the system associated with precise force monitoring and robust workpiece clamping. In this study, a new micro-USM system with regards to measurement and monitoring of static force as well as tooling and workpiece clamping is developed. A force measurement and control system is proposed which is well suited for machining conditions in micro-USM. Furthermore, a reliable and quick setup for the vacuum chuck is introduced, which is capable of consistently transmitting the ultrasonic vibration from horn to the workpiece. Measurement of acoustic characteristics as well as experimental investigations is carried out to validate the functionality of the proposed system.

Keywords Micro-ultrasonic machining · Static force measurement · Vacuum chuck

1 Introduction

Last decade has witnessed a rapid maturity of the highly sophisticated micromanufacturing technologies to generate miniaturized components in new fields such as micro-electromechanical systems (MEMS), pressure and flow sensors, semiconductor devices, and biotechnology instruments. Employing the proper materials to fulfill the functional requirements of microparts in each field as well as developing the related micromachining techniques is a challenging task. Materials such as silicon, glass, alumina, silicon carbide, lead zirconate titanate, graphite, and quartz crystal, typically known as hard–brittle and non-conductive materials, are frequently used in aforementioned components and systems. Among all mechanically based and energy-based micromachining processes used to fabricate miniaturized components and micro-structures of hard–brittle materials, micro-ultrasonic machining (micro-USM) has shown promise as an effective and practical technique [1–4].

The process have two key merits: One is the possibility of using a tool with lower hardness compared to that of workpiece, and the other is the removal of material with zero surface or sub-surface thermal damage in machined zone. Moreover, the nature of material removal in USM does not require direct tool-to-workpiece interaction but utilizes abrasives within a liquid medium as micro-cutting tools. Therefore, the process is well suited for increasing strict demands of dimensional and geometrical accuracy with a stress-free sub-surface in processing the micro-components made from hard and brittle materials for MEMS application.

Since the introduction of micro-USM in the mid 1990s [5], there has been gradual improvements in the configuration of micro-USM system regarding the tool–workpiece interface monitoring, force measurement and monitoring, tooling system, workpiece holding, and horn design which have resulted in enhancement of the process efficiency. However, some technical problems such as repeatability and controllability remain to be resolved for micro-USM to become a reliable commercial micromachining technique [6]. Also, the major concerns in micro-USM process are the

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accuracy of the setup and dynamic behavior of the system associated with precise force monitoring and robust workpiece clamping, respectively.

Minute forces in the order of a few grams have to be generated and maintained in micro-USM. This necessitates a reliable force sensing and monitoring system to control the conditions of machining gap which results in a stable micromachining process. Acoustic emission (AE) technique was used in micro-USM process to detect the tool–workpiece contact and hence to reduce the probability of tool breakage [3, 7]. However, the AE output signal is adversely affected by the intrinsic behavior of the ultrasonic vibration generator.

Moreover, a digital balance with resolution of 10 mg and response time of 10 ms was proposed and testified in [5]. Also, an electronic balance with a minimum index of 1 mg was installed in a micro-USM experimental setup as the sensor for feedback control, and a holder for ultrasonic transducer was placed on the balance [8]. Similar works are also reported in [6, 9, 10]. As an alternative method, a double-beam strain gauge dynamometer with a maximum allowable load of 1.2 N was used to measure the static force in micro-USM process with the method of tool vibration [11]. However, using dynamometer with such a small working range is not feasible in the micro-USM by the approach of vibrating the workpiece because the weight of the ultrasonic stack and holder would exceed the load capacity of the dynamometer.

Applying the vibration to workpiece rather than tool is an attractive method developed by Egashira and Masuzawa [8]. It has merits such as simplicity in design and operation of the spindle system, precision of tooling system, effective agitation of slurry, and ease of delivery of the abrasive particles into machining zone [3, 8]. Besides, this configuration eliminates the adverse effect of tool wear on the vibration amplitude of tool tip which is the case in micro-USM based on the method of tool vibration [12]. Nevertheless, significant characteristics in this approach such as reliable chucking of the workpiece as well as consistent transmission of vibrations from horn to the workpiece influences the process performance and yet to be addressed to enhance the maturity of this process from the practical point of view. Simple mounting of workpiece to the ultrasonic horn such as using the two-sided adhesives may not deliver the vibration uniformly across the workpiece.

In this study, a new force measurement system with a rapid response control is proposed for micro-USM process which is capable of measuring the small forces and stabilizing the static force through a reliable control of the tool infeed. In addition, it is well adapted to various machining conditions in the process.

The experimental setup in the proposed micro-USM system is based on the method of workpiece vibration, and a special designed full-wave booster horn in combination with a standard booster is used to vibrate the workpiece with a frequency of 50 kHz. Also, a new approach using vacuum chuck for holding the workpiece is introduced which is capable of rapid clamping and unclamping the workpiece without causing the fracture in thin and fragile workpieces. In addition, the design is capable of consistently delivering the vibration to the workpiece so that machining with various amplitudes of vibration, suitable for micro-USM process, is achievable with this configuration.

2 Configuration of proposed micro-USM system

The miniaturization of the tool imposes some constraints on the implementation of the micro-USM process, especially in the fabrication and assembly of the tooling system. Mounting and aligning the micro-tools with different sizes are the key issues in this process which affect the accuracy of micro-holes. In this work, the rotation of the tool has been adopted to reduce form errors and to provide flexibility in the tooling system. Holding and vibrating the workpiece simultaneously while maintaining its stability during the machining process is made possible with the design of an integrated vacuum chucking system.

The experimental setup, shown in Fig. 1, consists of four main sub-systems, namely, generation and transmission of ultrasonic vibrations, tooling, workpiece clamping, and motion control. An ultrasonic generator converts the low-frequency voltage into a high-frequency electric voltage. Electrical energy then is transformed to elastomechanical ultrasonic vibration in ultrasonic transducer by piezoceramic converters. Subsequently, the mechanical vibration is transmitted to workpiece via booster and horn. The tooling system comprises a precision mandrel, micro-tool, v-shaped bearing, and a DC motor. Precision mandrel holds the

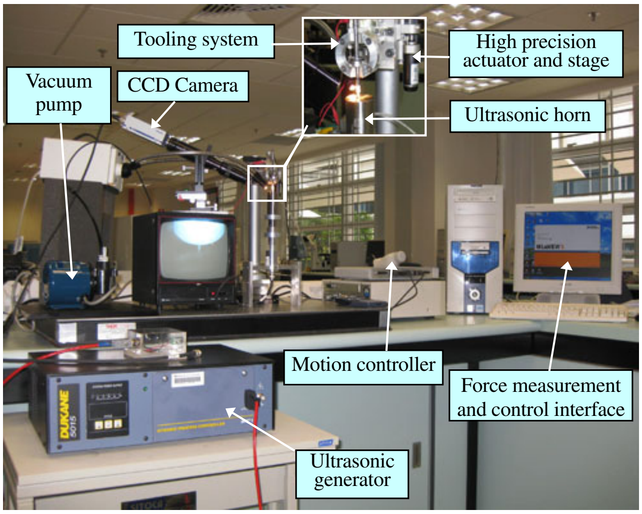


Fig. 1 Setup of micro-USM system

micro-tool, and it is coupled with DC motor with a rotational speed up to 6,000 rpm. The design of tooling system is such that the micro-tool can be fabricated on a WEDG unit of a micro-EDM machine, and then the set of mandrel together with prepared micro-tool can be removed from the EDM machine and mounted on v-shaped bearing of micro-USM system.

The whole tooling system is mounted on a three-axis stage. The micro-tool motion is controlled with a minimum incremental motion of 0.03 μm for *z*-axis and 100 μm for both *x*-axis and *y*-axis. An integrated piezomotor controller/driver is used for tool positioning and control in *z*-axis. The employed *z*-axis actuator ensures highly reliable motion with 30-nm sensitivity and no loss of position when power is removed. This configuration provides an accurate control over the infeed of the tool in the direction of the workpiece oscillation.

For initial machining tests, aluminum oxide powder with average particle size of 3 μm was employed as abrasive within the slurry, and the abrasive slurry was delivered manually into the machining zone. An automatic system for slurry feeding has to be made for longer machining duration.

3 Experimental investigations

3.1 Measurement and control of static force

The static load between micro-tool and vibrated workpiece is measured and controlled in the experimental setup using a precision load cell. Figure 2 illustrates the tooling system with integrated load cell which acts as a force sensor. This design has a merit in that the sensor can be mounted on tooling system without hampering the accurate holding and rotation of micro-tool. Also, it provides a lightweight and compact design which is a high demanding factor in tooling components of micromachining systems. Moreover, utilizing the sensor in tool side eliminates the measurement error arising from dead weight of the ultrasonic stack and fixture as well as the noise and vibration of ultrasonic horn. The sensor can be utilized in both tension and compression; hence, it is capable of precision measurement of variations in contact force between tool and workpiece.

The system is designed such that the machining force can be constantly monitored by the force sensor in order to control the infeed motion of the tool using the computer interface and hence keeping the machining force as constant. Moreover, the system benefits from a built-in overload protection feature.

3.2 Integrated vacuum chuck and horn design

Difficulty in holding the workpiece against ultrasonic horn hampers the efficient use of the micro-USM by the method of workpiece vibration. The frequency of horn vibration is 50 kHz in the present system, and connecting of workpiece to the horn is an important stage in machining process which could affect the accuracy and reliability of the process. Moreover, the diameter of the employed micro-tool is less than 300 μm, and it is prone to breakage. Therefore, any unpredicted displacement of the workpiece should be avoided using a secure clamping system. Using simple methods for attachment of the workpiece to the horn such as sticking by glue or double-sided tape could give rise to rapid detachment of the workpiece.

In this study, the workpiece is held against the ultrasonic horn using a vacuum system as shown in Fig. 3. A fine hole has been machined at the center of the horn face in axial direction, and it meets another hole into which the vacuum tube is connected in a radial direction. The important point

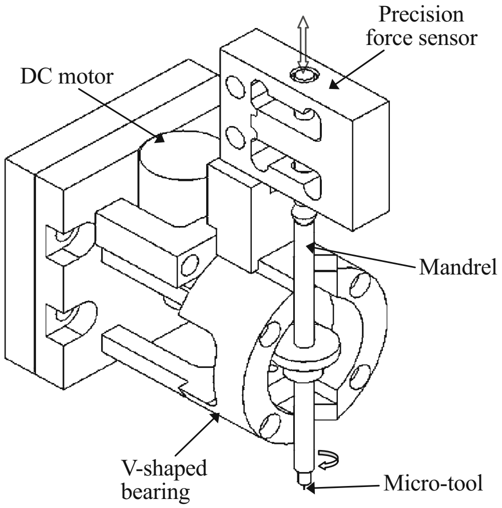


Fig. 2 Tooling system with integrated force sensor

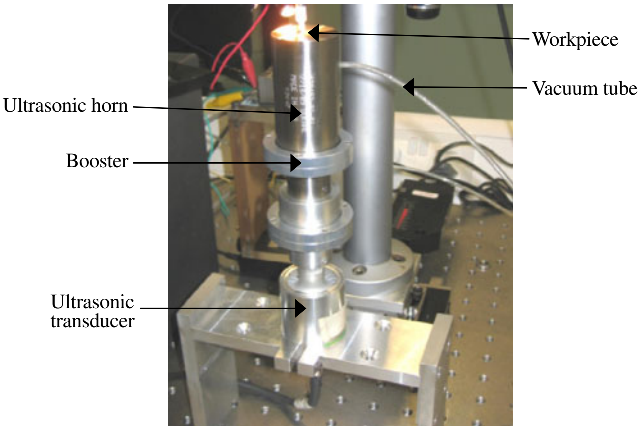


Fig. 3 Ultrasonic horn with integrated vacuum chuck in micro-USM system

is to introduce the vacuum line in the position of nodal point of the ultrasonic horn where the amplitude of vibration is close to zero. This is done by accurate design and fabrication of the horn and cautious mounting of the horn to booster. The vacuum hole should not be threaded; hence, the vacuum tube is connected to the oscillating ultrasonic horn by press fitting. The reason is that machining any thread for vacuum connection may result in cracking. The vacuum tube is connected to a vacuum pump through a liquid separator with filter. Therefore, one can ensure that the abrasive slurry is not allowed to enter the vacuum pump. The proposed method enables a fast, reliable, and productive workpiece clamping system in micro-USM process.

In this setup, an aluminum booster together with a full-wave titanium horn, which has a recess to accommodate the workpiece, is used to transmit the vibration from ultrasonic transducer to the workpiece. Nominal output vibration amplitude of the system ranges between 0.8 and 5 μm using a combination of the reverse booster and horn with the same ratio of 0.5:1 and adjustment of the output power of ultrasonic generator.

4 Discussion of results

4.1 Measurement of amplitude and frequency of vibration

The actual frequency and amplitude of the vibrated workpiece, held against the ultrasonic horn, were measured in order to verify the functionality of the integrated vacuum chuck in the proposed micro-USM system. The workpiece used is a silicon material with dimensions of 9.2×9.2 mm and thickness of 600 μm. A Polytec™ laser scanning vibrometer was used for measurements. The scanning head of the vibrometer includes the scanner mirrors, a video camera, and the interferometer with a helium–neon laser as light source.

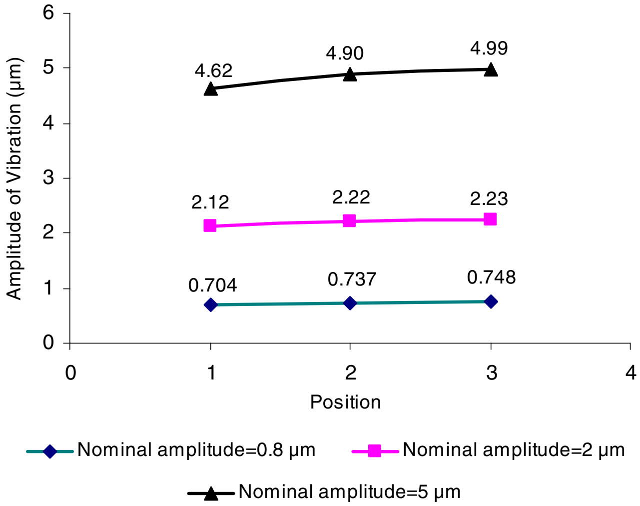


Fig. 4 Actual amplitude of vibration in different positions on the vibrated workpiece with vacuum clamping

Table 1 Frequency of vibration (kilohertz) in different positions on the vibrated workpiece

Position	Nominal amplitude		
	0.8μm	2μm	5μm
1	49.81	49.75	49.75
2	49.63	49.63	49.69
3	49.75	49.88	49.75

Actual amplitudes corresponding to three nominal amplitudes including 0.8, 2, and 5 μm were measured on workpiece surface in three different points with 3-mm spacing to cover the whole clamping area. Figure 4 depicts the measured values of amplitude in different positions.

As shown in Fig. 4, the variation in amplitude of vibration is negligible with change in position across the workpiece especially for lower range of amplitude. The minimum and maximum variations in amplitude of vibration are equal to 5.2% and 8%, respectively. It implies that the vacuum clamping system is capable of consistently delivering the ultrasonic vibration from horn to the workpiece and keeping the amount of amplitude nearly constant throughout it.

Table 1 represents the frequency of vibration in different positions as an important parameter in micro-USM. The mean and standard deviation of the measured frequency values are equal to 49.74 and 0.08 kHz, respectively. These results show that the ultrasonic vibrations can be transmitted to the workpiece effectively by the proposed vacuum chuck, hence resulting in more stability in machining conditions of micro-USM process.

4.2 Measurement of lateral displacement

The lateral displacement of the workpiece, held on the vibrated horn by vacuum, was measured to evaluate the positioning accuracy of the vacuum clamping system. Low amplitude of vibration (0.8 μm) was introduced into horn

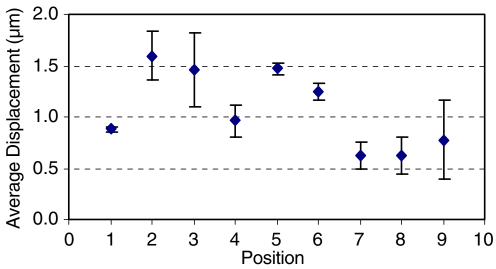


Fig. 5 Lateral displacement in different positions on the vibrated workpiece with vacuum clamping

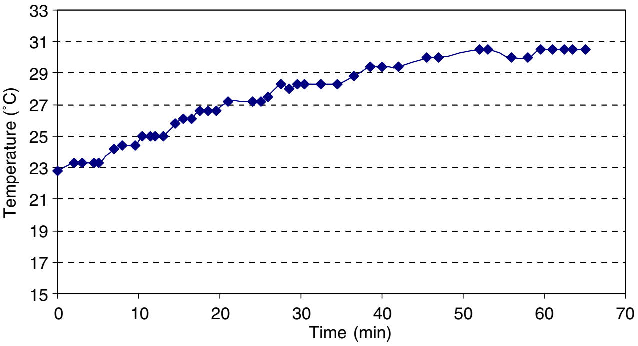


Fig. 6 The effect of vibration time on workpiece temperature clamped by vacuum chuck

with a nominal frequency of 50 kHz. Figure 5 presents the average lateral displacement and standard deviation error in nine different positions along the edge of the workpiece and perpendicular to the vibration direction of the ultrasonic horn. The spacing between positions was selected as 2 mm, and three readings were taken in each position.

As depicted in Fig. 5, the maximum lateral displacement is 1.59 μm which corresponds to position #2. Hence, the maximum error in dimensional accuracy due to the displacement of the workpiece from its initial position on the ultrasonic horn is equal to 1.59 μm. Moreover, minimum displacement is 0.62 μm which takes place in position #7.

4.3 Measurement of surface temperature on the vibrated workpiece

The temperature of the vibrating workpiece was measured as an indication of stability of the horn–workpiece attachment using a Raytk non-contact (infrared) thermometer. As shown in Fig. 6, the temperature of the workpiece increases slowly over time, and it flattens at about 30°C after 45-min vibration time.

Since any detachment of the workpiece from ultrasonic horn results in heat generation and sudden increase in the temperature of horn-workpiece interface, the observed trend of temperature suggests that the workpiece is vibrated effectively along with the ultrasonic horn, which could give rise to achieving well-defined process parameters and hence a stable machining process.

4.4 Machining of micro-holes on the silicon workpiece material

Micro-holes were machined on silicon using the developed micro-USM system in order to verify the functionality of the proposed setup configuration. The nominal frequency and amplitude of vibration were set to 50 kHz and 0.8 μm, respectively. Also, the machining load was set to 20 mN for machining experiments. Aluminum oxide powder with the average particle size of 3 μm was used for the slurry with concentration of 2% (wt. to water). Figure 7a depicts a micro-hole machined on silicon wafer using a tungsten micro-tool with cylindrical flat-ended shape and diameter of 150 μm. The depth and diameter of the machined micro-hole are 350 and 167 μm, respectively. Also, machining duration is 25 min which yields a machining speed of 14 μm/min.

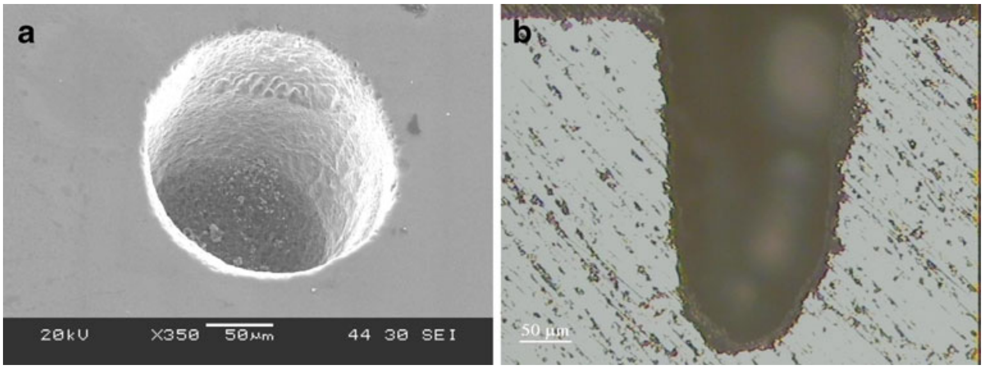
The optical microscope image for cross-section of the machined micro-hole is shown in Fig. 7b. The longitudinal profile of the micro-hole has a taper form with an incline angle close to 7º, which is attributed to corner and side wear of the micro-tool during the machining process.

Tool wear is an important performance measure in micro-USM which affects both machining speed and hole accuracy [13]. Apart from corner and side wear, longitudinal wear is also present, and it accounts for the majority of material loss in micro-tool [14]. The longitudinal tool wear rate is defined as $\Delta l/t$, where Δl is reduction in tool length and t is the machining duration. For above micro-USM operation, $\Delta l=105$ μm and $t=1{,}500$ s, resulting in a tool wear rate of 0.07 μm/s.

5 Conclusions

This paper presents a new method for measuring the static force and clamping the workpiece for the micro-ultrasonic

Fig. 7 **a** SEM image of a machined micro-hole on silicon wafer using a micro-tool with diameter of 150 μm; **b** microscope image of the cross-section of machined micro-hole with depth of 350 μm



machining process. The proposed force measurement and control system provides a compact configuration and prevents the adverse effects of horn vibration as well as fixture weight on the accuracy of force measurement. The high accuracy force measurement system integrated with a high precision actuator and *z*-axis stage was capable of controlling the small forces in micro-USM processes. In addition, the vacuum clamping system was capable of holding the workpiece firmly onto the ultrasonic vibrating horn throughout the machining time.

Actual amplitude and frequency of vibration of the workpiece were measured using a laser scanning vibrometer. The results showed that the minimum and maximum variation in amplitude with regard to the position across the workpiece is 5.2% and 8%, respectively. Also, experimental results showed that the mean and standard deviation of the frequency of vibrations are equal to 49.74 and 0.08 Hz, respectively, for the nominal frequency of 50 kHz. Moreover, the maximum lateral displacement of the workpiece is 1.59 μm. These results showed that the ultrasonic vibrations can be transmitted to the workpiece effectively by the proposed vacuum chuck. Finally, in order to verify the overall functionality of the designed force measurement and workpiece clamping systems, a tungsten micro-tool with a diameter of 150 μm was used successfully to machine micro-holes on the silicon workpiece. The depth of generated holes is equal to 350 μm, and machining duration is 25 min for each hole, which yields a machining speed of 14 μm/min. Further work to establish the process characteristics of micro-USM is currently being undertaken.

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