International Journal of Machine Tools & Manufacture ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Investigations on a directly coupled piezoactuated tool feed system for micro-electro-discharge machine

Muralidhara [a], Nilesh J. Vasa [b,*], Singaperumal Makaram [a]

[a] Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India
[b] Department of Engineering Design, Indian Institute of Technology Madras, Chennai 600036, India

ARTICLE INFO

Article history:
Received 17 September 2008
Received in revised form
3 August 2009
Accepted 10 August 2009

Keywords:
Micro-EDM
Micromachining
Piezoactuator
Tool feed control
Wear depth
Gap voltage

ABSTRACT

A directly coupled piezoactuated tool feed mechanism is proposed and a prototype micro-electro-discharge machine (micro-EDM) is developed. The piezoactuator is used to feed the tool and also to sense the tool displacement from a reference position. The hysteresis behavior of the piezoactuator is also incorporated through an electromechanical model for estimating the actual tool displacement. Simulation results for piezoactuator displacement are compared with the experiment and a maximum error of 15% was observed. Further, in order to control the tool feed rate during machining, a tool feed controller based on the gap voltage feedback is developed. A contact-based measurement technique is integrated with the tool feed controller to measure the tool wear and the depth of material removed. Micromachining experiments have been conducted on a copper workpiece with copper and tungsten as tool materials. The experimental results obtained through the contact-based measurement technique are in agreement with the tool-displacement simulations with a maximum error of about 10%.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

Micro-electro-discharge machining (micro-EDM) of different materials, which are electrically conducting, is gaining importance due to the recent advancements in miniaturization of electro-mechanical systems. The main challenge is to machine high aspect ratio 3D shapes like microchannels, reservoirs, microholes, cantilever beams, etc. [1]. In micro-EDM, the pulse energy provided during machining is of the order of few hundreds of microjoules and a small gap of the order of few microns have to be maintained between the tool and the workpiece to sustain the spark discharges. Thus, tool feed control is a critical requirement in micro-EDM. Further, both workpiece and tool materials are being eroded. During machining, debris produced between the tool and the workpiece interface, which are to be removed in order to avoid a short circuit condition. The debris will also reduce the spark gap at the bottom and side surfaces and the spark may be produced at the side surface even though a proper spark gap is maintained at the bottom surface. Hence this will result in an oscillatory motion of the tool while adjusting its feed rate to the sum of material removal rate and tool wear rate [2]. This oscillatory motion of the tool is also expected to result in pumping of the dielectric fluid present in the machined hole [3]. Along with the dielectric fluid, the debris pumped out of the machined hole and fresh dielectric fluid fill the tool and the workpiece interface. Tool electrode jump motion is provided while machining deep holes to flush out the debris from the workpiece–tool interface [4,5]. These requirements of micro-EDM demand for an actuator to feed the tool at the desired machining rate as well as to control the tool movement, which will not only avoid the sparks occurring with longer delay time but also avoid short circuiting of tool and workpiece.

Servo DC motors, stepper motors and electromechanical piezodrives have been used in recent micro-EDM machines. These electromechanical drives require a high-resolution closed-loop position control system, which makes the system complex. On the other hand, in micro-EDM, the maximum size of the tool is of few hundreds of micrometers and hence the actuator, which not only holds the tool but also feeds the tool, need not have a high load carrying capacity. A local actuator module utilizing electromagnetic force for feeding the micro-EDM tool electrode has been reported [6], which improved the speed and accuracy of micro-machining. Micro-EDM with an inchworm type of tool feed mechanism with two clamping mechanisms along with three piezoactuators [7] and servo scanned 3D micro-EDM with a piezoactuator [8] have been reported.

Piezoelectric actuators are extensively used for applications demanding high positional accuracy. They also exhibit fast response, high stiffness, low wear and tear and have compact design. However, they exhibit hysteresis behavior between the

* Corresponding author. Tel.: +91 44 22574706; fax: +91 44 22574732.
E-mail address: njvasa@iitm.ac.in (N.J. Vasa).

0890-6955/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmachtools.2009.08.004

applied voltage and the resulting displacement and this behavior should be considered while implementing the tool feed control. Michael et al. [9] have reported electromechanical modeling of piezoceramic stack actuator considering hysteresis behavior. Furthermore, Helen et al. [10] have modified this electromechanical model to estimate displacement of the piezoactuator under dynamic loading conditions. The piezoactuator stack with certain modification can be extended for a controlled tool feed system in micro-EDM.

In addition, during the process, tool wear has to be compensated continuously to reach the desired depth of machining. The required tool wear compensation is determined by the process model or based on machining experiments and the amount of tool feed is calculated before actual machining starts. During machining, the required number of pulses is counted in real time, which produces the desired spark between tool and workpiece. This data is converted into tool wear length and correction to the programmed tool wear length is made intermittently [11–13].

Microwire-EDM with transistor-type pulse generator has been reported by Yan et al. [14], where a pulse discrimination and control circuit are used to control the tool feed during machining. Improvements in machining characteristics of micro-EDM using transistor-type isopulse generator as against conventional RC-type pulse generator along with the servo feed control have been reported by Han et al. [15]. A comprehensive study on the tool wear during micro-EDM has been reported by Pham et al. [16]. They conducted micromachining experiments on different tool and workpiece combinations and reported variations in wear ratio with machining depth using a contact-based tool wear measurement system. However, piezoactuated tool feed control mechanism along with an *in-situ* axial tool wear and machining depth measurement system is necessary for real-time tool feed control to achieve desired machining depth in micro-EDM.

In the present study, an alternative approach of tool feed control by directly coupling the micro-EDM tool with piezoactuator and *in-situ* measurements of machining depth and axial tool wear incorporating contact sensing technique have been considered as shown in Fig. 1. This paper describes initially the electromechanical model of the piezoactuator and comparison of the modeled behavior of the actuator with the experimental behavior. Subsequently, a micro-EDM set-up and the piezoactuator-based tool feed control mechanism are explained. Finally, studies related to tool and workpiece wear measurements are discussed and the results are summarized.

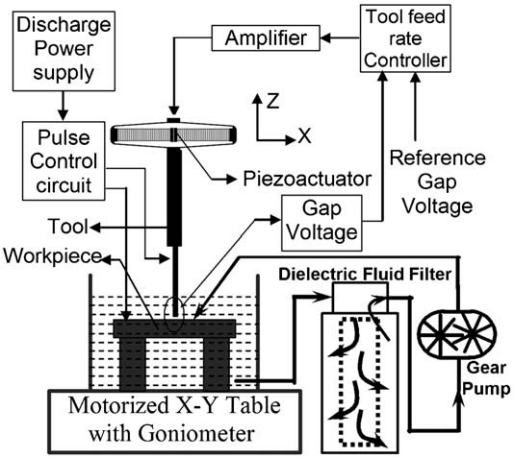

Fig. 1. Block diagram of the micro-EDM set-up.

2. Piezoactuator in micro-EDM

2.1. Modeling of piezoelectric actuator

A piezoelectric actuator (Cedrat Technologies, APA400M) was used for feeding and controlling the tool in the *Z*-direction. It consists of two piezostacks arranged in series and a flexural link to amplify the displacement of these two piezostacks. The maximum displacement of the piezoactuator is 445 μm at 150 V. Experiments were carried out to measure the displacement along the *Z*-direction (amplified displacement) by varying the input voltage to the piezoactuator. A green-light interferometer was used to measure the horizontal (*X*) displacement of the piezoactuator. Based on the experiments, displacement amplification is found to be linear and an amplification factor of approximately 18 was obtained through a linear fit.

An electromechanical model incorporating the hysteresis behavior for the piezoelectric actuator has been developed based on the models available in the literature [10,11]. In the present model, along with the piezostack displacement, the effect of flexural amplifier on the piezostack displacement and the displacement amplification of the flexural amplifier are considered. Fig. 2(a) shows the electromechanical interaction of the piezoactuator and Fig. 2(b) represents the equivalent block diagram. The hysteresis behavior of the piezoactuator is represented by block *H*, and the piezoelectric effect is represented by the piezoelectric transducer with transformer ratio *T*. The applied voltage V_{in} is divided into voltage due to hysteresis effect V_H and the voltage for electromechanical

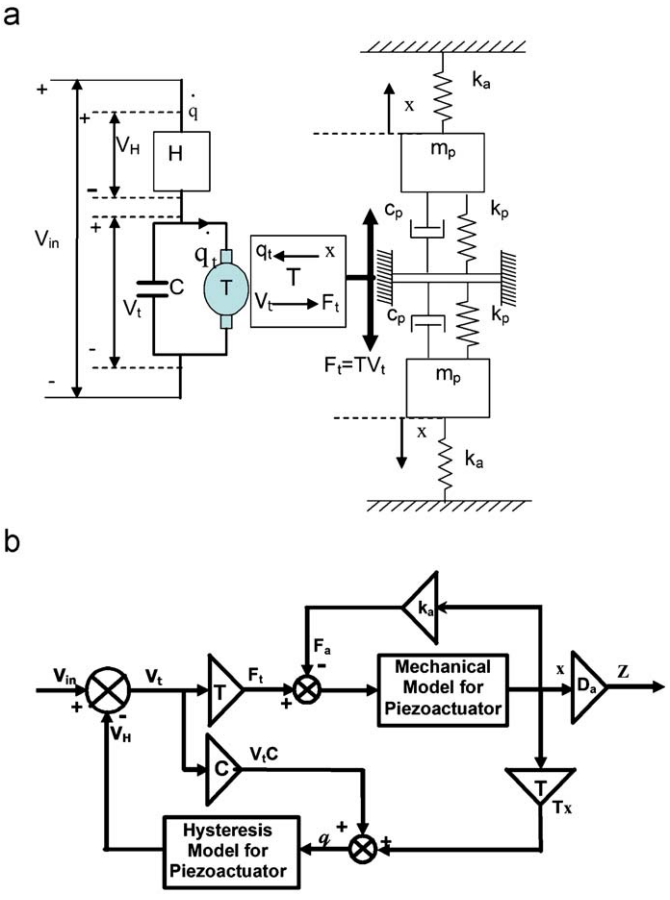

Fig. 2. Model of the Piezoactuator: (a) electromechanical interaction and (b) equivalent block diagram.

Please cite this article as: Muralidhara, et al., Investigations on a directly coupled piezoactuated tool feed system for micro-electro-discharge machine, International Journal of Machine Tools and Manufacture (2009), doi:10.1016/j.ijmachtools.2009.08.004

transduction V_t. The piezoelectric transducer converts voltage V_t to a force F_t. This force F_t is converted into actuator displacement by considering piezostack material as a spring-mass-damper system with m_p, c_p and k_p as mass, damping coefficient and material stiffness, respectively. The flexural displacement amplifier of the actuator is considered as a spring element with spring stiffness k_a, which exerts a force of F_a in the opposite direction to that of F_t. The difference in F_a and F_t results in the displacement x of the actuator. The electrical charge q_t is the transduced charge from the mechanical domain and is proportional to the displacement of the piezostack. The capacitance of the piezostack is represented by C. The displacement amplification provided by the flexural amplifier is represented by D_a. The amplified vertical displacement at the tool is Z. This model representing the electromechanical interaction of the piezoactuator was simulated for different input voltage waveforms and at different frequencies to study the behavior of the developed model. Mechanical and electrical properties of the piezostacks are tabulated in Table 1.

2.2. Behavior of the piezoactuator used in the tool feed mechanism

A Matlab–Simulink model was developed for the piezoactuator stack displacement. Simulations were carried out for different input waveforms and at different frequencies to investigate the behavior of the piezoactuator and the results were also compared with the experiment. The input signal was fed to the piezo-actuator driver, and a pre-calibrated inductive pick-up was used to sense the displacement of the piezoactuator. The output was acquired through a data acquisition system. Fig. 3(a) shows the piezoactuator displacement characteristics for 10 mHz (100 s cycle time), 0–120 V sinusoidal input voltage signal. Experimental displacement values are in agreement with the simulation results within a maximum error of 8–10 μm except near the trough of the waveform. The displacement error is around 30–35 μm at this region. This might be due to a minor difference in the parameter values considered for estimating the hysteresis behavior of the piezostacks. Also, piezostacks would experience an external force of the flexural amplifier at zero input voltage. In the experimental set-up an initial offset of about 50 μm between the tool and the workpiece was provided. Hence, the displacement error observed near the trough of the waveform, as shown in Fig. 3(a), did not effect the subsequent measurement.

Fig. 3(b) shows the displacement characteristics for 1 Hz, 0–120 V sinusoidal input voltage signal. A displacement error of about 25 μm at the crest of the waveforms is observed. This might be attributed to the slow response characteristics as a result of the creep behavior of the piezoactuator. Fig. 4 shows the estimated and experimental actuator displacement for a square-wave voltage input with an amplitude of 120 V. As shown in Fig. 4, when the piezoactuator was subjected to a step input (0–120 V), initially a displacement error of about 30 μm was observed. Nevertheless, the displacement error was reduced to 10–12 μm within 5–6 s after the step input. This is due to the creep behavior of the piezoactuator, which is not considered in the present electromechanical model of the actuator. However, in the micro-EDM with the piezoactuated tool feed mechanism, the creep behavior of the piezoactuator is not expected to affect the tool feed measurement as voltage input to the piezoactuator will be adjusted automatically to maintain a stable sparking condition. But, during measurement, creep behavior is compensated by incorporating the closed-loop tool feed control as explained in Section 4.

During deep-hole micro-EDM, intermittent tool motion away from the workpiece was provided to flush the micro- and nano-sized particles from the tool and the workpiece interface [3,12,13]. As the machining depth increases, the density of debris at tool–workpiece interface is expected to increase due to ineffective flushing conditions. In the present design of the piezoactuated tool feed mechanism, this was achieved by applying a voltage signal to generate a tool-jump motion as shown in Fig. 5. Simulation and experimental results indicate a maximum displacement error of about 10 μm at regions where the voltage signal is linearly increasing with time. However, when the input

Table 1
Parameters considered for piezostack model.

Parameter	Symbol	Value
Number of wafers	n	200
Thickness of wafers (mm)	t	0.1
Cross-sectional area of wafers (mm^2)	A	25
Relative permitivity	$K_{33}{}^T$	2900
Electromechanical coupling factor	K_{33}	0.7
Elastic constant (m^2/N)	$S_{33}{}^E$	2.22×10^{-11}
Mass (kg)	m_p	0.00481
Piezostack stiffness (N/m)	k_p	6×10^6
Damping coefficient (N s/m)	c_p	150
Capacitance (F)	C	4×10^{-6}
Transformer ratio (C/m)	T	14
Stiffness of the flexural amplifier (N/μm)	k_a	6

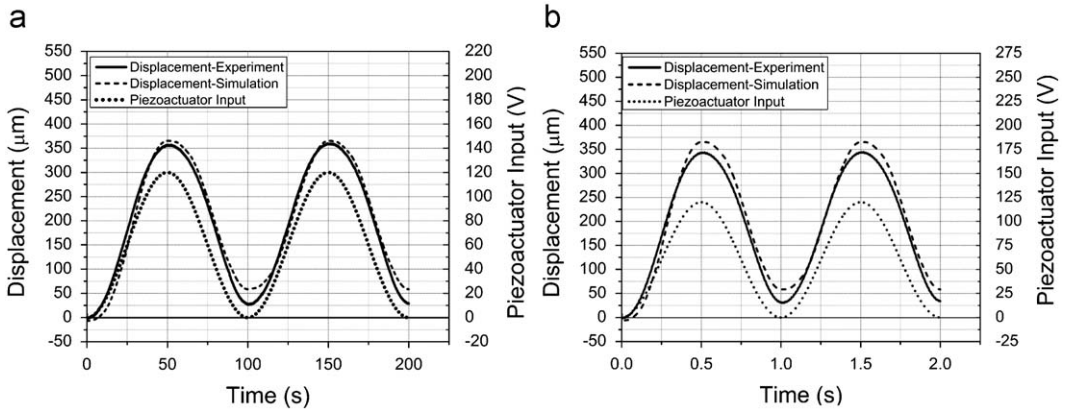

Fig. 3. (a) Piezoactuator displacement at 10 mHz sinusoidal signal input and (b) piezoactuator displacement at 1 Hz sinusoidal signal input.

Please cite this article as: Muralidhara, et al., Investigations on a directly coupled piezoactuated tool feed system for micro-electro-discharge machine, International Journal of Machine Tools and Manufacture (2009), doi:10.1016/j.ijmachtools.2009.08.004

voltage was reduced to zero in order to retract the tool to allow flushing of the debris, a small amount of displacement error was observed. This may be due to the effect of compliance of the mechanical amplifier on the piezoelectric stack under a step loading and unloading. If initial tool offset from the workpiece is higher than this error, it is not expected to affect the micromachining.

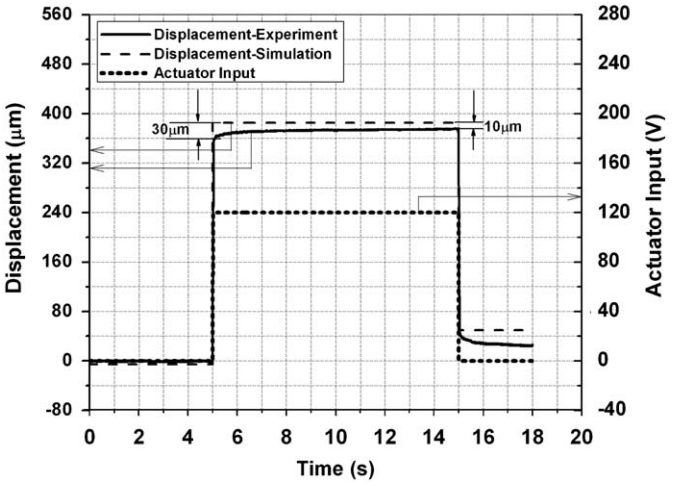

Fig. 4. Piezoactuator displacement for square signal input.

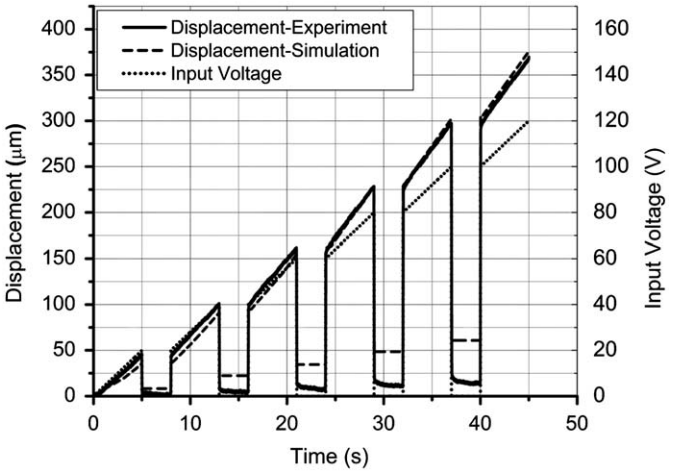

Fig. 5. Displacement profiles for electrode-jump motion in micro-EDM.

3. Piezoactuated tool feed mechanism

3.1. Micro-EDM Set-up

Fig. 1 shows a schematic of the prototype micro-EDM that was developed incorporating the piezoactuated tool feed mechanism. It consists of a motorized rotary table with an accuracy of 0.1° and two motorized linear stages having a positional accuracy of 1 μm. This arrangement is capable of fabricating microchannels with various shapes, such as rectangular, circular and spiral and fabricating either blind or through microholes. Transistor-type pulse control circuit was used to generate high-voltage pulses between tool and workpiece at the desired frequency and duty cycle [14,15]. The conventional transistor-type pulse control circuit has been modified to reduce the time delay. Isolated DC power supply drives the pulse generator circuit, which reduces the delay due to the voltage attenuator used in conventional transistor-type pulse control circuit. Since the pulse control circuit is isolated from the high-voltage path, the insulating circuit present in a conventional transistor-type pulse control circuit is also eliminated, further reducing the time delay. A non-contact-type inductive displacement sensor was integrated to determine the actual displacement of the piezoactuator/tool. An *in-situ* measurement technique was also implemented to measure the machining depth, axial tool wear and the total displacement of the tool via electrical contact sensing. Kerosene was used as the dielectric medium with a recirculation and filtering system.

3.2. Tool feed control

Fig. 6 shows the block diagram of the developed tool feed control system. Tool feed control is achieved based on the average gap voltage as the feedback signal. In the proposed set-up, the tool is moved at a low feed rate till the gap between the tool and the workpiece reaches a gap equivalent to the desired spark gap. When the tool–workpiece gap is equal to the spark gap, sparks are produced at the supplied pulse frequency, resulting in melting and removal of workpiece and tool materials. This results in increase in the spark gap and the average gap voltage also increases. The gap voltage signal is filtered and the DC component of this signal is compared with a reference voltage. This comparator output switches a ramp generator to produce voltage signal with either positive or negative slope from the current voltage level. This signal is amplified and supplied to the actuator, which in turn moves the tool towards or away from the workpiece.

The performance of the tool feed control was investigated by tool feed measurements carried out while machining a copper sheet of 0.7 mm thickness with a copper tool of 270 and 150 μm diameter. Figs. 7(a)–(c) show the experimental and estimated tool feeds during machining for three different machining conditions

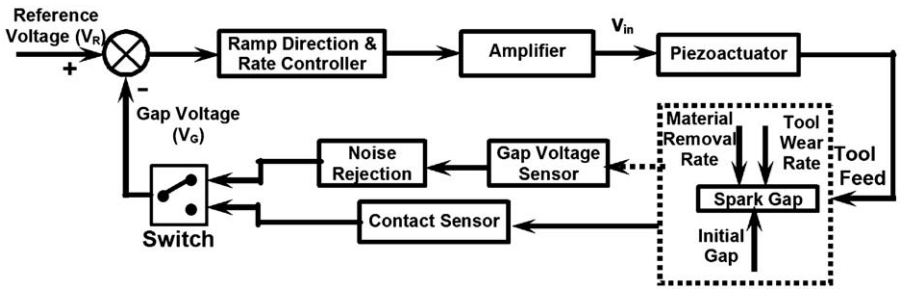

Fig. 6. Block diagram of the tool feed control system.

Please cite this article as: Muralidhara, et al., Investigations on a directly coupled piezoactuated tool feed system for micro-electro-discharge machine, International Journal of Machine Tools and Manufacture (2009), doi:10.1016/j.ijmachtools.2009.08.004

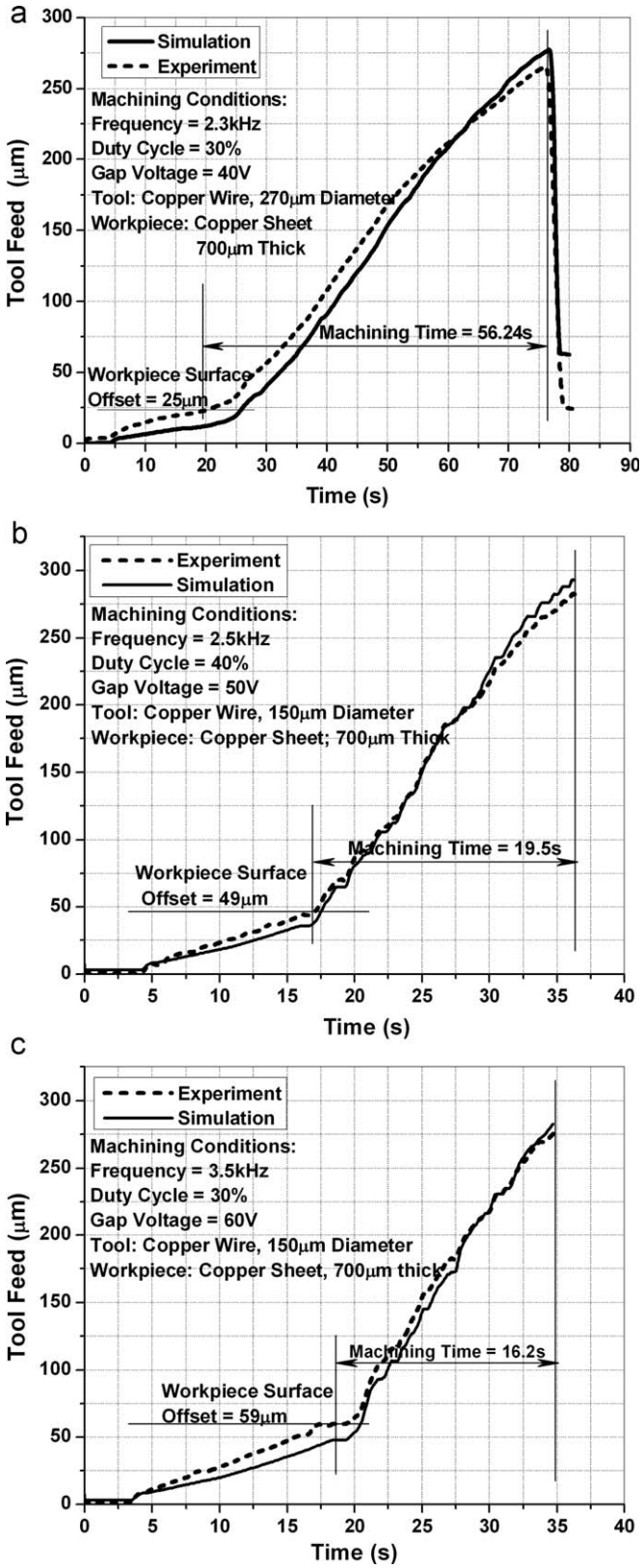

Fig. 7. Tool feed during machining at different process parameters.

given in Figs. 7(a)–(c). Estimated values were obtained using the developed piezoactuator model and converting the actuator input voltage into displacement value. Experimental tool-displacement values were obtained by mounting non-contact-type inductive sensor on the piezoactuator. From the home position, tool was fed towards the workpiece surface at a feed rate of 1 μm/s till the gap between the tool and the workpiece reaches a value corresponding to the spark gap. When the required spark gap is reached, machining process started and the controller adjusted its feed rate based on the gap voltage and with the feed rate decided by the sum of material removal rate and tool wear rate, as observed in Fig. 7. Machining time in Fig. 7(a) is about 2.9 times higher than that in Fig. 7(b), mainly because the tool diameter is 1.8 times bigger. Furthermore, in Fig. 7(c), machining time is less as the discharge energy is higher than that in Fig. 7(b). From Figs. 7(a)–(c), it can be concluded that the piezoactuator model is capable of predicting the tool displacement with maximum error up to 10%. This error might be due to the calibration error of the inductive pick-up sensor and the error related to the minor difference in values of the model parameters. Based on Fig. 7, the machining time and hence the tool feed rate can be calculated.

4. Tool and workpiece wear measurements

A contact sensor-based *in-situ* measurement technique was incorporated with the tool feed control system as shown in Fig. 6 to estimate the axial tool wear and machining depth. A single-pole double-throw switch was used to select the machining and the measurement mode of operation. To measure material removal and tool wear depths, a contact sensor, based on electrical continuity measurement, was proposed to sense the contact between the tool and the workpiece [16]. Tool from home position is moved towards the workpiece at a slow feed rate, and based on the contact sensor signal the controller switched its output signal to positive and negative slopes. This type of control signal was necessary for sensing the contact as the piezoactuator exhibits creep behavior.

Fig. 8 shows the approach adopted in measuring the axial tool wear and machining depth via contact sensing. As shown in Fig. 8, the difference between 'Z_1' and 'Z_3' reading represents the tool wear and the difference between 'Z_2' and 'Z_3' readings represents the depth of the blind hole. The total tool feed is represented by the difference between 'Z_1' and 'Z_2' readings.

Machining experiments were carried out with copper tool (270 μm diameter) and copper sheet (0.7 mm thick) as workpiece. Machining was performed at a pulse frequency of 2.3 kHz, 30% duty cycle, and at a gap voltage of 40 V. Fig. 9(a) shows the actuator input voltage signal and the corresponding sensor output signal while measuring axial tool wear and machining depth. The peak value of the actuator input signal represents the physical contact of the tool with the workpiece. But after reaching the peak value, the actuator input voltage reduces to a certain amount to compensate for the creep behavior of the piezoactuator. This can be ascertained by observing the corresponding sensor signal. It is observed that sensor output signal reaches a peak value and remains at that value even though there is a decrease in the actuator input voltage. This indicates that the tool feed controller tries to reduce input voltage to the actuator to compensate for displacement due to the creep, maintaining the contact between the tool and the workpiece. The values of Z_1, Z_2 and Z_3 were estimated by converting the actuator voltage data into displacement data using the developed piezoactuator model and compared with the experimental value obtained from the displacement sensor. For the specified machining condition, machining depth and axial tool wear were found to be 180 and 70 μm, respectively, resulting in total tool feed of 250 μm as shown in Fig. 9(b). The machining depth and axial tool wear shown in Fig. 9(b) are obtained using contact-based measurements. Based on the input voltage, the piezoactuator model estimated a

Please cite this article as: Muralidhara, et al., Investigations on a directly coupled piezoactuated tool feed system for micro-electro-discharge machine, International Journal of Machine Tools and Manufacture (2009), doi:10.1016/j.ijmachtools.2009.08.004

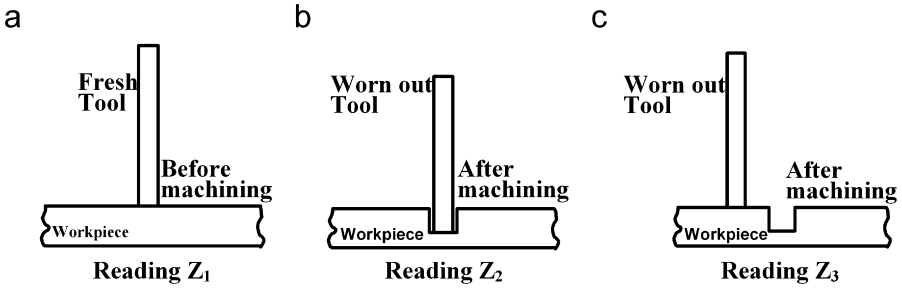

Fig. 8. Wear measurement technique employed in micro-EDM: (a) reference reading (Z_1)—at unmachined surface, (b) reading after blind-hole machining (Z_2)—at machined surface and (c) reading after blind-hole machining (Z_3)—at unmachined surface.

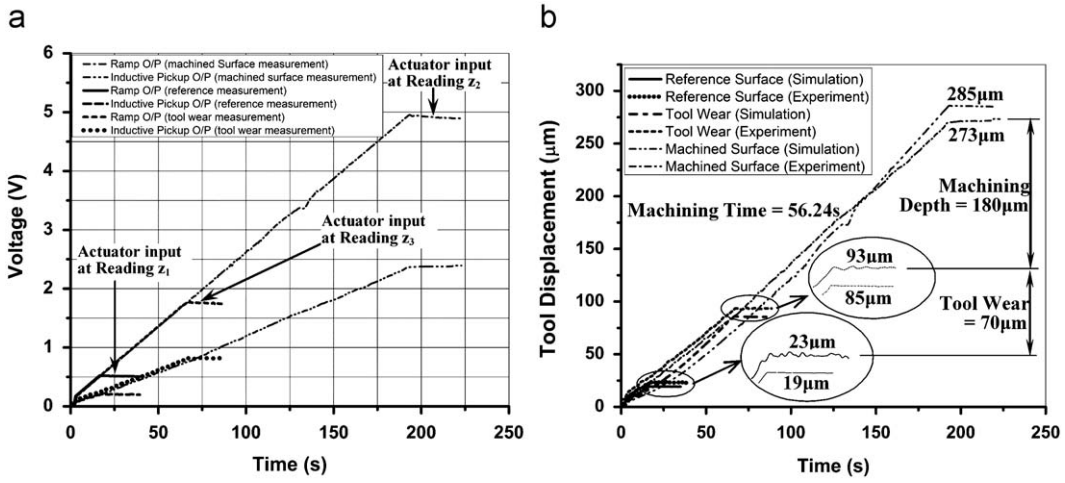

Fig. 9. (a) Actuator input and displacement sensor output signals during tool wear and machining depth measurements and (b) estimated and actual tool feed profile during tool wear and machining depth measurements.

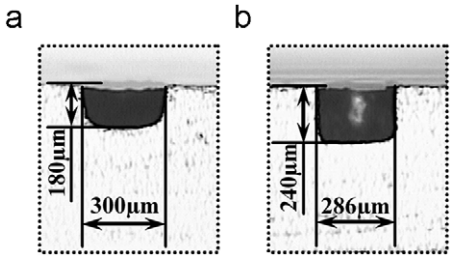

Fig. 10. Cross-section of the micro-machined holes on copper workpiece with (a) copper tool (⌀270 µm) and (b) tungsten tool (⌀252 µm). The tool feed was 250 µm.

machining depth of 200 µm and a tool wear of 66 µm, resulting in an error of 11% and 5.7%, respectively. The micromachined depth was verified by observing the cross-section of the blind hole under an optical microscope (ZEISS-AXIOSKOP 2 MAT, Magnification: 5 ×) and the images were recorded using AxioVision software. Figs. 10(a) and (b) show the micromachined blind holes with copper (⌀270 µm) and tungsten (⌀252 µm) tools, respectively. Based on the measurements under a microscope, the blind-hole depth with the copper tool was found to be 180 µm, which was in agreement with the *in-situ* contact-based measurement as shown in Fig. 9(b). Similar characteristics were also observed when the tungsten tool was used for machining copper workpiece and the blind-hole depth was obtained as 240 µm for the same tool feed and the tool wear length was measured as 10 µm. In this case also the measured values were in agreement with the *in-situ* contact-based measurements. This clearly shows that the contact-based measurement technique proposed with the piezoactuated tool feed mechanism for micro-EDM is capable of measuring the depth of machining and the tool wear length.

5. Conclusions

A novel approach of directly coupled piezoactuated tool feed system is proposed for a micro-EDM. Hysteresis behavior of the piezoactuator is modeled using an electromechanical approach and the displacement amplification of the flexural amplifier is also included in the displacement modeling. Based on the simulation results obtained through the electromechanical model developed for the piezoactuator, the actuator displacement can be estimated with a maximum error of 15%. The micro-EDM incorporating the piezoactuated tool is used in micromachining experiments. A gap voltage-based feedback signal was found to be suitable for micro-EDM system with directly coupled piezoactuated tool feed control and the developed piezoactuator model was found to be capable of estimating the tool feed during micromachining with an average error of 7.5%. *In-situ* electrical contact-based measurement approach was adopted for the tool wear and material removal measurements. The proposed *in-situ* axial tool wear and machining depth measurement technique is demonstrated for copper micromachining using copper and tungsten tool materials. Based on the actuator input voltage, the piezoactuator model was found to be estimating the axial tool wear and machining depth measurements with a maximum error of 10% compared to that of

Please cite this article as: Muralidhara, et al., Investigations on a directly coupled piezoactuated tool feed system for micro-electro-discharge machine, International Journal of Machine Tools and Manufacture (2009), doi:10.1016/j.ijmachtools.2009.08.004

the actual value obtained through inductive pick-up sensors. The proposed approach will be useful for real-time tool feed control providing compensation for tool wear to reach the desired depth of micromachining.

References

[1] D.T. Pham, S.S. Dimov, S. Bigot, A. Ivanov, K. Popov, Micro-EDM—recent developments and research issues, Journal of Materials Processing Technology 149 (2004) 50–57.
[2] Y.F. Chang, VSS controller design for gap control of EDM, International Journal of JSME 45 (3) (2002) 712–721.
[3] S. Cetin, A. Okada, Y. Uno, Effect of debris distribution on wall concavity in deep-hole EDM, International Journal of JSME 47 (2) (2004) 553–559.
[4] W.M. Wang, K.P. Rajurkar, K. Akamatsu, Digital gap monitor and adaptive integral control for auto-jumping in EDM, ASME Journal of Engineering for Industry 117 (1995) 253–258.
[5] C. Serken, O. Akira, U. Yoshiyuki, Electrode jump motion in linear motor equipped die sinking EDM, Journal of Manufacturing Science and Engineering 125 (2003) 809–815.
[6] Y. Imai, T. Nakagawa, H. Miyake, H. Hidai, H. Tokura, Local actuator module for highly accurate micro-EDM, Journal of Material Processing Technology 149 (2004) 328–333.
[7] L. Yong, G. Min, Z. Zhaoying, H. Min, Micro electro discharge machine with an inchworm type of micro feed mechanism, Journal of International Society for Precision Engineering and Nanotechnology 26 (2002) 7–14.
[8] H. Tong, Y. Li, Y. Wang, D. Yu, Servo scanning 3D micro-EDM based on macro/micro-dual-feed spindle, International Journal of Machine Tools and Manufacture 48 (2008) 858–869.
[9] G. Michael, C. Nikola, Modeling piezoelectric stack actuators for control of micromanipulation, IEEE Control Systems 17 (1997) 69–79.
[10] M.S.G. Helen, B.M. Ridha, Electromechanical modeling of piezoceramic actuators for dynamic loading applications, Transactions of the ASME—Journal of Dynamic Systems, Measurement and Control 128 (2006) 558–567.
[11] P. Bleys, J.P. Kruth, B. Lauwers, A. Zrud, R. Delpretty, C. Tricarico, Real-time tool wear compensation in milling EDM, Annals of the CIRP 51 (1) (2002) 157–160.
[12] C. Yih-Fang, C. Zhi-Hao, Electrode wear-compensation of electric discharge scanning process using a robust gap-control, Mechatronics (2004) 1121–1139.
[13] S.H. Yeo, W. Kurnia, P.C. Tan, M. Mushan, Development of in situ monitoring and control of micro-EDM process, in: Proceedings of the 35th International MATADOR Conference, Taiwan, July 18–20, 2007, pp. 81–84.
[14] M. Yan, H. Chien, Monitoring and control of the micro wire-EDM process, International Journal of Machine Tools and Manufacture 47 (2007) 148–157.
[15] F. Han, S. Wachi, M. Kunieda, Improvement of machining characteristics of micro-EDM using transistor type isopulse generator and servo feed control, Precision Engineering 28 (4) (2004) 378–385.
[16] D.T. Pham, A. Ivanov, S. Bigot, K. Popov, S. Dimov, A study of micro-electro discharge machining electrode wear, IMechE Journal of Manufacturing Engineering Science 221 (2007) 605–612.

Please cite this article as: Muralidhara, et al., Investigations on a directly coupled piezoactuated tool feed system for micro-electro-discharge machine, International Journal of Machine Tools and Manufacture (2009), doi:10.1016/j.ijmachtools.2009.08.004