The International Journal of Advanced Manufacturing Technology (2018) 97:1557–1564
https://doi.org/10.1007/s00170-018-2027-5

ORIGINAL ARTICLE

Experimental study on the heat-affected zone of glass substrate machined by electrochemical discharge machining (ECDM) process

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Received: 14 December 2017 / Accepted: 9 April 2018 / Published online: 28 April 2018

Abstract

Electrochemical discharge machining (ECDM) is an unconventional microfabrication technology which is used for creating microchannels on glass workpieces. Since melting and evaporation are the main mechanisms of material removal in glass workpiece and fabrication of microchannels in ECDM process, the material properties of heat-affected zones (HAZ) would be changed. In this paper, microchannels were machined on soda lime glass in different machining conditions and the nano-indentation test, which is the key tool for identification of changes in material properties of HAZ, was conducted on machined workpieces for measuring the hardness of microchannels' edges. Experimental results showed that applying a magnetic field in both 15 and 30 wt% electrolyte concentrations leads to an increase in the hardness of the channel edge up to 87 and 24%, respectively. In fact, in the presence of a magnetic field, a magneto-hydrodynamic convention is created, which affects the hydrogen gas bubbles' movement. So, the electrical conductivity of the solution is enhanced and finally by occurring a more consecutive electrical discharge, a smaller heat-affected zone is created. In addition, due to generation of higher thermal energy, by increasing the electrolyte concentration and applied voltage level, the larger HAZ is created. Analyzing the load-displacement curves of nano-indentation test shows that the hardness of samples machined in the presence of KOH electrolyte is lower than NaOH electrolyte. The potassium ions are larger than sodium ions, leading to a decrease in the sample's strength and increase in the HAZ.

Keywords Electrochemical discharge machining (ECDM) · Heat-affected zone (HAZ) · Magnetic field · Indentation and hardness · Microchannel · Load-displacement curve

1 Introduction

Among machining technologies, using electrochemical discharge machining by applying chemical and thermal phenomenon at the same time is the most appropriate method to create microchannels on non-conductive materials such as glass pieces. For the first time, Kurafuji used the ECDM method for machining micro-holes [1]. Also, the ECDM has been used for creating both 2D and 3D structures [2, 3]. Several studies have been conducted in order to improve the performance of ECDM process by studying the effect of tool rotation, pulse voltage [4], electrolyte composition [5], applying the magnetic field [6], and the presence of surfactant [7] on process.

In ECDM process, the glass workpiece is immersed in an electrolytic cell, in which the cathode and the anode are connected to a DC power supply. By applying a voltage, the electrolysis is occurred in the electrolyte cell, which causes the formation of hydrogen and oxygen gas bubbles at the cathode and anode electrodes, respectively. When the applied voltage exceeds a specific level called critical voltage, the hydrogen gas bubbles coalesce together and form a gas film around the tool, making the cathode insulated from the electrolyte. In this stage, the electrical resistance of the hydrogen gas film breaks down and the electrical discharge occurs. If the tool is placed at an appropriate distance from the workpiece, generated heat by the electrical discharge and chemical etching causes the material removal of workpiece [8]. During ECDM process, the machining zone heats up according to the collision of sparks and so some changes in the material properties would occur.

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Table 1 ECDM process conditions

Electrolyte type	KOH/NaOH
Electrolyte concentration	15 wt%, 25 wt%, 30 wt%
Lorentz force direction	Upward
Electrolyte temp.	25 °C
Tool rotation speed	800 rpm
X-axis speed	10 μm/s
Applied voltage	30, 32, 35, and 37 V
Power source	DC (0–5 A/0–60 V)
Tool immersion depth	2 mm
Workpiece	Soda lime glass (dimension = 1 × 10 × 40 mm^3)
Cathode	Tungsten carbide drilling tool (diameter = 0.5 mm)
Anode (auxiliary electrode)	Stainless steel plate (dimension = 3 × 40 × 50 mm^3)

The first studies in the field of the changes in the properties of the machined samples were conducted by Didar et al. [9], in which they reported a decrease in the hardness and density of the machined zones by conducting the nano-indentation test on the samples.

Sabahi et al. [7] used a surfactant-mixed electrolyte during ECDM process and reported that application of surface active agents had a significant effect on reducing the HAZ. In fact, in the presence of surfactants, the thickness of the gas film was reduced, so the stray erosion was decreased at the entrance of microchannels' surface.

The formed bubbles around the tool electrode can be classified into three regions. The first region is named adherence region, and the second and the third regions are called bubble diffusion region and bulk region, respectively. Inter-electrode gap is also referred to the second and third region. The bubbles in this gap increase the inter-electrode resistance, which consequently affect the electrical conductivity of the electrolyte and the efficiency of the process [10]. Therefore, it is expected that the presence of factors, which can transfer the bubbles from these two regions to a distant area, could have a positive effect on the quality of the machining process.

This study attempts to identify the affecting factors on the hardness and HAZ of samples machined by ECDM process. In order to achieve this goal, the effect of different parameters including an upward magnetic field, different electrolyte type and concentrations, and different applied voltage level is investigated on the hardness of machined samples, as a criteria of material property, and the results are reported.

2 Experimental details

In the current study, a two-axis micromachining setup is used for creating microchannels with the length of approximately

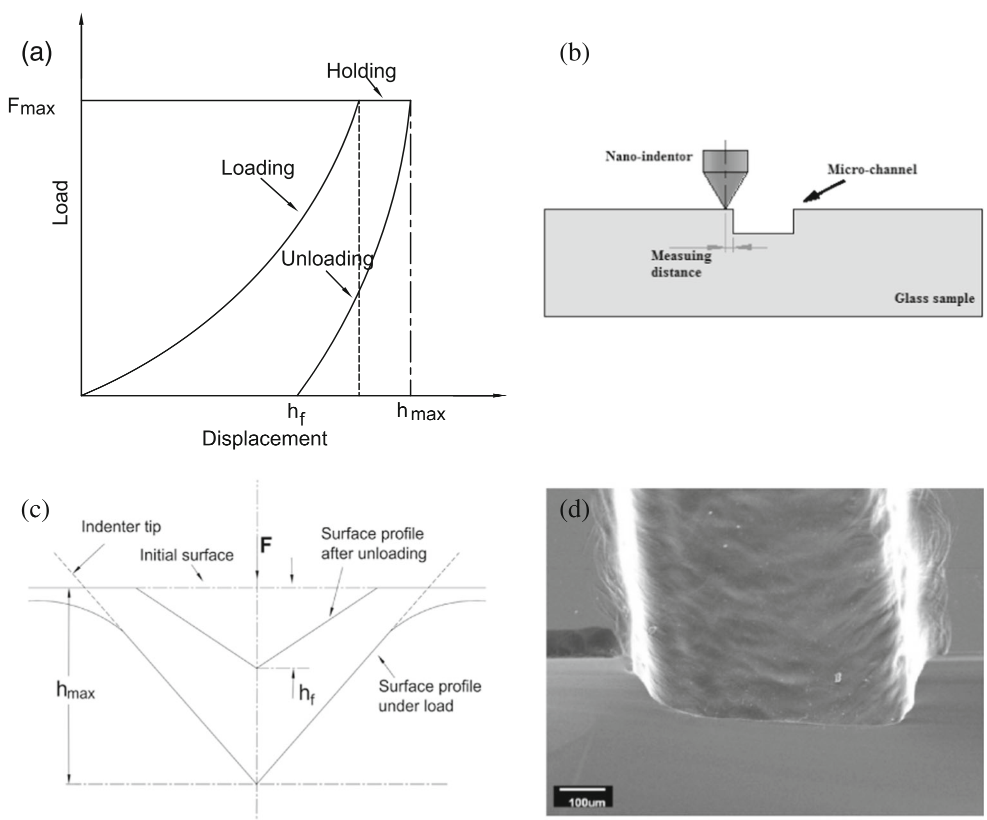

Fig. 1 The schematic of (a) load-displacement graph, (b) hardness measuring distance, (c) contact geometry through nano-indentation testing, and (d) SEM image of machined microchannel, where h_{max} is maximum depth, h_f is the final depth, and F_{max} is the maximum load exerted on the sample

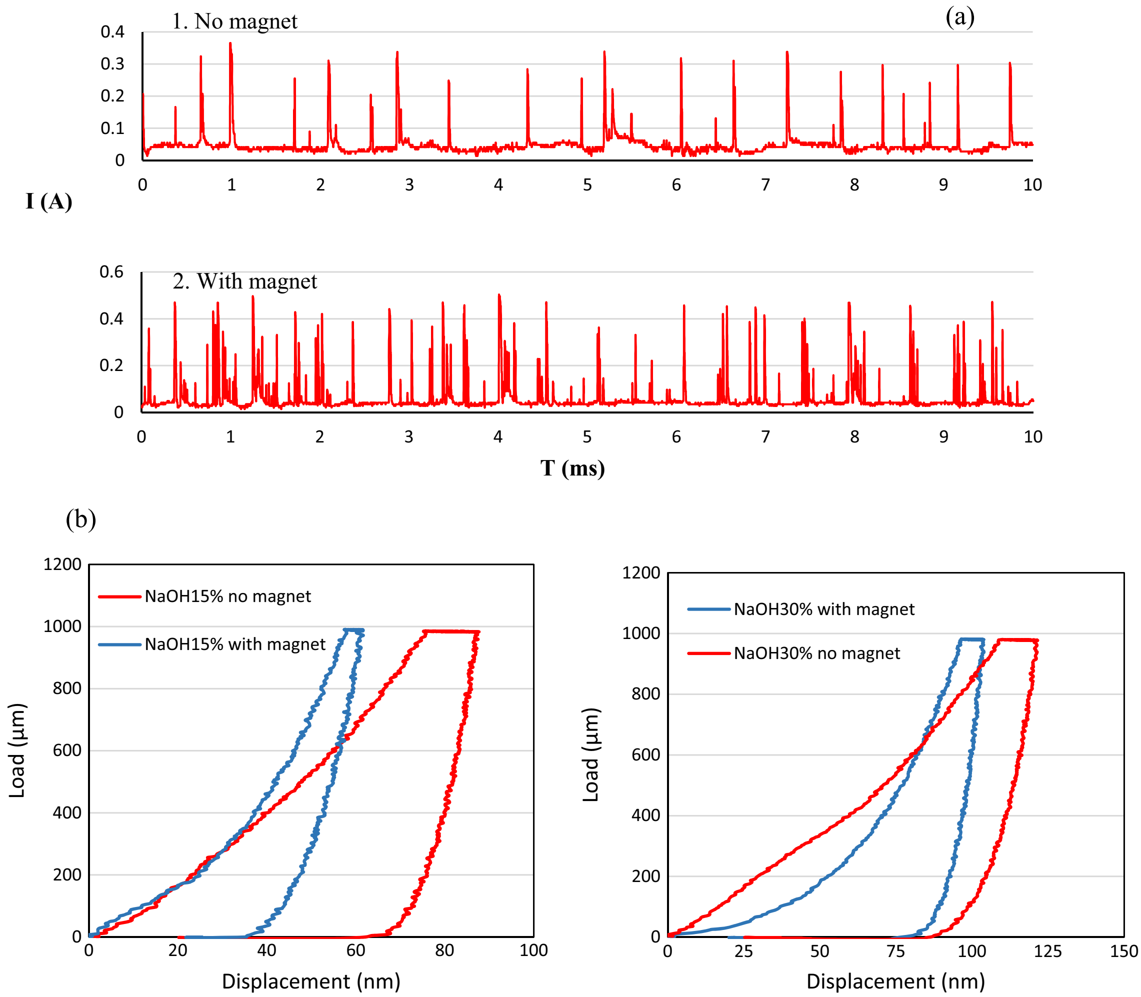

Fig. 2 (a) Current signals of process in the presence and absence of magnetic field (electrolyte: NaOH 15 wt%). (b) Load-displacement graphs of nano-indentation test in different machining conditions

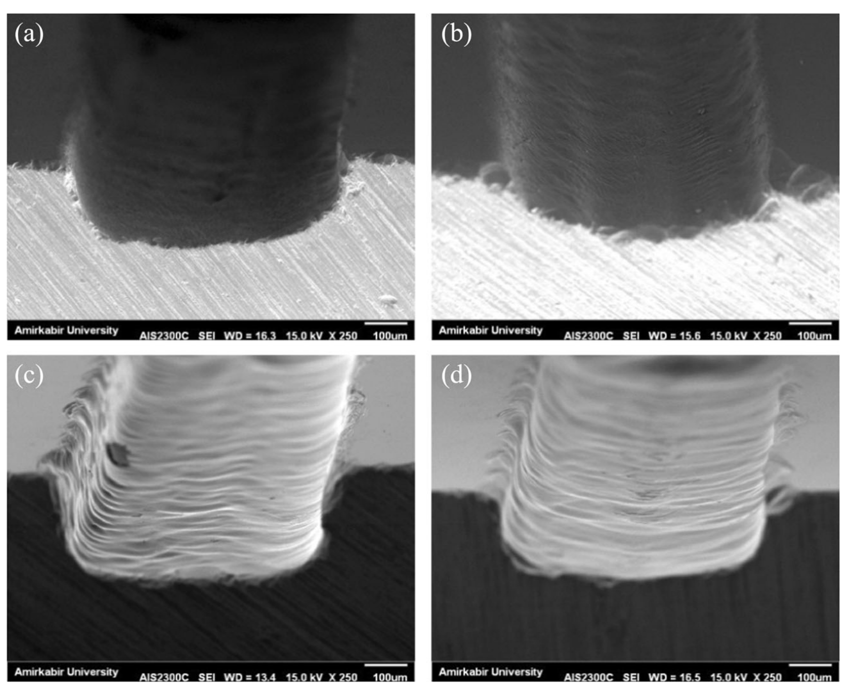

Fig. 3 SEM image of machined microchannels. (a) NaOH 15 wt% with magnet. (b) NaOH 15 wt% no magnet. (c) NaOH 30 wt% with magnet. (d) NaOH 30 wt% no magnet

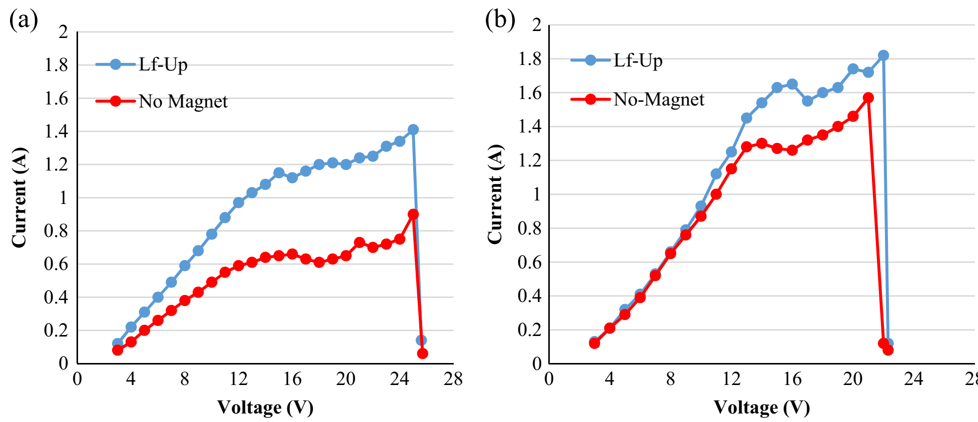

Fig. 4 I-V curves of NaOH solution ((a) 15 wt% and (b) 30 wt%) in the presence and absence of an upward magnetic field

10 mm on glass workpiece as is described in [7, 11] with the schematic diagram and real processing cell figures. Table 1 represents the adjusted parameters for the electrochemical discharge micromachining procedure of this study.

In nano-indentation test, it is important to ensure that the contaminations are removed from machined samples, so, before starting the test, the samples were washed in an ultrasonic bath for 180 s. The test is conducted on the surfaces of the samples in the distance of 100 μm next to the channel edges as the following steps [12]:

1. Engaging the Berkovich indenter tip of system and glass surface
2. Exerting and increasing the load up to 1000 μN at a constant rate (loading)
3. Keeping the maximum load for 10 s in order to reduce the creep effect (holding)
4. Decreasing the load to zero at a constant rate (unloading)

Figure 1 shows the schematic of load-displacement curve, measuring distance, contact geometry in nano-indentation test, and SEM image of machined microchannel.

3 Results and discussion

3.1 Effect of applying magnetic field on the HAZ

In this section, the effect of applying an upward magnetic field on the hardness of the heat-affected zones of machined microchannels in both 15 and 30 wt% NaOH electrolyte is investigated.

Figure 2 shows the current-time graphs and the nano-indentation test results for the microchannels machined in different machining conditions. Evaluating the current signals registered by oscilloscope is a key tool for online monitoring of the ECDM process, from which some valuable information such as the presence or absence of the gas film, the quality of the gas film, and the number of sparks can be obtained [13]. In the current-time graphs, the peaks with the duration shorter than a millisecond indicate the electrical discharges in the gas film. As these peaks become higher and electrical discharge occur consecutively (Fig. 2a, (2)), the quality of the gas film and, consequently, the quality of the machining process will be improved [14]. It is observed that the presence of magnetic field in both 15 and 30 wt% electrolytes resulted in the reduction of the HAZ. In fact, due to the increase in the hardness of the microchannel's edge, the nano-indentation curves are shifted to the left and the maximum depth is reduced. In lower concentrations of electrolyte, the effect of a magnetic field on the departure of gas bubbles from the inter-electrode gap is more tangible.

Koza et al. [15] stated that the presence of a magnetic field would decrease the bubble coverage fraction as well as the diameter of gas bubbles. The reduced gas film thickness would reduce the fluctuation in the discharge activity, which is important in the formation of lower heat-affected zones. Also, by decreasing the bubble coverage fraction, a high surface level of the electrode is involved in the electrolysis process and the efficiency of the process would be enhanced [15–17].

The gas void fraction (ε) is one of the main parameters contributes in the electrical conductivity of alkaline solutions. Increment of the gas void fraction would lead to an increase in the inter-electrode resistance and decrease in the electrical conductivity and efficiency of the process. The Bruggeman and Maxwell relations have been used by several researchers

Table 2 The inter-electrode resistance (Ω) in different conditions

Lorentz force	Electrolyte concentration	
	15 wt%	30 wt%
$F_L = 0$	17.4	8.5
F_L_Up	10.6	7.6

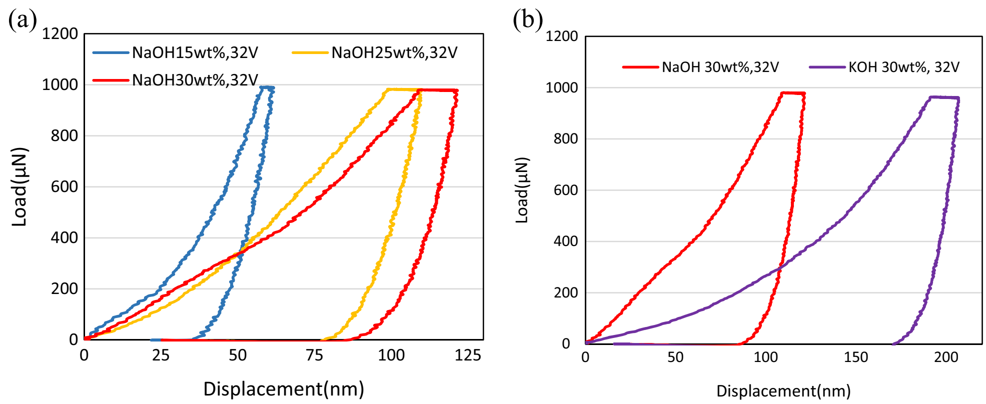

Fig. 5 Load-displacement graphs of nano-indentation test in the presence of (a) NaOH 15, 25, and 30 wt% and (b) NaOH 30 wt% and KOH 30 wt%

to quantify the effect of ε on the conductivity of the electrolyte solution [10].

$$k_{\mathrm{eff}} = k(1-\varepsilon)^{3/2} \tag{1}$$

$$k_{\mathrm{eff}} = k\left(1+1.5\frac{\varepsilon}{1-\varepsilon}\right)^{-1} \tag{2}$$

where k is the electrical conductivity of the solution without bubbles and k_{eff} is the conductivity of the solution considering the bubbles (the efficient conductivity of the electrolyte). If the number of hydrogen gas bubbles presented in the bulk and diffusion regions increases, the gas void fraction would be increased, and subsequently a decrease in $\frac{k_{\mathrm{eff}}}{k}$ would occur.

The application of a magnetic field results in the creation of magneto-hydrodynamic (MHD) convection, which affects the bubbles' movement direction. In the electrolysis process of alkaline solutions, presence of an upward magnetic field results that the buoyancy and Lorentz force exert on hydrogen gas bubbles in the same direction, so more gas bubbles would be transferred from diffusion and bulk regions, which would lead to a decrease in the gas void fraction, increase in the electrical conductivity of solution, and occurrence of consecutive electrical discharge [11, 18]. It is also worth mentioning that the higher thermal energy generated in the presence of a magnetic field would result in fabrication of deeper microchannels [7, 11] and has a minor effect on the entrance of channels. Figure 3 shows the SEM image of machined microchannels in the presence and absence of magnetic field in both NaOH 15 and 30 wt%.

In the current study, the inter-electrode resistance is measured in different conditions using the current-voltage graphs of process (Fig. 4) that is one of the common tools for measuring the resistance. As it was mentioned, the inter-electrode resistance affects the electrical conductivity of the solution and a reduction in the inter-electrode resistance would result in increment of electrical conductivity. Table 2 provides the measured inter-electrode resistance in the presence and absence of a magnetic field.

Table 3 The mobility and electrical conductivity of various ions ([21–23])

	K^+	Na^+	OH^-
Mobility ($m^2\ s^{-1}\ v^{-1}$) × 10^{-8}	7.62	5.19	20.64
Conductivity ($s\ cm^2 mol^{-1}$)	73.5	50.1	198.6

3.2 Effect of electrolyte type and concentration on the HAZ

Figure 5 shows the loading-unloading curves of samples machined in the presence of different types of alkaline electrolyte and different concentrations. The number of cations and

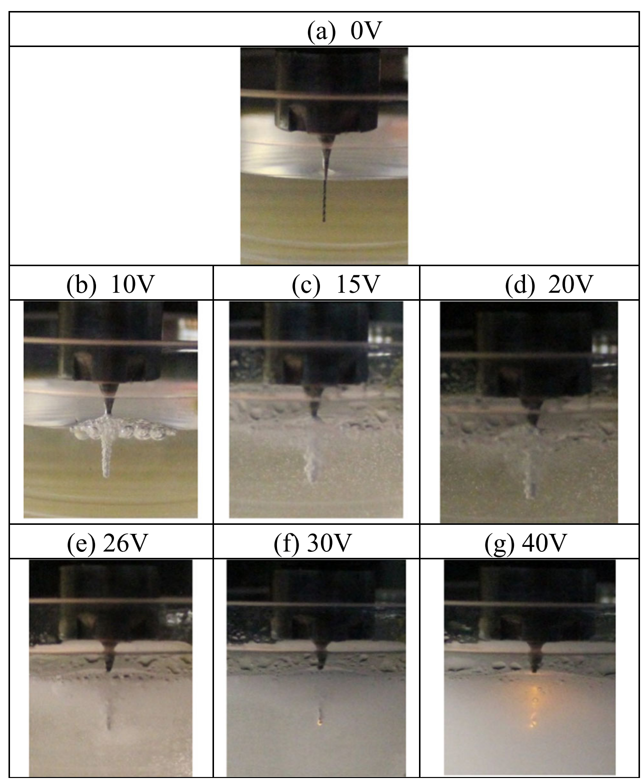

Fig. 6 Shots of gas film formation around tool electrode in various machining voltages

anions in the electrolyte and their charge and molar ionic conductivity affect the electrical conductivity of the solution. By comparing the mobility and conductivity of K+ and Na+ (Table 3), it has been found that the electrical conductivity and mobility of potassium ions are higher than sodium ions [19, 20], which lead to higher current and delivering more heat power to the workpiece in the same machining conditions. In other words, the thermal energy of the electrochemical discharge machining process is proportional to the current and it increases as the current of the process increases [10]. The mean heat power generated during the process can be estimated using Eq. (3):

$$P_E = (U - U_d)I - RI^2 \quad (3)$$

where U is the terminal voltage which is applied during machining process, U_d is the water decomposition potential, I is the mean current, and R is the inter-electrode resistance of the electrolyte.

Furthermore, quantity of ions in the solution is enhanced by increasing the electrolyte concentration, so more thermal energy would be generated during the process and larger HAZ would be obtained, subsequently. It should be mentioned that the K+ ions are larger than Na+ ions, leading to a decrease in the sample's strength and increase in the HAZ [10]. In addition, in electrolyte with higher concentration, more heat would be delivered on the glass surface and larger HAZ would be created as a result (Fig. 5(a)).

3.3 Effect of applied voltage level on the HAZ

Figure 6 depicts the morphologies of gas film formation obtained in different applied voltage levels. These pictures were captured using Canon camera (EOS550D).

It can be seen that by increasing the applied voltage, the electrolysis process accelerates and the number of hydrogen gas bubbles surrounding the tool electrode increases. Because the gas bubbles are denser close to the tool electrode, they coalesce together and form the gas film around the tool. With further increase in voltage, the electric resistance of gas film is broken and electrical discharge takes place in the gas

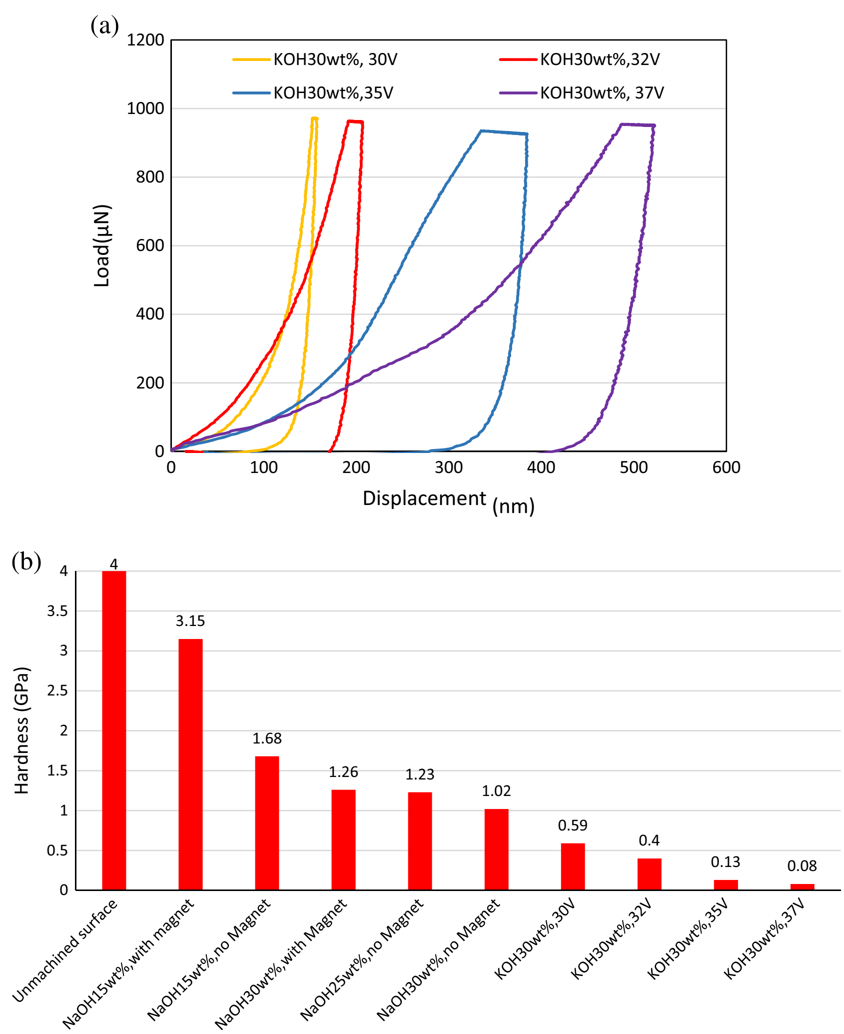

Fig. 7 (a) Load-displacement graphs of nano-indentation test (applied voltage: 30, 32, 35, and 37 V). (b) Hardness of heat-affected zones of samples in different machining conditions

film. When the voltage exceeds a certain limit, sparking would occur with the light emission. By increasing the applied voltage, the spark energy increases and the sparks spread in a greater range of tool electrode (Fig. 6(g)). This will increase the heat-affected zone of the microchannel due to stray erosion, which is caused by the collision sparks.

From Fig. 7, it is clearly seen that by increasing the voltage from 30 to 37 V, the hardness of the microchannel's edge is reduced significantly. In fact, the total generated thermal energy during the ECDM process and the amount of released energy by each spark are associated with the applied voltage. Increasing the applied voltage would result in an increase in the temperature of the machining zone, increase in the energy spark collision, and increase in the heat-affected zones, consequently [10]. Furthermore, by applying very high voltages to the process, the electrolyte turbulence would be enhanced (Fig. 6(f, g)) that would destroy the stable gas film, which has a negative effect on the quality of the machining process and machined structures [7, 24]. Figure 7(b) shows the value of hardness of samples in different machining conditions.

4 Conclusion

The present contribution aims to investigate the hardness of microchannel edges using nano-indentation test. The main conclusion of current study can be summarized as follows:

1. Using an upward magnetic field reduced the inter-electrode resistance about 40 and 11% in the presence of NaOH 15 and 30 wt%, respectively.
2. The heat-affected zone of the microchannels is reduced in the presence of an upward magnetic field due to a decrease in the gas void fraction, an increase in the electrical conductivity, and occurrence of more consecutive electrical discharge. For example, by applying a magnetic field in NaOH 15 wt%, the hardness of the microchannel's edge was enhanced from 1.68 to 3.15 GPa.
3. The application of KOH electrolyte resulted in lower hardness and larger heat-affected zone compared to NaOH. The mobility and electrical conductivity of potassium ions are higher than those of sodium ions, the result of which is generation of more heat power and larger HAZ consequently. Also, the K+ ions are larger than Na+ ions, leading to a decrease in the sample's strength and increase in the HAZ. For example, the hardness of machined samples in KOH 30 wt% and NaOH 30 wt% was 0.4 and 1.02 GPa, respectively.
4. Due to generation of higher thermal energy, increasing the electrolyte concentration and applied voltage led to enhancement of HAZ.

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