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Investigating the effect of mixed alkaline electrolyte (NaOH + KOH) on the improvement of machining efficiency in 2D electrochemical discharge machining (ECDM)

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Abstract Since the microchannels have a vital role in microelectromechanical systems (MEMS), microfluidic and lab-on-a-chip devices, the surface quality, material removal rate (MRR), and geometrical accuracy of microchannels should be controlled well. The electrolyte nature is one of the dominant and important factors that affect the accuracy and performance of electrochemical discharge machining (ECDM). In this contribution, two alkaline electrolytes, NaOH and KOH, were mixed in equal proportion. It was observed that using NaOH + KOH mixed electrolyte at 15 and 25 wt% concentrations provides more electrical conductivity than KOH and NaOH separately at the same concentrations. It results in the fabrication of deeper microchannel with sharper sidewalls compared to KOH and NaOH, while its surface quality is preserved as well. Also, using 25, 30, and 35 wt% mixed electrolyte, due to higher viscosity compared to KOH, improved the surface quality of channels up to 35, 42, and 36%, respectively. Analyzing the waveform of the current response of various electrolytes showed that the microchannel with poor MRR and surface quality will be fabricated in the presence of salt electrolytes due to the generation of very low energy and unstable electrochemical sparks. In another part of the experiments, scanning electron microscopy (SEM) images and energy-dispersive X-ray (EDX) analysis of the tungsten carbide (WC) tool used in different electrolytes showed that the tools used in NaOH and NaNO$_3$ had more severe wear compared to KOH and mixed electrolyte. Also, at the applied voltages of 50 V, the tool erosion was more serious compared to tool erosion at 35 V.

1 Introduction

Electrochemical discharge machining is an unconventional microfabrication technology which is used for machining non-conducting materials such as glass and ceramics, by applying chemical and thermal phenomena simultaneously [1]. Using glass pieces in equipment related to optical applications, microelectromechanical systems (MEMS); microfluidic, medical devices; and many modern industries are widely used because of special properties like transparency, biocompatibility, and low thermal and electrical conductivity. Electrochemical discharge machining (ECDM) is a mixture of electrical discharge machining (EDM) and electrochemical machining (ECM) methods in which the material removal rate is much higher than the other methods [2]. Electrochemical discharge machining was first used in microhole drilling [3].

In the 1990s, Esashi et al. presented the first application of ECDM in the field of electromechanical microsystems [4]. At the same time, several studies were conducted on the principles of the electrochemical discharge machining process [5, 6]. Yang et al. stated that one of the important mechanisms that assist in material removal of workpiece is high-temperature chemical etching [7]. They investigated the effect of various electrolytes on the micromachining time of borosilicate experimentally. According to their results, the micromachining time

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of hydroxide salts (NaOH and KOH) was less compared to that of chloride salts (NaCl and KCl). Fascio et al. introduced spark-assisted chemical engraving (SACE) to shape 3D microstructures on glass pieces [8]. With this appellation, they showed that in this process, the chemical etching contributes in the material removal mechanism as well as in melting the workpiece. Finally, Wüthrich and Fascio published the first review paper in this field in 2005 [9]. They pointed out some main limiting factors of the process and also presented the possible solutions. In another study, Wüthrich et al. stated that the dimensions of machined structures are associated with the thickness of the gas film and the tool electrode [1]. They also showed that the wettability of the electrode would affect the gas film thickness. So, they reduced the gas film thickness using surfactant (liquid soap)-mixed electrolyte, which increases the wettability of the tool-electrode. As a result, the formation of thin gas film decreases the critical voltage from 20 to 15 V.

Once again, Wüthrich et al. stated that evaluating the current signals between the two electrodes is a way for on-line monitoring of the ECDM process, from which some valuable information such as the presence or absence of gas film, local electrolyte temperature, etc. can be obtained [10].

Didar et al. investigated the parameters affecting the microchannels machined by the ECDM process including the applied voltage, the tool velocity, and the tool distance from the workpiece [11]. The microchannel depth and contour quality were evaluated quantitatively and qualitatively.

Cheng et al. studied the effect of machining parameters on the gas film quality [12]. They stated that the thickness of the gas film surrounding the tool electrode is one of the most effective parameters in the machining quality, and as the gas film becomes thinner, higher machining quality would be achieved. They used current signal analysis for monitoring the gas film quality. They represented that in the voltage much lower than the critical voltage, the bubbles have sufficient time to coalesce and grow up, so a thicker gas film will be formed and unstable discharge activity inside the gas film will be generated. Also, by increasing the electrolyte concentration, a thinner gas film could be achieved at lower applied voltages. They also showed that using a flat sidewall tool would result in higher gas film quality compared to the cylindrical tool.

Ziki et al. investigated the texture of machined microchannels by the ECDM process [13]. They used NaOH electrolyte solution and showed that the surface texture is a function of electrolyte motion state during machining. The viscosity of the electrolyte is known as the most important factor in the formation of surface texture, and they demonstrated that when the electrolyte with higher viscosity is used, the texture of the channel surface will be changed from a featherylike pattern to a smooth and spongy-like pattern.

In order to improve the performance of 2D machining by the ECDM process, the effect of the tool rotation, pulse voltage [14], electrolyte composition [15], applying the magnetic field [16], and the presence of ultrasonic vibration [17] have been investigated.

Salonitis et al. developed a thermal-based model in the die-sinking electrical discharge machining process in order to optimize the process parameters for increasing the productivity of the process. Their model showed that an increase of the discharge current would result in higher material removal rate and surface roughness [18].

In addition to studying the surface and geometrical quality of microchannels machined by the ECDM process, some researchers studied the tool wear in different machining conditions. Yang et al. studied the wear of the tungsten, tungsten carbide (WC), and stainless steel 304 tools used in the electrolyte solution of 5 M KOH and the applied voltage of 28–46 V [19]. They showed that the highest current density would occur at the edges of the tool electrode and result in higher erosion near the rim of the tool electrode. Also, according to their results, using tungsten carbide tool as cathode would result in microholes with higher precision and lower tool wear compared to other studied materials. Kim et al. investigated the effect of pulsed voltage on the tool wear at a voltage of 40 V [20]. They used a graphite tool with diameter of 300 to 700 μm and KOH 25 wt% solution as electrolyte. They indicated that the tool wear rate increases with increasing the duty ratio and also decreasing the tool diameter. In another work, Ziki and Wüthrich measured the thermal expansion of the tool due to the generated heat during the process and also measured the tool wear for three different tool materials including tungsten, steel, and stainless steel [21]. According to the obtained results, stainless steel has the highest tool expansion with less tool wear. Also, they applied pulsed voltage to the process to enhance the machining accuracy by controlling the tool temperature.

Behroozfar and Razfar studied the tool wear during electrochemical discharge microdrilling [22]. They used brass, steel, and tungsten carbide tools which have different melting temperatures. Their results showed that using WC and steel with high melting temperature would decrease the tool wear in high applied voltages.

Electrochemical discharge machining is a complex hybrid process, and several parameters affect the performance of machining. The best machining accuracy can be achieved by keeping the process output including surface quality, material removal rate (MRR), the amount of machining overcut, and the sidewall taper angle of produced microchannels in the acceptable range. This contribution attempts to improve the machining efficiency of 2D electrochemical discharge machining (ECDM). To acquire this purpose, for the first time in this study, mixed alkaline electrolyte (NaOH + KOH) was used in 2D milling in order to impact the electrical conductivity and viscosity of the solution. Meanwhile, the tool wear of tungsten carbide tool electrode was investigated by SEM and

EDX analysis methods in different machining conditions. Depth and entrance overcut as geometrical accuracy, the surface quality of the produced microchannels and also the tool wear were evaluated and compared under different machining conditions. According to the results, the appropriate machining condition was reported.

2 Experimental design

2.1 Experimental setup

The experimental setup combined the chamber process (electrochemical cells) and precise X-Z table. A schematic figure of the setup is shown in Fig. 1. Each axis (X and Z) can be moved with the velocity of 0–120 μm/s by separate stepper motors. A rotating axis, which is connected to a DC motor, is mounted on the Z axis and is composed of a collet chuck. The collet chuck will hold the tool electrode, and its axial run out is less than 5 μm. The DC motor provides the rotational motion of

the tool electrode, which is in a range of 0–1500 rpm. The process chamber consists of an end-flatted tungsten carbide (WC) drilling tool with 0.5 mm diameter (cathode), a stainless steel plate with dimensions of $3 \times 40 \times 50$ mm^3 as an auxiliary electrode (anode), electrolyte solution, a soda lime glass with dimensions of $1 \times 10 \times 40$ mm^3 as the workpiece, and a DC power source (0–5 A/0-60 V) as the power supply.

The glass workpiece was held by an acrylic base holder. The tool electrode was mounted in the collet holder. The distance between the tool and the workpiece surface was adjusted to the desired gap (15 μm) with the help of a depth micrometer. This gap was verified by dial indicator with a resolution of 1 μm. Then, the processing cell was filled with electrolyte and the glass workpiece was completely immersed into the electrolyte so that the distance between the top surface of the glass and electrolyte was about 2 mm. The desired machining voltage was applied by the DC power source. By generating the electric current between the tool electrode and the auxiliary electrode, the electrolysis occurred in the electrolyte cell. Finally, with the movement of the tool on the glass surface,

Fig. 1 a A schematic diagram of ECDM setup. b A real processing cell of ECDM. c Spark generated through gas film
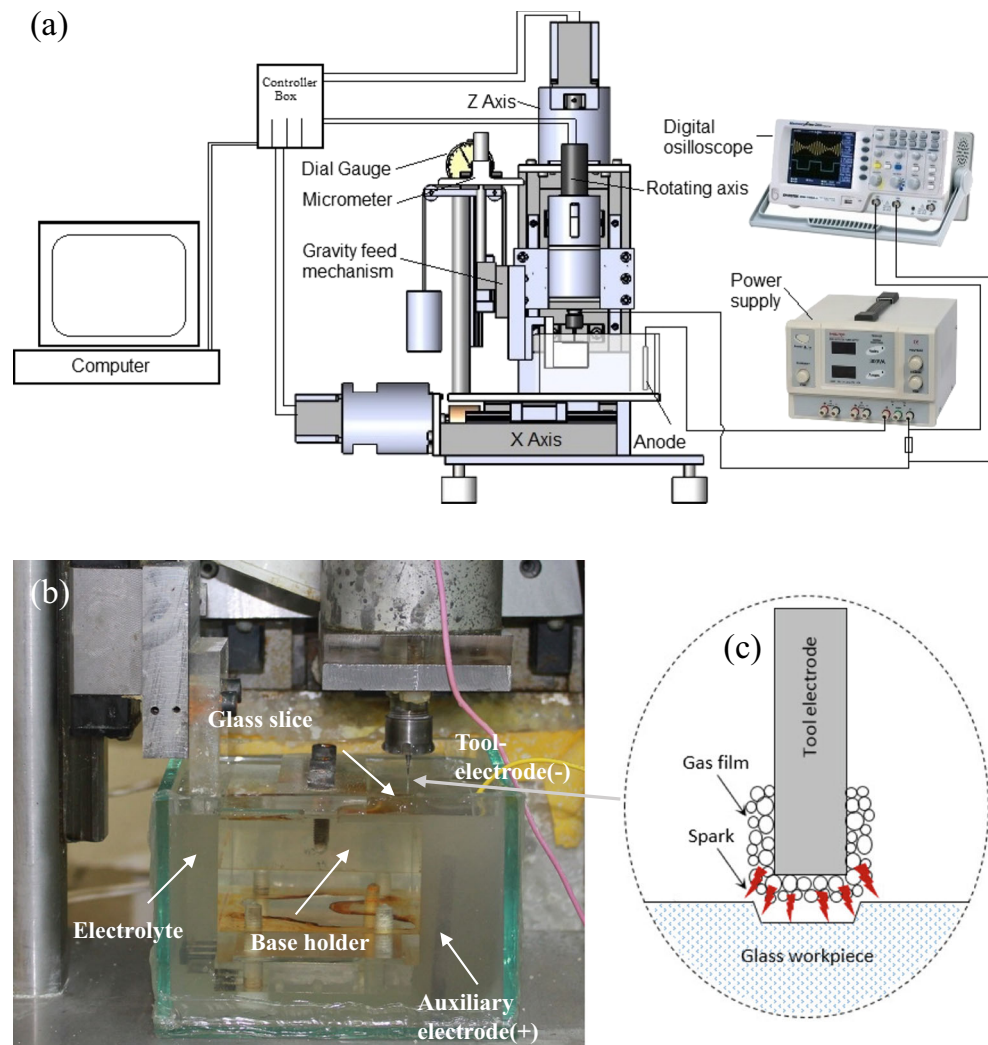
microchannels with the length of approximately 10 mm were fabricated on the glass. For investigating the microchannel dimensions, the glass pieces were cut perpendicular to the microchannel direction and ground with emery paper. The cross section of the channels were recorded and determined with an Xsp-136 digital microscope. Likewise, the surface roughness of the samples was measured by a surface roughness tester model "Mahr Perthometer M3." The current signals were registered by GW-INSTEK GDS-1072A-U, 70 MHz-1 G SA/s, a two-channel digital oscilloscope. The viscosity and the electrical conductivity of the electrolytes were measured by BROOKFIELD DV-IT + Pro viscometer and conductivity portable meter ProfiLine Cond 3110, respectively. In addition, scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM/EDX) was used to analyze the surface of the tools.

2.2 Machining procedure

The tool electrode and the auxiliary electrode were immersed in the electrolyte. By applying the DC voltage between the two electrodes, the electrolysis process would occur in the electrolyte cell and hydrogen and oxygen gas bubbles would be generated. The hydrogen gas bubbles surrounded the tool electrode (cathode). When the applied voltage exceeds a certain level, which is named critical voltage, the hydrogen gas bubbles coalesce together and form a gas film around the tool. This makes the tool electrode to be insulated from the electrolyte. In this stage, the electrical resistance of the hydrogen gas film will break down and consequently, electrical discharge occurs. If the glass workpiece is located in an appropriate distance (lower than 25 μm) from the tool electrode, the heat generated by the electrical discharge machining and chemical etching causes the removal rate of the workpiece [9]. Tables 1 and 2 show the adjusted parameters for the electrochemical discharge micromachining procedure conducted in this study.

All of the experiments were done in full factorial design. In order to enhance the accuracy of results, each experiment was repeated three times. Deionized water was used for dissolving electrolytes in order to reduce the effect of undesirable ions on the machining performance.

Table 1 ECDM process conditions for alkaline solutions

Electrolyte type	KOH/NaOH/KOH + NaOH
Electrolyte concentration	15,25, 30, 35 wt% (800 mL)
Electrolyte temp.	25 °C
Tool rotation speed	800 rpm
X-axis speed	10 μm/s
Applied voltage	32 V

Table 2 ECDM process conditions for salt solutions

Electrolyte type	NaCl/NaNO$_3$
Electrolyte concentration	25 and 30 wt% (800 mL)
Applied voltage	50 V

3 Results

In this section, the effect of electrolyte type and concentration on ECDM performance is discussed. So, the critical voltage, the waveform of the current signals, the electrical conductivity, and the viscosity of solutions was investigated for determining the effect of various electrolytes. Also, the outputs of ECDM process including the depth and width of microchannels as geometrical accuracy parameters, the surface quality of the produced channels, and tool wear were evaluated and compared under different machining conditions.

3.1 Effect of electrolyte type and concentration on the critical voltage

The electrical conductivity of the electrolyte is one of the parameters that affect the critical voltage, in which enhancement of the electrical conductivity results in decrement of the critical voltage. Wüthrich and Hof stated that lower critical voltage results in thinner gas film and subsequently, machining can be done in lower voltages [23]. The gas film thickness is one of the dominant and important factors that influence the quality of machining performance. Also, the reduced critical voltage will diminish the fluctuation of the discharge activity, which is important in repeatable machining.

Table 3 shows the critical voltage of the process using different electrolyte types and concentrations.

As can be seen, NaNO$_3$ and NaCl electrolytes have the most critical voltage value. Also, using NaOH would result in higher critical voltage compared to KOH and NaOH + KOH. The electrical conductivity of the solution depends on the concentration and the composition of the electrolyte. In fact, the electrical current is transported by ions in an electrolytic solution, and the number of cations and anions in the electrolyte, their charge and molar ionic conductivity, affects the electrical conductivity of the solution. By comparing the mobility and conductivity of K$^+$, Na$^+$, OH$^-$, Cl$^-$, and NO$_3^-$ ions, it has been found that the electrical conductivity and mobility of potassium ions are higher than of sodium ions. Also, these values for chloride and nitrate ion are much lower than for OH$^-$ ions (Table 4).

As it is evident from Table 3, the mixed electrolyte at the concentration of 25 wt% has lower critical voltage than other electrolytes. It should be noted that the mobility of ions in an electrolyte singly is different from their mobility in mixed

Table 3 Critical voltage value for different electrolytes

	15 wt%	25 wt%	30 wt%	35 wt%
NaOH	26.4	25.5	25	25.7
KOH	24.2	22.6	21.4	21.3
NaOH + KOH	21.2	20.2	21	21.4
NaNO3	–	37.4	35.5	–
NaCl	–	34	34.4	–

electrolytes [27], so, it seems that the electrical conductivity of the electrolyte can be changed by combining it with other electrolytes. For this purpose, NaOH + KOH mixed electrolyte with equal combination ratio is used in this study. It was observed that using NaOH + KOH mixed electrolyte at the concentration of 15 and 25 wt% provides more electrical conductivity compared to KOH and NaOH separately (Fig. 2). However, further rise in electrical conductivity of higher concentration of mixed electrolyte could not be seen due to the ionic interactions in the thick electrolytes. The electrical conductivity of various solutions at room temperature was measured by the conductivity meter.

3.2 Effect of electrolyte type and concentration on the depth of microchannels

As it was mentioned before, a proper amount of gas bubbles would be generated at the critical voltage and coalesced together to form a gas film. The gas film formation time is a specified period of time and sparking would occur after that. This period is not constant and depends on a variety of factors such as voltage level, electrolyte type, and concentration. In general, the gas film formation time is about a few milliseconds and it would be decreased by increasing the temperature and the voltage [28]. By applying the voltage lower than the critical voltage, the gas film would not completely be formed and the sparking would not occur. So in the ECDM process, the applied voltage should be adjusted higher than the critical voltage to guarantee the generation of large volumes of bubbles, which results in the formation of gas film regularly and occurrence of the electrical discharge consecutively. Whatever the gas film forms in a very short time and consecutive discharges take place as well, a high-quality gas film will be formed and the quality of machining process would be increased.

From Fig. 3, it is clear that using mixed electrolyte would result in higher current signal compared to the other electrolytes. On the other hand, the thermal energy of the electrochemical discharge machining process is proportional to the current and it increases as the current of the process increases [29], so it is expected that using the mixed electrolyte would lead to deeper microchannels due to generating high thermal energy.

The two most notable points that are inferred from the current-time graphs are as follows:

1. The peaks with the duration more than a millisecond represent the gas film formation stage. Increment in the number of these peaks would limit the material removal rate
2. The peaks shorter than the millisecond duration represent the discharges that take place in the gas film [30].

It is seen that by using the salt electrolytes (NaNO$_3$ and NaCl), the total number of discharges that occurred in the gas film is reduced and the gas film formation time is increased compared to the alkaline electrolytes (Fig. 3d, e), which leads to the instability of the sparks. Thus, it is expected that using salt electrolytes will lead to poor material removal due to lower number and non-uniform discharges that occurred in the gas film. According to the results obtained from the experiments, the depth and MRR of the channels produced in salt electrolytes could not be reported by any theoretical (by calculating the removed volume) or experimental methods (by weighting the sample). As it is mentioned before, melting and evaporation of the workpiece due to electrochemical discharge and also high-temperature chemical etching are the most effective mechanisms that assist in the material removal of the workpiece in the ECDM process. The chemical etching process of the glass workpiece needs the presence of OH radicals which react chemically with the workpiece by accumulation on the surface. The presence of alkaline solutions will intensify the chemical etching by providing more OH radicals on the glass substrate compared to salt solutions, which would lead to enhancement of MRR and the quality of the microchannel surface.

Figure 4 illustrates the depth of microchannels conducted on the soda lime glass in terms of the type and concentration of alkaline electrolytes.

As it is clear from Fig. 4, the depth of the microchannels machined in the presence of NaOH + KOH 15 and 25 wt% are more than NaOH and KOH electrolytes at the same concentrations due to the higher electrical conductivity and higher current signal compared to KOH and NaOH separately. Figure 4 also illustrates that the depth of channels produced by KOH electrolyte is more than NaOH at similar conditions. According to Fig. 3b, c, the higher current sparks would occur in the case of using KOH as electrolyte compared to NaOH

Table 4 The mobility and electrical conductivity of various ions [24–26]

	K$^+$	Na$^+$	OH$^-$	NO$_3^-$	Cl$^-$
Mobility($m^2 s^{-1} v^{-1}$).10^{-8}	7.62	5.19	20.64	7.4	7.91
Conductivity($S\ Cm^2 mol^{-1}$)	73.5	50.1	198.6	71.5	76.4

Fig. 2 The electrical conductivity of alkaline solutions at different levels of concentration
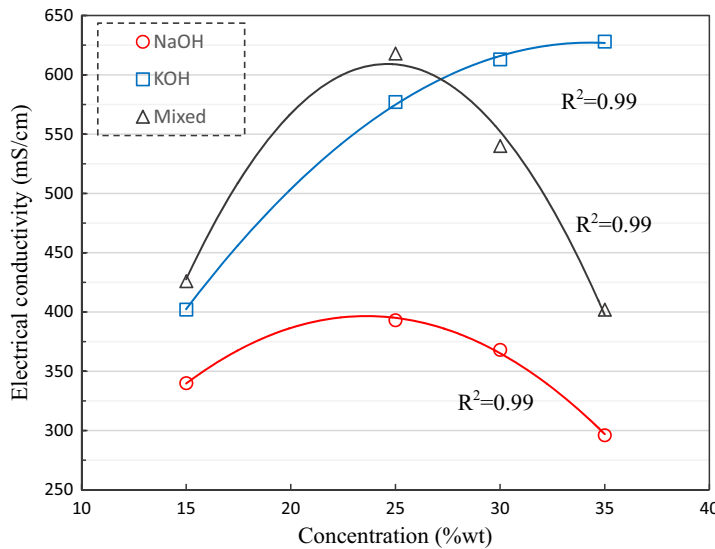
Electrolyte concentration	Electrolyte Type		
	NaOH	KOH	Mixed
15wt%	340	402	426
25wt%	393	577	618
30wt%	368	613	540
35wt%	296	628	402

which can deliver more heat power to the workpiece; also, the larger K^+ ions replace Na^+ ions and decrease the glass workpiece's strength, which results in producing deeper microchannel in the presence of KOH electrolyte [29].

As the bubble detachment time would decrease by increasing the electrolyte concentration [29], the presence of a more concentrated electrolyte will lead to the occurrence of a greater amount of electrical discharge in the gas film in comparison

Fig. 3 ECDM current signals in the presence of various electrolytes at the concentration of 25 wt%; the applied voltage for alkaline electrolytes = 32 V and for salt electrolytes = 50 V
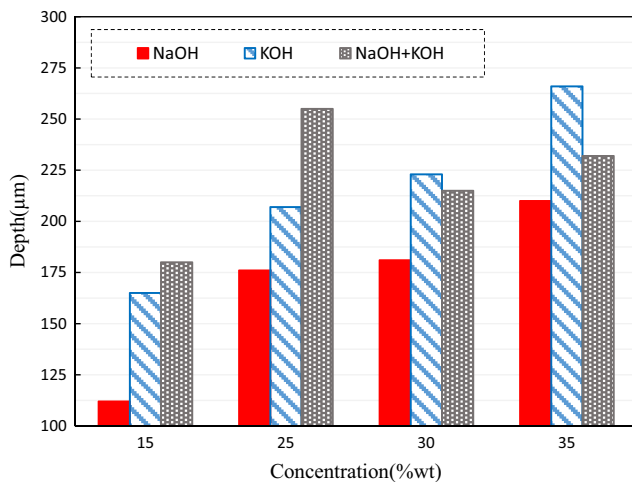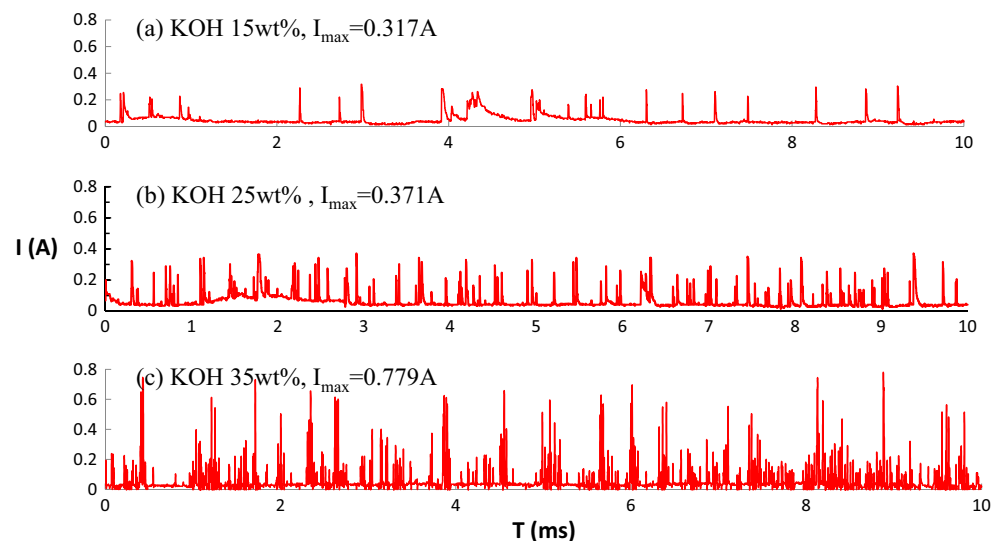
Fig. 4 The depth of microchannel profile in the presence of various electrolytes

3.3 Effect of type and concentration of electrolyte on the width of microchannels

The entrance overcut and the sidewall taper angle of the microchannel are the main indicators of the geometrical accuracy of the machined microchannel [14]. The entrance width of the machined microchannels was higher in NaOH electrolyte compared to in the other electrolytes due to the lower electrical conductivity of NaOH (Fig. 6). As it was mentioned before, increasing the electrical conductivity would decrease the critical voltage and the gas film thickness subsequently. The thinner gas film would limit the stray erosion on the microchannel surface, and so, microchannels with sharp sidewalls and high geometric quality would be produced.

For strong electrolytes like NaOH and KOH, at low concentrations, the electrical conductivity is proportional to the electrolyte concentration. Increasing the electrolyte concentration would result in increment of the electrical conductivity due to the greater quantity of ions, which carries the charge. Also, more stable gas film (by decreasing the bubble detachment time and the gas film formation stage) would be achieved. Furthermore, the presence of a greater quantity of OH^- ions at high concentrations will reduce the surface tension of the electrolyte, so thinner gas film and an improved machining accuracy would be resulted [12].

However, it should be noted that when the electrolyte concentration exceeds a certain limit, the electrical conductivity would be reduced due to ionic interactions. Thus, the electrical conductivity reaches a maximum value as a function of the electrolyte concentration [29]. This maximum value is different for various electrolytes. For

with dilute electrolyte and consequently, the material removal rate will be increased (Fig. 5). In addition, an increase in the electrolyte concentration brings about more hydrogen gas bubbles and results in a greater amount of discharge energy at the sparking zone [31]. According to Fig. 4 in KOH and NaOH electrolytes, the depths of the microchannels were enhanced by increasing the concentration of electrolyte. While the depth of microchannels machined in the presence of mixed electrolyte decreased from concentration of 25 to 30 wt%, the depth of microchannels saw an upward trend. Since the electrical conductivity of mixed electrolyte peaked at the concentration of 25 wt% and then declined moderately, deeper microchannel was produced in the presence of 25 wt% mixed electrolyte.

Fig. 5 ECDM current signals in the presence of different concentrations of KOH electrolyte

Fig. 6 **a** The entrance width of microchannels vs. concentration in the presence of various electrolytes. **b** Optical images of geometrical quality of microchannels
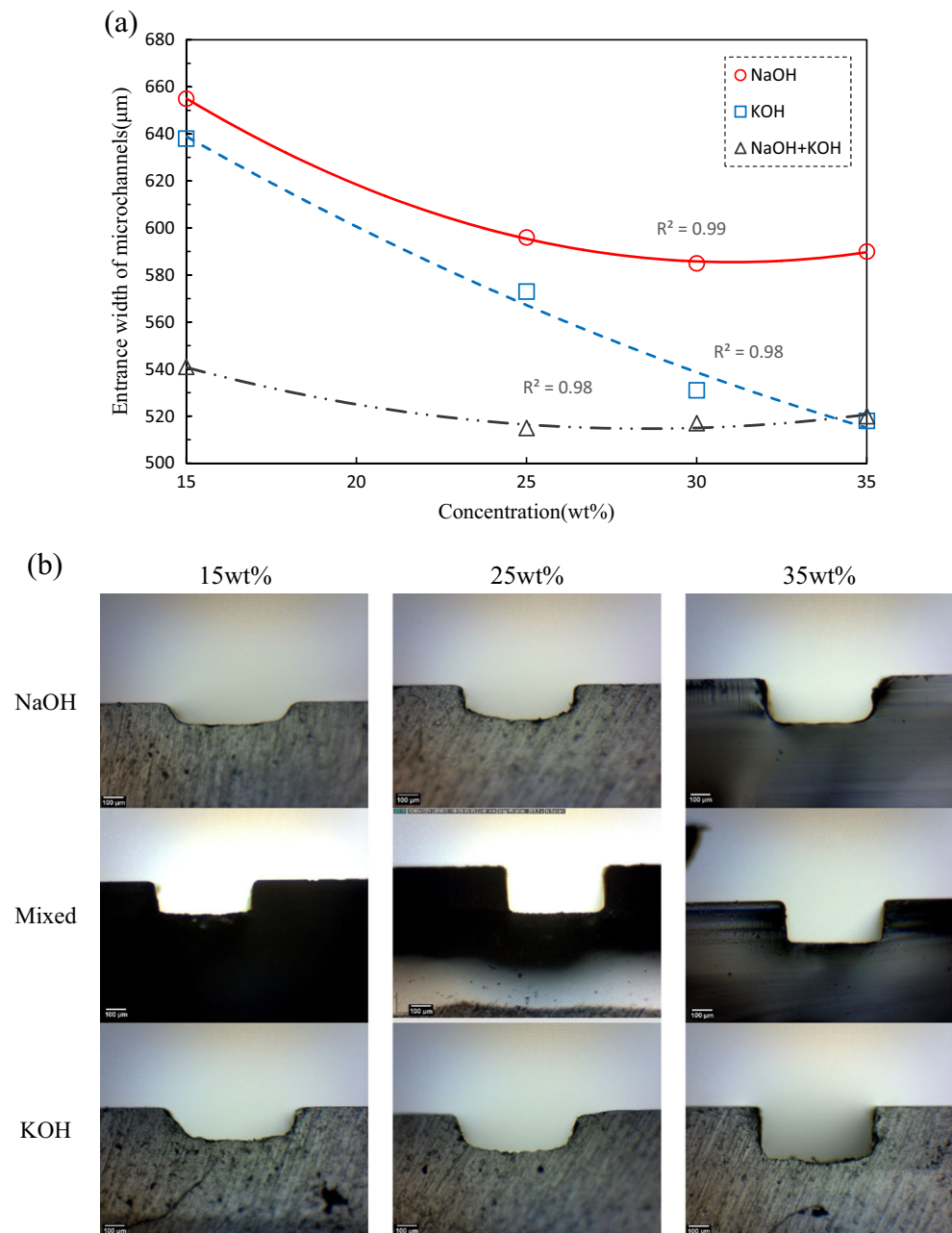
KOH electrolyte, the overcut value saw a downward trend from a concentration of 15 to 35 wt%. The electrical conductivity of the mixed electrolyte at the concentration of 15 and 25 wt% is higher than of NaOH or KOH singly, so the presence of mixed electrolyte would result in a lower overcut value of microchannels compared to the other electrolytes. For example, at a concentration of 15 wt%, the overcut value for microchannels machined in NaOH, KOH, and the mixed electrolyte is 655, 638, and 541 μm, respectively.

3.4 Effect of type and concentration of electrolyte on the surface quality of microchannels

Figures 7 and 8 show the texture of microchannels fabricated in different electrolytes with various concentrations.

As it is seen from Fig. 7, the texture and surface quality of the microchannels are different for various types and concentrations of the electrolyte. As high numbers of ions are available in the case of using high concentration of electrolyte, the electrolysis process would occur faster in comparison with that of using
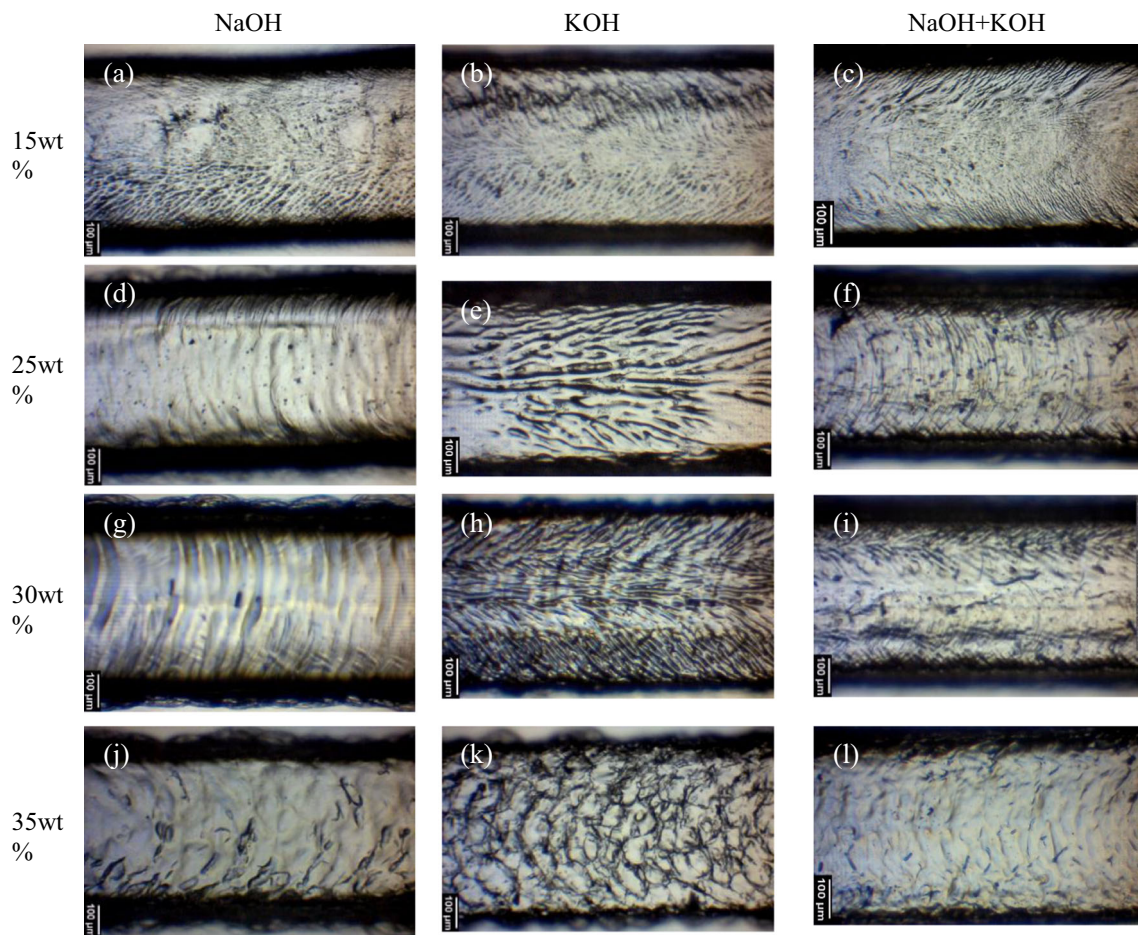
NaOH   KOH   NaOH+KOH

Fig. 7 Optical image of microchannels machined in alkaline electrolytes (applied voltage 32 V)

low electrolyte concentration. Inside the thick gas film, unstable discharge activity will be generated and microchannels with poor surface quality will be produced. At the concentrations lower than 15 wt%, not sufficient ions are available for the occurrence of the electrolysis process, so the gas bubble formation time and the gas film thickness would increase. In this study, all experiments were conducted in the presence of electrolytes with a concentration of 15% and over.

Ziki et al. demonstrated that when the electrolyte with higher viscosity is used, the texture of the channel surface will be changed from a feathery-like pattern to a smooth and spongy-like pattern [13]. From the experiments, it was seen that using the higher concentration of electrolyte (25 and 30 wt%) would result in better surface quality. Also, as it is apparent from Fig. 8, using NaCl and NaNO$_3$ as electrolyte results in the fabrication of a channel full of cracks on its surface. In the presence of salt electrolytes, the sparks are

Fig. 8 Optical image of microchannels machined in salt electrolytes. **a** NaCl 25 wt%. **b** NaNO$_3$ 25 wt%
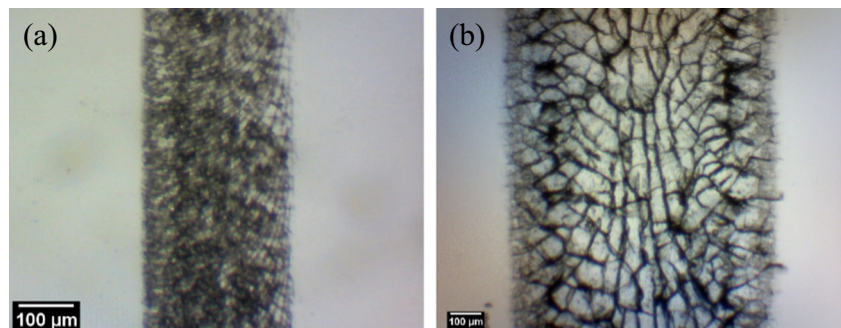
not uniform and the gas film reformation time is more than the alkaline electrolytes (Fig. 3d, e). Therefore, using salt electrolytes would result in the instability of sparks and have a negative effect on the microchannel surface quality.

The thermal conductivity is another property of the electrolyte that depends on the concentration and composition of the electrolyte. For electrolyte with higher heat conductivity, the cooling rate of the melted glass workpiece will increase, which subsequently increases the possibility of forming cracks on the glass surface [13]. Figure 7j, k indicates that the unsmooth microchannel surfaces with thermal cracks were produced in the presence of NaOH and KOH 35 wt%. In general, the thermal conductivity of aqueous solutions is low and enhanced by increasing the concentration [32]. Also, the density of KOH electrolyte is more than NaOH due to the larger size of K^+ ions compared with Na^+, and since the electrolyte with higher density will result in higher thermal conductivity, more thermal damage and thermal cracks will appear on the channel surface machined in the presence of KOH electrolyte.

Table 5 represents the viscosity of the electrolytes in different concentrations. According to the explanations, it is expected that the surface quality of microchannels machined in the presence of NaOH electrolyte would be better compared with other used electrolytes. Also, Fig. 9b demonstrates that using mixed electrolyte at the concentration of 25, 30, and 35 wt% due to the higher viscosity compared to KOH improved the surface quality of channels up to 35, 42, and 36%, respectively.

3.5 Effect of electrochemical parameters on tool wear

Since in spark-based process the electrical discharges which hit on the tool surface have a strong effect on the tool wear [22], it seems that parameters affecting the electrical discharge energy and the number of the produced sparks play an essential role in the tool erosion. The most important factors that affect the spark energy and generated heat in the machining area are the applied voltage level, electrolyte type, and concentration. High thermal energy would enhance the tool surface temperature and subsequently, the plastic deformation would occur due to the softening of the tool material. Increasing the applied voltage will lead to higher current density and generation of more gas bubbles which increases the
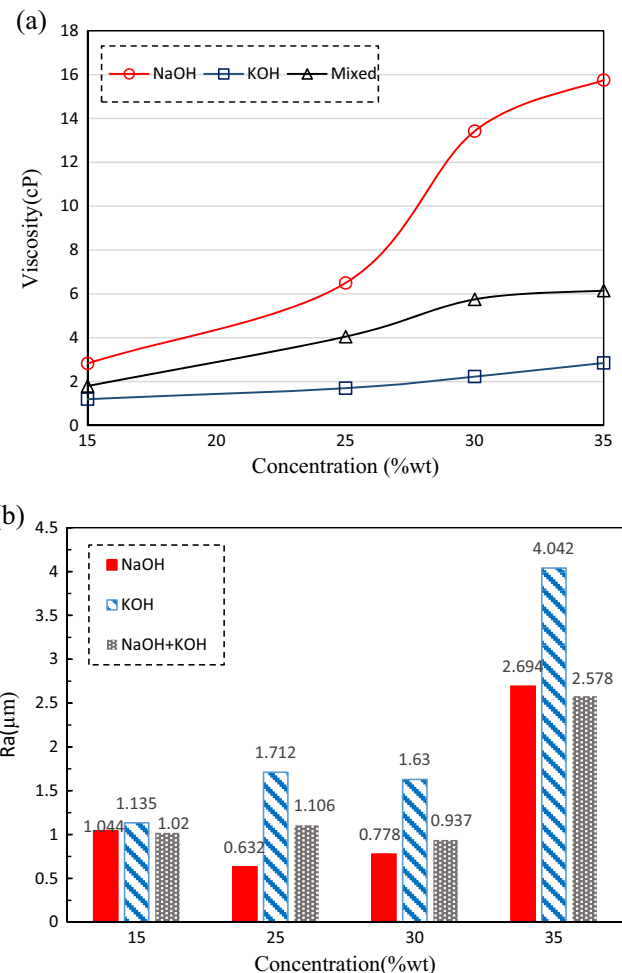

Fig. 9 a The viscosity of various electrolytes at room temperature. **b** Surface roughness of microchannels in different machining conditions (electrolyte type = NaOH, KOH, NaOH + KOH; concentration = 15, 25, 30 and 35 wt%; applied voltage = 32 V)

number of discharges around the tool [20]. Also, applying higher voltages will increase the spark energy and the sparks spread in a greater range of tool-electrode.

In this study, scanning electron microscopy (SEM) images and energy-dispersive X-ray (EDX) analysis of the surface tool were used to investigate the tool wear. Table 6 shows the adjusted parameters for determining the tool wear. It should be noted that before scanning electron microscopy, tools were washed in an ultrasonic bath to eliminate contaminations on the tool surfaces.

Table 5 The viscosity (cP) of various electrolytes at room temperature

Electrolyte type	Electrolyte concentration			
	15 wt%	25 wt%	30 wt%	35 wt%
NaOH	2.83	6.5	13.42	15.75
KOH	1.2	1.7	2.23	2.85
Mixed	1.8	4.05	5.75	6.15

Table 6 ECDM parameters for wear tests

Electrolyte type	KOH/NaOH/KOH + NaOH/NaNO$_3$
Electrolyte concentration	15 wt% and 25 wt%
Machining time	17 min
Applied voltage	35 and 50 V
Tool immersion	2 mm

3.5.1 Effect of level of applied voltage and electrolyte type on the tool wear

The SEM images and the results of EDX analysis of surface tools in different conditions are shown in Figs. 10 and 11.

As it is observed from Fig. 11a, the base tool consists of 67.58% tungsten, 20.87% carbon, 3.90% cobalt, and small amounts of other elements. The surface of the tool is coated to enhance the hardness and wear resistance of the base metal. Also, the copper is used in the core of tools in order to increase
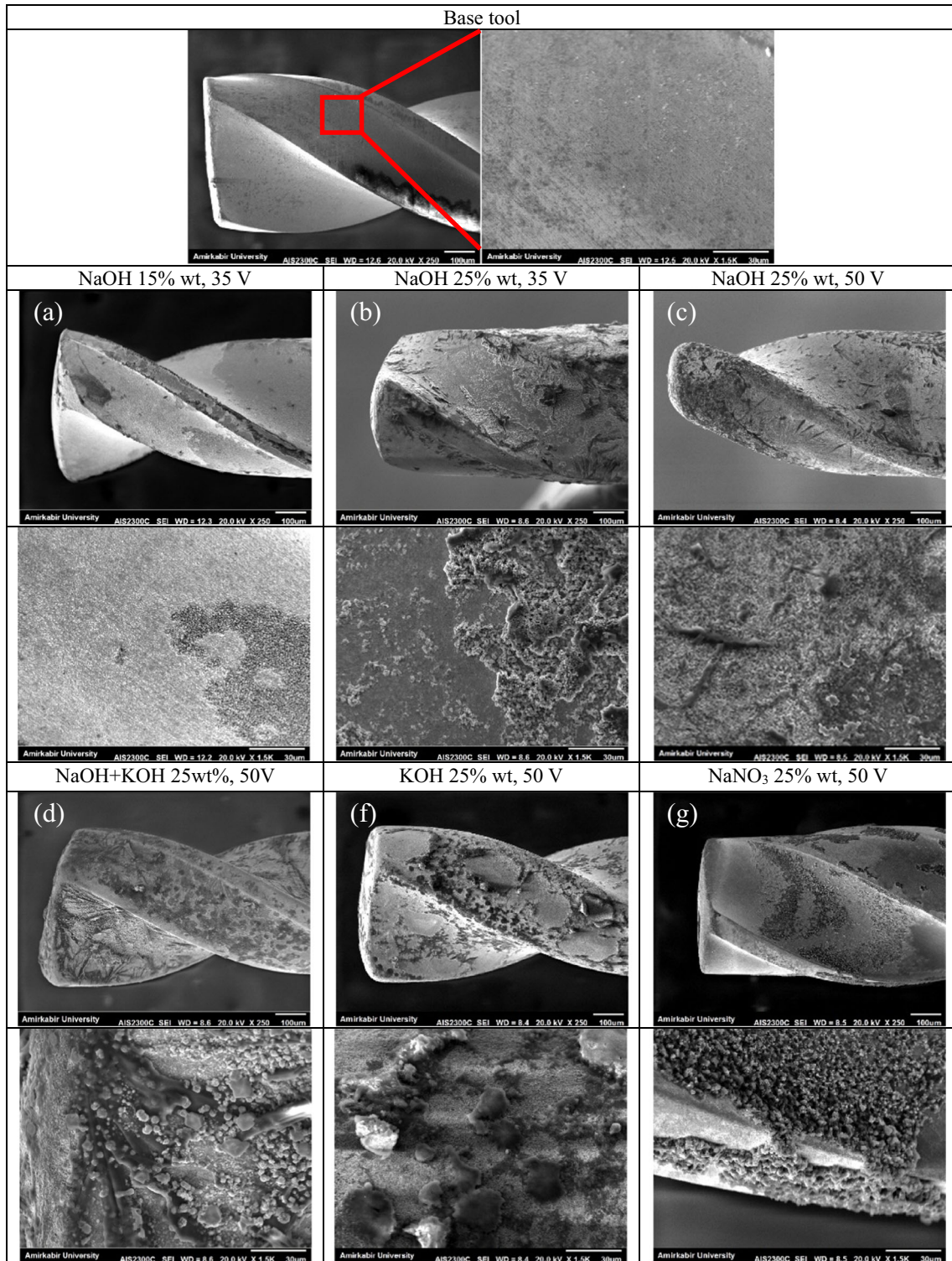

Fig. 10 SEM image of tool electrodes in different machining conditions

element	wt%
W	67.58
Co	3.90
C	20.87

(a) Base tool

element	wt%	element	wt%
W	31.71	Na	4.24
Cu	25.32	O	30.41
C	2.23	Co	0.83

(b) NaOH 25wt%, 35 V

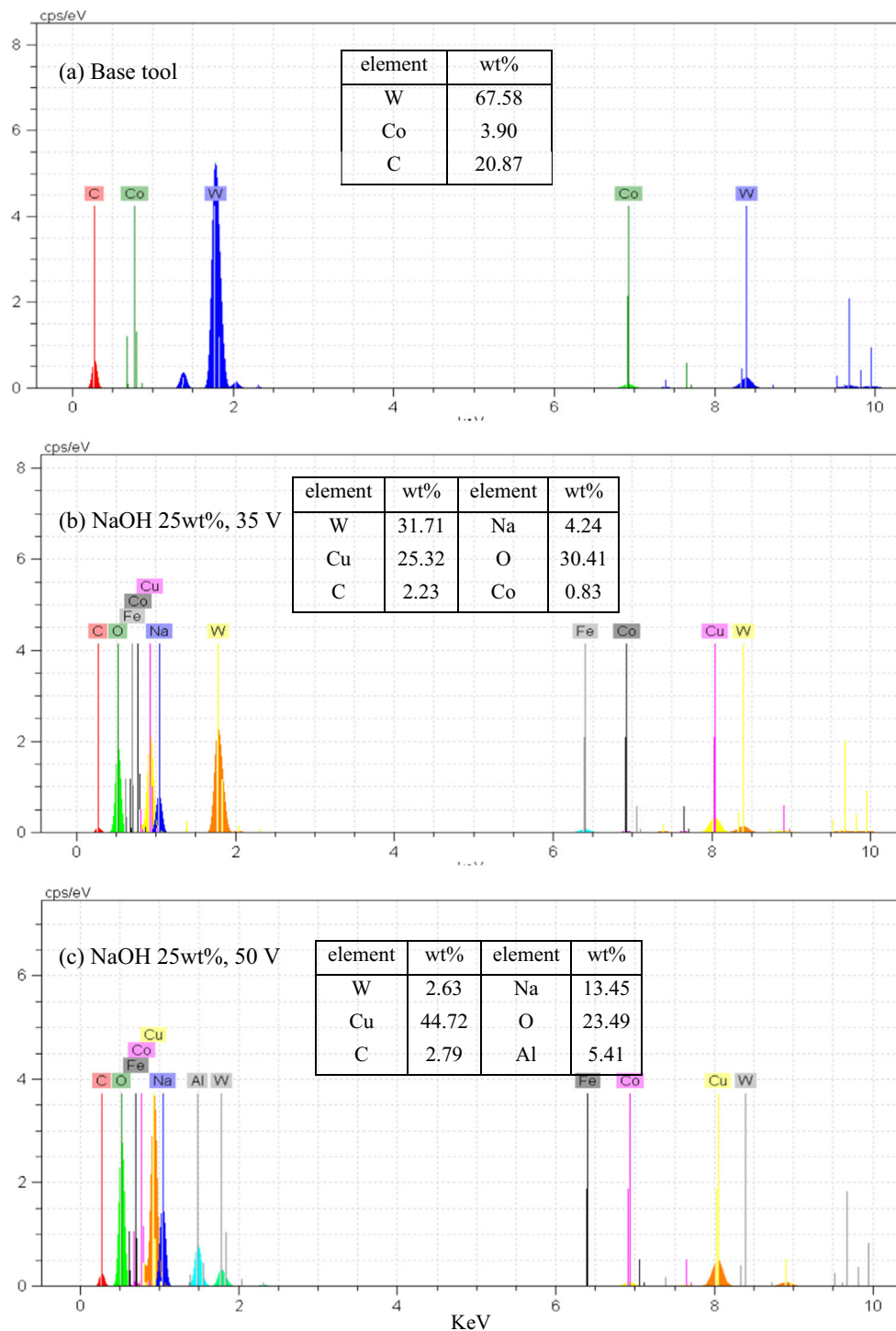| element	wt%	element	wt%
W	2.63	Na	13.45
Cu	44.72	O	23.49
C	2.79	Al	5.41

(c) NaOH 25wt%, 50 V

Fig. 11 EDX analysis results of tool electrodes used in different machining conditions

the toughness of microdrilling tools, which are susceptible to fracture. The results of the EDX analysis results represent a significant increase in the percentage of copper (Cu), sodium (Na), and oxygen (O) and decrease in the percentage of tungsten (W) and carbon (C). The reduction of tungsten element at the tool surface, which was used at the applied voltage of 35 and 50 V, is 53 and 96%, respectively. Also, the increment of copper element at the applied voltage of 35 and 50 V is 25 and 45%, respectively. It can be concluded that applying voltage of 50 V to the process will lead to severe tool wear in comparison with the voltage of 35 V. In general, changing the tool appearance, loss of tungsten coating, and the appearance of
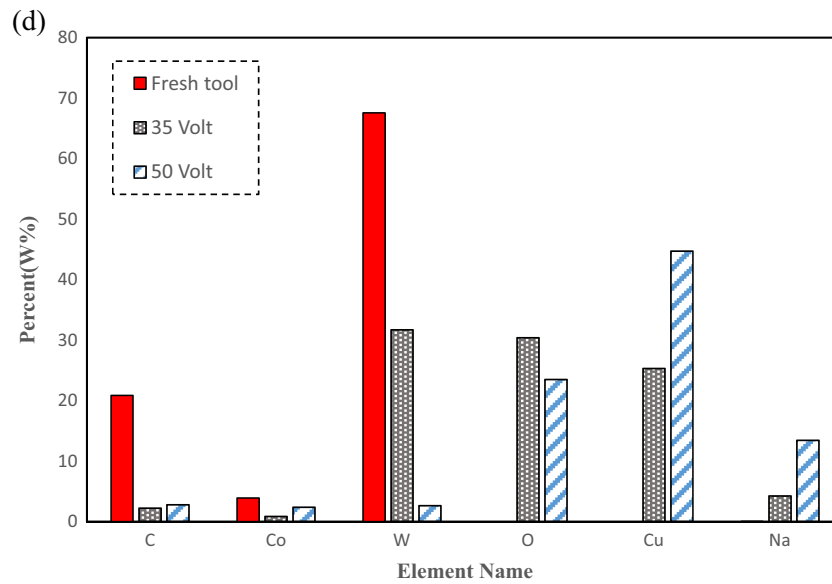
(d)

Fig. 11 (continued)

the copper element in the EDX analysis results were considered as a criterion of tool wear. Jiang et al. stated that higher current density would be generated near the rim of the tool bottom [33]. It is expected that the tool erosion will be more serious at the rim of tool. Behroozfar and Razfar stated that at the voltage of 50 V, the surface temperature of the tool will increase up to 2800 °C [22], so it seems that the formation of spherical particles on the used tool surface is because of the re-solidification of tungsten particles after surface melting due to the fast cooling rate of the tool electrode. These particles have occasional condensation. The tool used at 50 V includes more spherical particles than the tool used at a voltage of 35 V.

Increasing the percentage of sodium element in the tool surface used in NaOH electrolyte is because of the acceleration of Na^+ ions to the cathode (tool) and hitting on it.

The electric field intensity between the anode and cathode affects the acceleration of ions. Since the higher applied voltage will result in a more intense electric field, as it is seen in Fig. 11d, at the voltage of 50 V, higher percentage of sodium element is observed on the tool surface compared to the voltage of 35 V.

According to the results of the SEM and EDX analyses, the wear of tools used in NaOH and $NaNO_3$ was more severe and shows significant erosion at the edges of the tool with more re-solid particles compared to the tools used in the KOH and mixed electrolyte. Since Wüthrich demonstrated chemical etching as one of the reasons of tool wear is chemical etching [29], it seems that the electrolyte type has different effects on tool wear (Fig. 12).

Fig. 12 EDX analysis results of tool electrodes used in various electrolytes at the concentration of 25 wt%
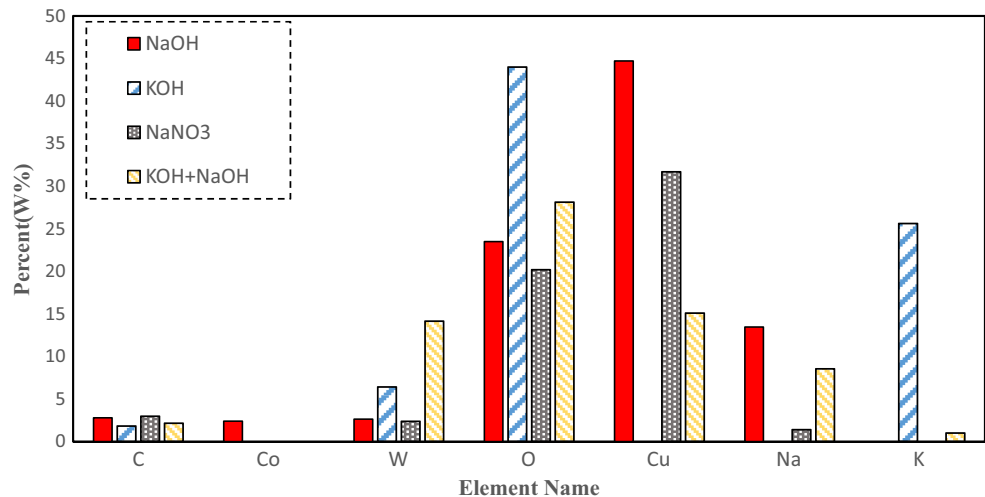
3.5.2 Effect of electrolyte concentration on the tool wear

As noted, the number of ions in the electrolyte is determined on the basis of the electrolyte concentration. A greater quantity of ions will result in a faster electrolysis process, and the production of hydrogen gas bubbles will be facilitated and as a result, the gas film restoration will be improved. It can be concluded that enhancement of the electrolyte concentration brings about an increase in the rate of sparking in the electrochemical discharge machining. In this part of the experiments, two concentrations of 15 and 25 wt% were used to study the influence of electrolyte concentration on the tool wear. As is seen from Figs. 10a, b, the tool used in concentrations of 25 wt% leads to severe wear at the edges of the tool and has more re-solid particles on its surface.

4 Conclusion

The present contribution aims to achieve optimal parameters for diminishing the tool wear, thermal damages, unsmooth surface, and overcut deviation as accuracy parameters in fabricating 2D structures on the glass substrate. Applying machining conditions that keeps all outputs in the acceptable range is important. The main conclusion of the current study can be summarized as follows:

1. By measuring the electrical conductivity of all used alkaline electrolytes, it was found that the electrical conductivity of solution in the case of using NaOH + KOH mixed electrolyte instead of NaOH and KOH at the concentration of 15 wt% rose by around 86 and 24 mS/cm, respectively. The figures for the concentration of 25 wt% were 225 and 41 mS/cm, respectively.
2. The presence of NaOH + KOH 25 wt% resulted in an increase in the depth of microchannels up to 19 and 31% compared to KOH and NaOH, respectively. The figures for the concentration of 15 wt% were 8 and 38%, respectively.
3. Increment of the electrical conductivity brought about a decrease in the critical voltage which led to limitation of the stray erosion on the microchannel surface and producing microchannels with sharp sidewalls and high geometric quality. For example, at the concentration of 15 wt%, the overcut value for microchannels machined in NaOH, KOH, and mixed electrolyte is 655, 638, and 541 μm, respectively.
4. Using more viscous electrolytes had a significant effect on the improvement of surface quality of microchannels. For example, in the case of using NaOH + KOH 25, 30, and 35 wt%, the surface quality of microchannels was improved up to 35, 42, and 36%, respectively, compared to

the case of using KOH electrolyte at the same concentrations.
5. The unsmooth microchannel surfaces with thermal crack were produced in the presence of 35 wt% electrolytes because of the enhancement of thermal conductivity and the cooling rate of the melted glass workpiece.
6. Microchannels with poor surface roughness and full of cracks were produced in the presence of salt electrolytes ($NaNO_3$ and NaCL) due to the low total number of spark generated in the gas film in comparison with alkaline electrolytes.
7. Applying high voltages to the process led to severe tool wear. The tungsten coating of the tool used in the presence of NaOH25 wt% was reduced up to 96% in the case of the applied voltage of 50 V compared to that of the voltage of 35 V which resulted in 53% tungsten element reduction.
8. Analyzing the SEM images of tools used in the presence of NaOH15 and 25 wt% showed that more re-solid particles would appear on the surface of the tool used in NaOH25 wt%, the meaning of which is that the tool wear will increase by increasing the electrolyte concentration.
9. The SEM and EDX analysis results showed that in the case of using KOH and mixed alkaline electrolytes, the tool wear was slight with less re-solid particles compared to the case of using NaOH and $NaNO_3$.

In order to produce microfluidic and lab-on-a-chip devices, the three-dimensional machining is recommended for future works. Also, for reducing the tool erosion, different approaches including applying pulse voltage to the process could be adopted.

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