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Electrical discharge machining of 6061 aluminium alloy

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Abstract: The wire electrical discharge machining (EDM) of 6061 aluminium alloy in terms of material removal rate, kerf/slit width, surface finish and wear of electrode wire for different pulse on time and wire tension was studied. Eight experiments were carried out in a wire EDM machine by varying pulse on time and wire tension. It is found that the material removal rate increases with the increase of pulse on time though the wire tension does not affect the material removal rate. It seems that the higher wire tension facilitates steady machining process, which generates low wear in wire electrode and better surface finish. The surface roughness does not change notably with the variation of pulse on time. The appearance of the machined surfaces is very similar under all the machining conditions. The machined surface contains solidified molten material, splash of materials and blisters. The increase of the pulse on time increases the wear of wire electrode due to the increase of heat input. The wear of wire electrode generates tapered slot which has higher kerf width at top side than that at bottom side. The higher electrode wear introduces higher taper.

Key words: wire electrical discharge machining (EDM); 6061 aluminium alloy; material removal rate; kerf width; surface finish

1 Introduction

Machining processes remove unwanted material from a bulk workpiece and introduce the shape of the final product [1]. In conventional machining, the unwanted material is separated as chips by plastic deformation due to application of force by sharp cutting tools [2]. Electrical discharge machining (EDM) is one of the most extensively used non-conventional material removal processes where electrical discharge is used to machine electrically conductive parts regardless of hardness [3]. The electric discharge generates high thermal energy which removes material by erosion [4]. EDM process takes place in a dielectric fluid where the tool is one electrode in the shape of the cavity to be produced and the workpiece to be machined is the other electrode. The tool is then fed toward the workpiece in a controlled path to produce the shape of electrode or its movement [5]. The electrode and the workpiece do not make direct contact during EDM process. Therefore, this process eliminates issues related to chatter and vibration. EDM is a multipurpose process for machining intricate or complex shapes, which has typical advantage in the manufacture of mould, die, automotive, aerospace and surgical components from materials which are difficult to be machined by conventional methods. It is possible to drill a hole as small as 0.1 mm by EDM [3]. There are many researches on the EDM of different materials such as titanium alloys, alloy steel and metal matrix composites [5−8]. But there are very few investigations on the EDM of aluminium alloy. SELVAKUMAR et al [9] investigated wire electrical discharge machining (WEDM) of 5083 aluminum alloy using Taguchi experimental design (L9 orthogonal array) method, where pulse on time, pulse off time, peak current and wire tension were input parameters and the surface roughness and cutting speed were output parameters. The optimal machining parameters for the maximum cutting speed and the minimum surface roughness were decided based on the signal-to-noise (S/N) ratio. Finally, additive model was employed for prediction of all (34) possible machining combinations and a handy technology table was reported using Pareto optimality approach. Though this study presented some information on several input and output parameters on EDM of 5083 aluminum alloy,

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it does not give any information of underlying mechanisms. DAVE et al [10] also used Taguchi methodology to study microholes generated on 1100 aluminum alloy using micro-electro-discharge machining. Gap voltage, capacitance, pulse on time, electrode thickness and electrode rotation were input parameters, and top radius, bottom radius, taper angle and electrode depletion were output parameters. Though the above two studies presented some information on several input and output parameters on EDM of 5083 and 1100 aluminum alloys, it does not give any information of underlying mechanisms.

Aluminium alloys are well known as easy to machine materials in traditional machining because of high thermal conductivity and low hardness [11,12]. However, in case when a part with very complex shape needs to be produced then EDM can be the best option in terms of time and cost. Therefore, it is imperatively needed to understand the electrical discharge machining of 6061 aluminium alloy, which is the most popular among all the aluminium alloys. Considering the above facts, the electrical discharge machinability of 6061 aluminium was studied in terms of material removal rate, surface finish, kerf/slit width and wear of wire electrode. This will help the research community as well as the industry people to understand the behaviour of 6061 aluminium alloy when it needs to be processed by wire EDM.

2 Experimental

A series of wire electrical discharge machining (wire-EDM) of 6061 aluminum alloy were carried out by FANUC ROBOCUT α-0iD. The machining conditions and the compositions of 6061 aluminum alloy are given in Tables 1 and 2, respectively. The experimental parameters (variables as well as constants) were based on limitations of the wire-EDM as well as most commonly used values in the literature. The fixed parameters during machining were wire speed 10 m/min, flushing rate 10 L/min, open circuit voltage 85 V, servo voltage 44 V and zinc coated brass wire of diameter 0.25 mm. A 7 mm-long slot was produced on a plate of 137 mm × 42 mm × 9 mm in each experiment. Two important parameters, pulse on time and wire tension were varied during the experiments. The pulse on time controls the heat input and the wire tension controls the flexibility of the wire, i.e., the mechanical ability for carrying on the process steadily [7,8,14]. The cutting speed, kerf width, surface roughness and wire wear were investigated in this study.

Table 1 Experimental conditions

Experiment No.	Wire tension/N	Pulse on time/μs
1	17.64	1
2	17.64	2
3	17.64	3
4	17.64	4
5	14.70	4
6	11.76	4
7	8.82	4
8	5.88	4

Table 2 Chemical compositions of tested 6061 aluminum alloy (mass fraction, %) [13]

Mg	Si	Cu	Fe	Mn	Cr	Zn	Ti	Al
0.9	0.41	0.16	0.26	0.07	0.04	0.01	0.01	Bal.

3 Results

3.1 Material removal rate

The effect of pulse on time on the cutting speed is presented in Fig. 1. It shows that the cutting speed increases with the increase of pulse on time. The pulse on time controls the heat generation and spark formation. The increase of pulse on time increases the heat generation which improves the material removal and extends the heat for longer time, which helps to remove material efficiently. Thus, longer pulse on time increases the material removal rate. The increase of material removal rate is linearly proportional to the increase of pulse on time.

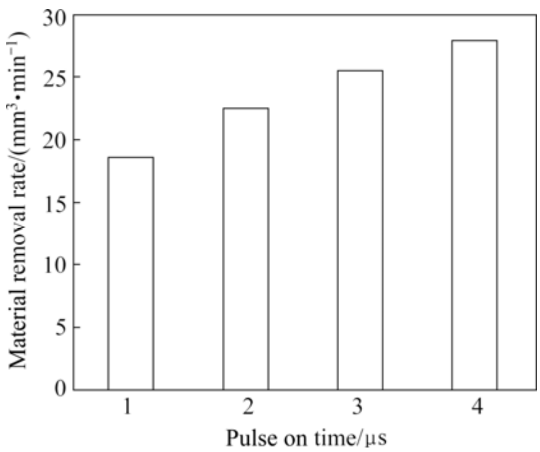

Fig. 1 Effect of pulse on time on cutting speed at wire tension of 17.64 N

Figure 2 presents the effect of wire tension on the material removal rate. It shows that the material removal rate is not affected by the wire tension significantly. The wire tension does not have anything to do with the temperature and spark but it controls the flexibility and straightness of the wire. The little variation of material

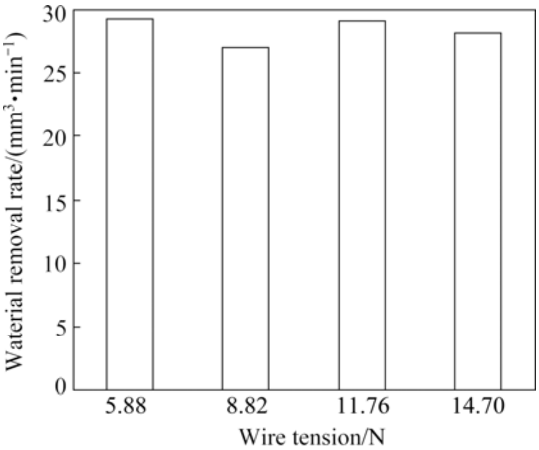

Fig. 2 Effect of wire tension on time on cutting speed (pulse on time 4 μs)

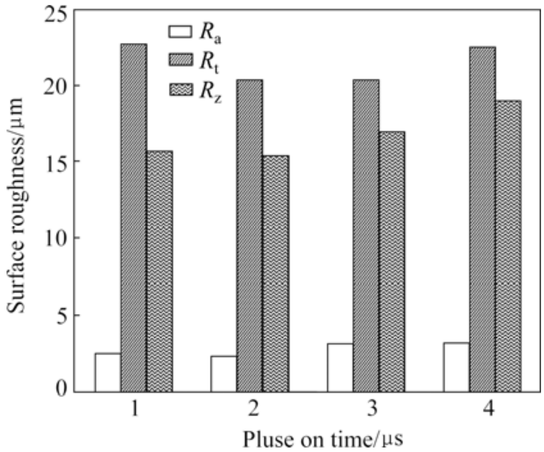

Fig. 3 Effect of pulse on time on surface roughness parameters (wire tension 17.64 N)

removal rate with wire tension is because of uncontrolled spark and variation of wire diameter may be due to concentration change of electrolyte and change of electrolyte flush rate.

3.2 Surface finish

The machined surface of a material generated using EDM is composed of many microscopic craters associated with the random spark discharge between the electrodes. Thus, the surface roughness largely depends on the size of spark crater. Figure 3 presents the effects of pulse on time on the arithmetic mean surface roughness (R_a), total height of the roughness profile (R_t) and the maximum height of the roughness profile (R_z). It shows that the variation of these surface parameters is minor for machining conditions considered in this investigation though shorter and longer pulse on time gives slightly higher surface roughness parameters. This irregular variation shows that the solidified melted materials and splashed material may have dominated the surface finish over the craters produced by the sparks. The images of the surface produced by EDM for different pulse on time presented in Fig. 4 show the similar quality of all the surfaces. All the surfaces are full of solidified melted material, splash of material and blisters. Thus, the variation in the surface roughness is minor.

The effect of wire tension on the surface roughness is given in Fig. 5. It shows a clear trend of decreasing surface roughness with the increase of wire tension though the variation of the corresponding surface roughness is not significant. It seems that the higher tension reduces the flexibility of the wire which generates the smoother surface. The images of surface

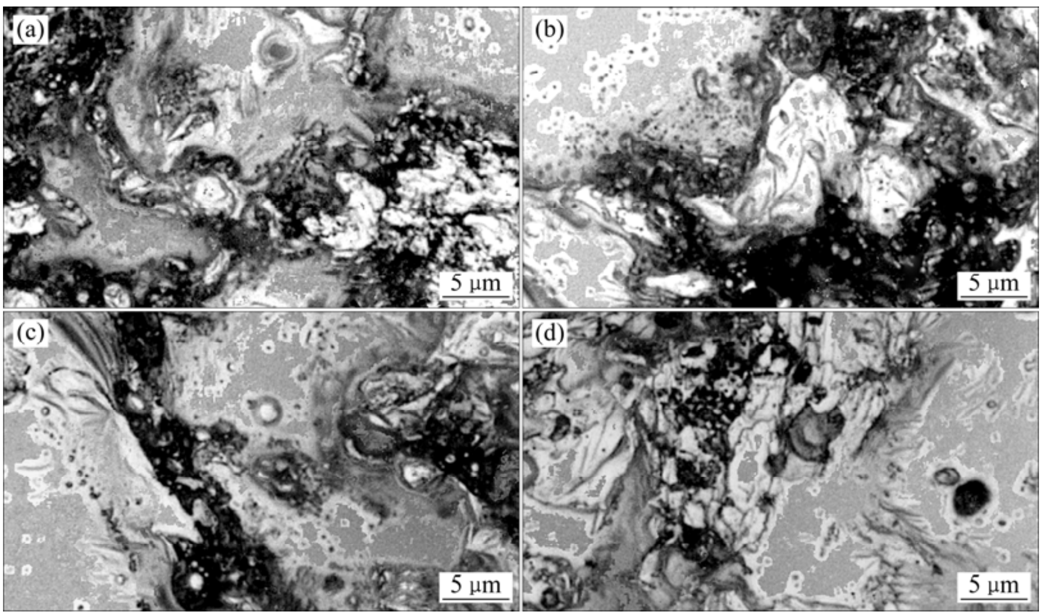

Fig. 4 Optical images of machined surface at wire tension of 17.64 N for different pulse on time: (a) 1 μs; (b) 2 μs; (c) 3 μs; (d) 4 μs

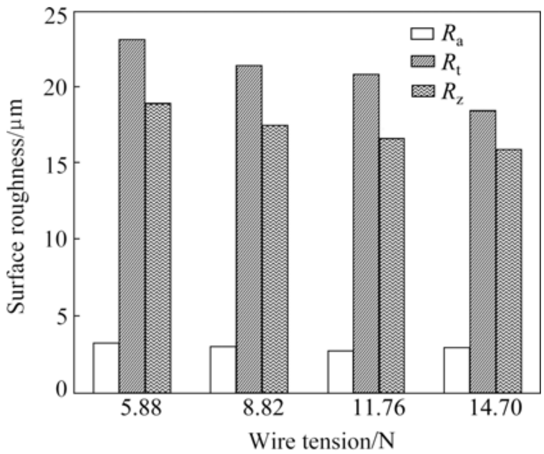

Fig. 5 Effect of wire tension on surface roughness parameters (pulse on time 4 μs)

of the machined workpiece are given in Fig. 6. There are no differentiable features among the surfaces and all are of similar appearance. The surfaces contain solidified melted metals, splashed metals and blisters.

3.3 Kerf width

The width of the kerf is always bigger than the diameter of the wire as the clearance requirements of EDM process and melting of the workpiece takes place around the wire during EDM [5]. Figure 7 presents the effect of pulse on time on the kerf width. It shows that the kerf width increases with the increase of pulse on time. In addition, the kerf width at the top surface is bigger than that at the bottom surface but the difference between the widths of the top and bottom kerfs increases with the increase of the pulse on time. The profiles of the kerf for different pulse on time are given in Fig. 8. No notable difference is found among the profiles and related surfaces. Thus, the pulse on time affects the kerf profile insignificantly.

The effect of wire tension on the kerf width is shown in Fig. 9. It shows that the kerf width increases with the increase of pulse on time and the kerf width at the top surface is bigger than that at the bottom surface. The higher tension in the wire reduces the flexibility of the wire and encourages a steady movement of the wire. This causes smaller width of the kerf at higher tension. The profiles of the kerf for different wire tensions are given in Fig. 10. No notable difference is found among the profiles and related surfaces. Thus, similar to the pulse on time, the wire tension does not affect the kerf profile significantly.

3.4 Wire diameter

The diameter of the electrode wire reduces after EDM of 6061 aluminium alloy. The effect of the pulse on time on the diameter of the wire after EDM is shown

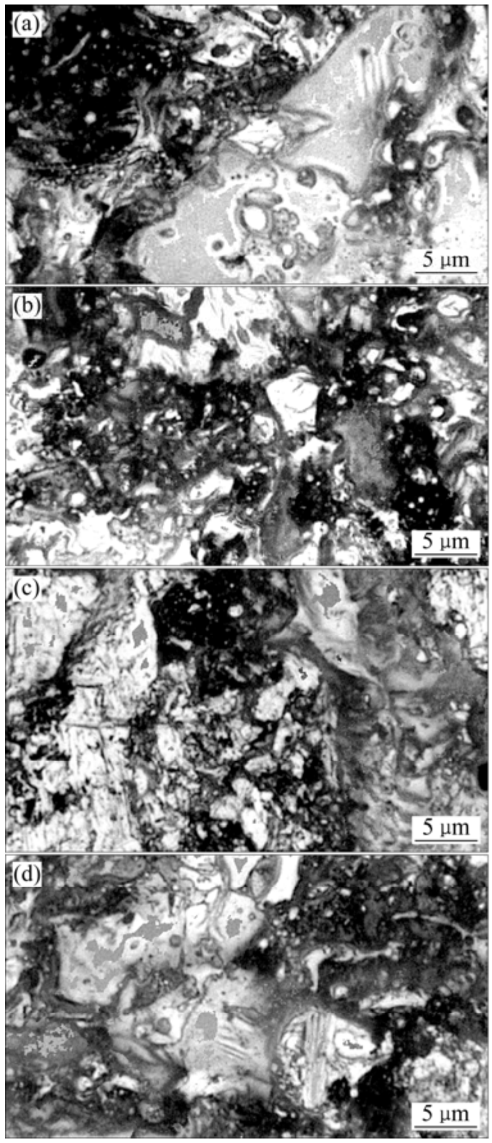

Fig. 6 Optical images of machined surface for pulse on time 4 μs at different wire tensions: (a) 5.88 N; (b) 8.82 N; (c) 11.76 N; (d) 14.70 N

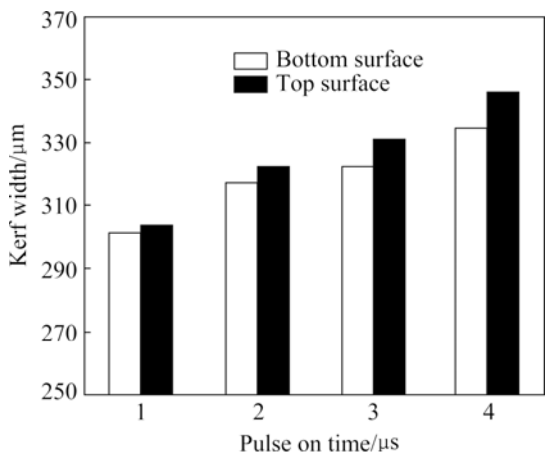

Fig. 7 Effect of pulse on time on kerf width (wire tension 17.64 N)

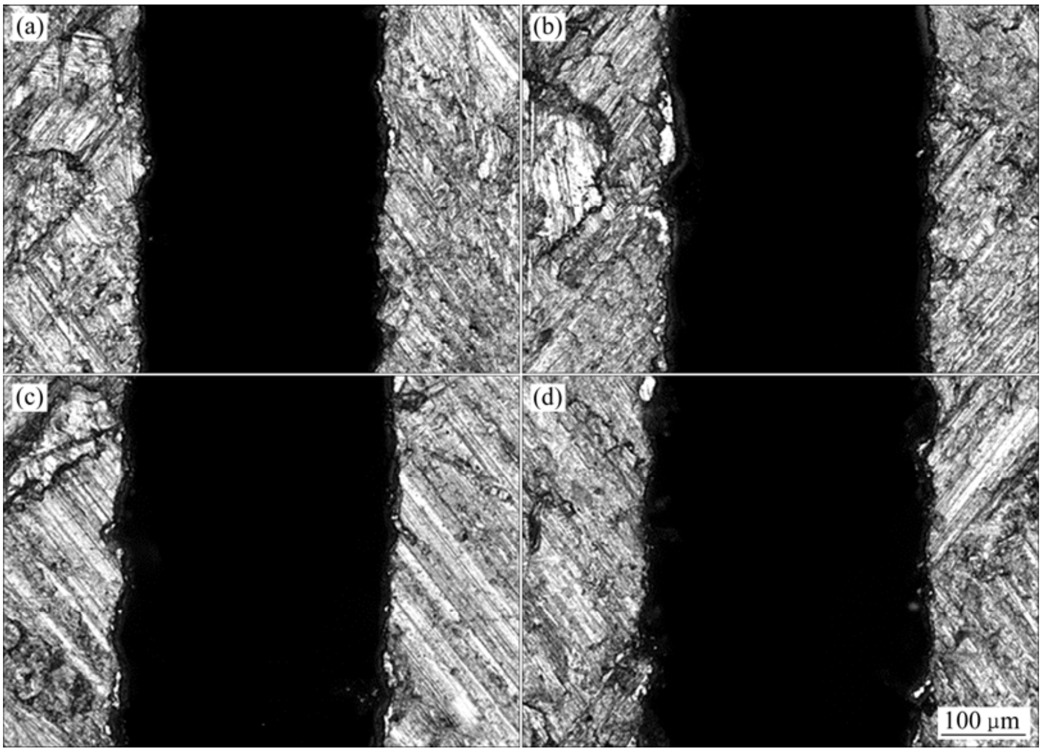

Fig. 8 Optical images of kerf profile/surface at wire tension 17.64 N for different pulse on time: (a) 1 μs; (b) 2 μs; (c) 3 μs; (d) 4 μs

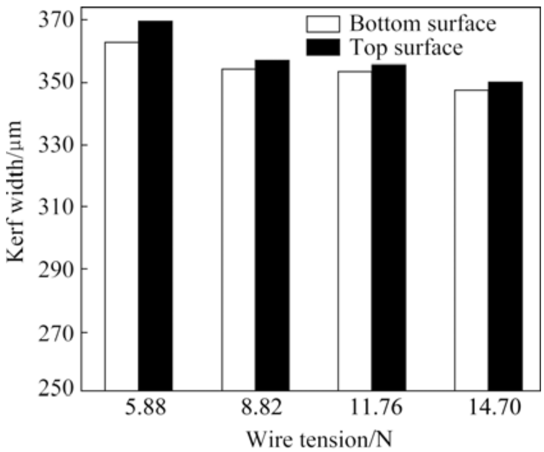

Fig. 9 Effect of wire tension on kerf width (pulse on time 4 μs)

in Fig. 11. It shows that the wire diameter decreases with the increase of the pulse on time. The decrease of wire diameter is not significant when the pulse on time is very short but the diameter drops significantly with the little increase of pulse on time. The decrease of the wire diameter continues at a smaller rate with the further increase of pulse on time. The higher the pulse on time causes higher heat input and longer use of heat. Thus, the higher pulse on time introduces more wear to the wire. Figure 12 shows the surfaces of the wire electrode after EDM. It shows that the wire surface has not been damaged much except some scratches (Fig. 12(a)). No splash of materials or blisters is noted on the surface. However, with the increase of the pulse on time, the progressive increase of damage of the wire surface is clearly visible (Figs. 12(b, c)). It seems that materials are also attached to the wire electrode. It is likely that workpiece material is splashed on the electrode and crates are created on the wire electrode due to sparks [3,15].

Figure 13 shows that wire diameter varies between 182 and 184 μm for the change of wire tension from 5.88 to 14.70 N. However, the diameter increases with the increase of wire tension after EDM. It can be explained as before. It seems that the less flexibility of the highly tensed wire experienced less wear due to steady EDM process. The SEM images of wire surface in Fig. 14 do not show significant influence on the wire surface as all the surfaces get almost similar appearance.

4 Discussion

An ionized channel between the nearest points of the workpiece and the wire electrode is formed with the application voltage at the start of the wire EDM process. Then, actual discharge takes place with a high intensity of current which reduces the resistance of the ionized channel progressively. The heavy flow of current further ionizes the channel and a powerful magnetic field is produced, which compresses the ionized channel and causes localized heating. The temperature of the electrodes

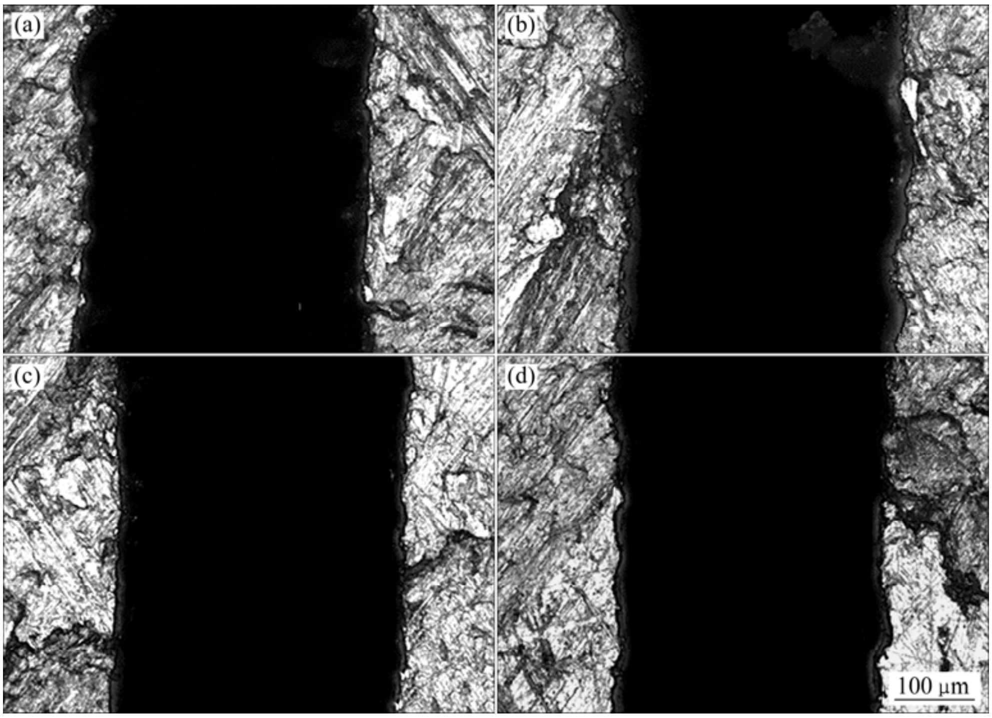

Fig. 10 Optical images of kerf surface for pulse on time 4 μs at different wire tensions: (a) 5.88 N; (b) 8.82 N; (c) 11.76 N; (d) 14.70 N

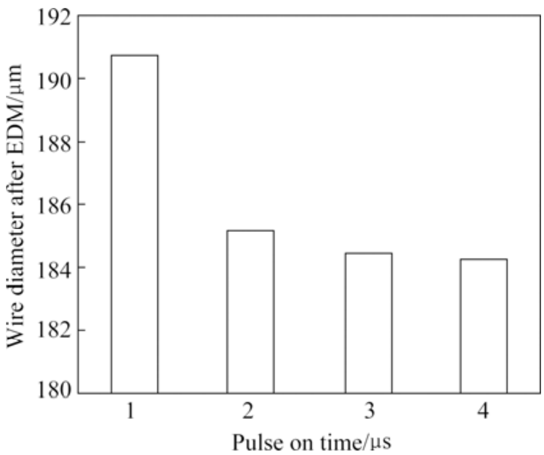

Fig. 11 Effect of pulse on time on wire diameter (wire tension 17.64 N)

is raised locally to more than the boiling point of the workpiece even with very short spark duration. Thus, erosion of the wire and work-piece occurs locally because of the melting and vaporizing [16]. The material removal rate depends mainly on the amount of heat applied (i.e. temperature and heating time). Thus, it is very natural that the longer pulse on time will increase the material removal rate [17,18]. For the similar reason the wire tension does not contribute to the material removal rate. Thermal spalling also contributes to the machined surface during the sparking due to abrupt temperature gradients from normal melting and evaporation [19].

The 6061 aluminium alloy got low melting point. It seems that the significant amount of materials melt even at low pulse on time. Thus, quality of surface remains same whether the pulse on time is longer or shorter. For both cases, the machined surface is full of solidified melted materials, splash of material and blisters. Thus, the surface roughness was not affected notably due to pulse on time for the range considered in this study. When the pulse on time is constant, the removal rate of material is expected to be constant. At this stage, it is likely that a steady machining process with high tension wire will provide a better surface finish compared with that of low tension wear.

During wire EDM process, both of the workpiece as well as wire electrode lose material at high temperatures due to erosion. However, the wire electrode continuously flows through the machining zone and is replaced with fresh form. The wire at the start of the entry in the machining zone is fresh with no wear. As it passes through the machining zone, its diameter decreases progressively, which means that the diameter of the wire is the biggest at the entry and is the smallest at the exit. The types of eroded wire electrode, workpiece elements and disintegrated products of dielectric fluid significantly affect the removal rate of material [20]. Thus, a tapered slot is expected, where the top kerf width is bigger than that of bottom. The amount of taper depends on that of

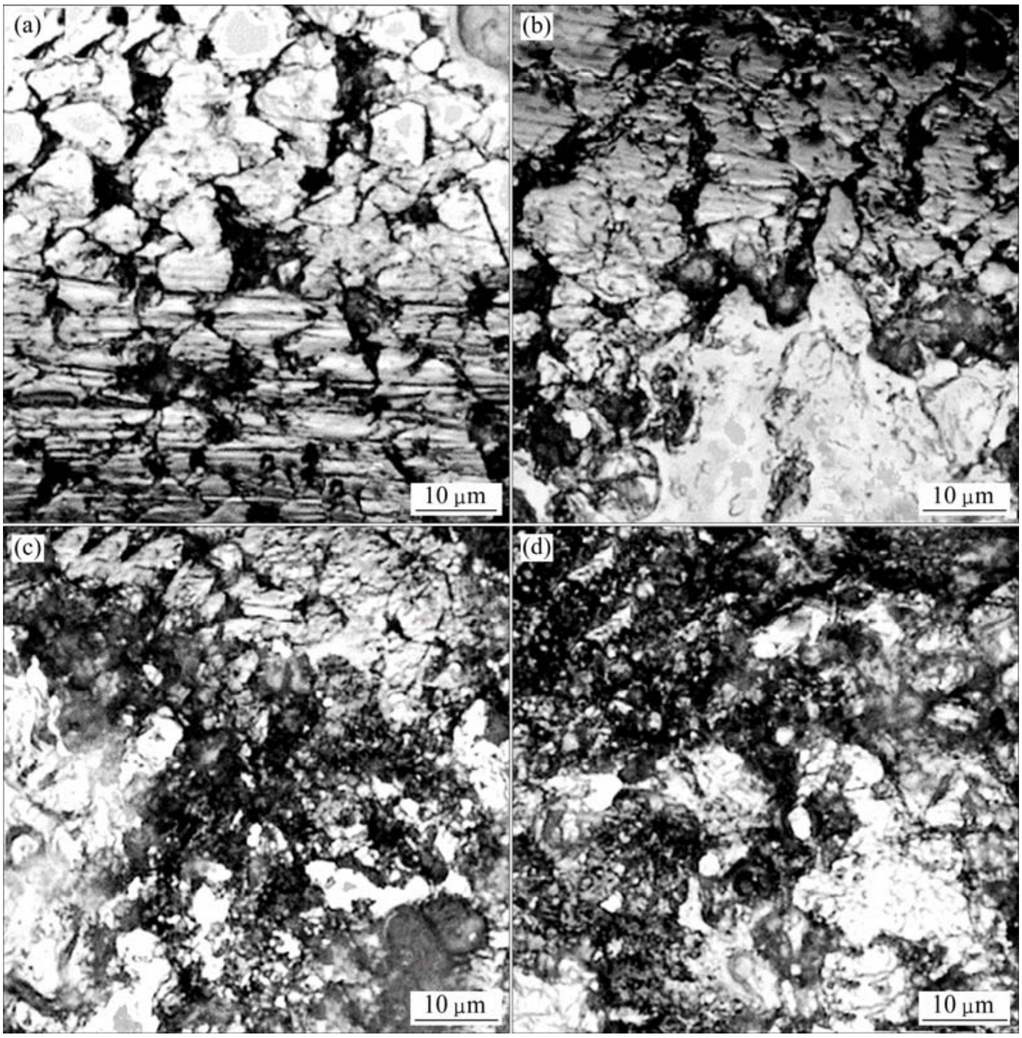

Fig. 12 Optical images of wire surface at wire tension of 17.64 N for different pulse on time: (a) 1 μs; (b) 2 μs; (c) 3 μs; (d) 4 μs

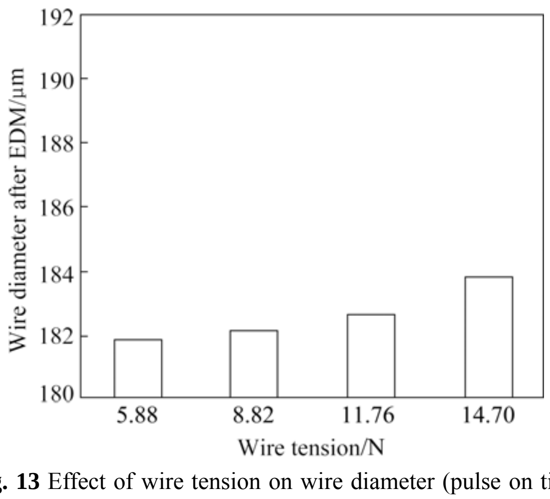

Fig. 13 Effect of wire tension on wire diameter (pulse on time 4 μs)

wear in the wire electrode. For example, the wear of the wire is smaller when pulse on time is 1 μs which introduced smaller taper to the slot. Thus, Fig. 7 shows smaller difference between top and bottom kerf widths. Similarly, when the wear of wire is higher at 4 μs of pulse on time, the difference between the widths of top and bottom kerf is bigger. It is already mentioned that higher tension in the wire electrode reduces the flexibility which provides steady machining process. Thus, tool wear as well as taper in the slot are reduced.

5 Conclusions

1) The longer pulse on time generates more heat and facilitates the removal rate of material. Similar to any other materials, the increase of pulse on time increases the removal rate of material for 6061 aluminium alloy. The contribution of wire tension on the removal rate of material is negligible.

2) The surface after EDM is full of solidified melted material, splash of material and blister. The low melting point of the 6061 aluminium alloy causes the material to melt at shorter pulse on time. Thus, the influence of pulse on time on the surface roughness and appearance is negligible. Though the wire tension does not affect the appearance of the machined surface, the surface roughness

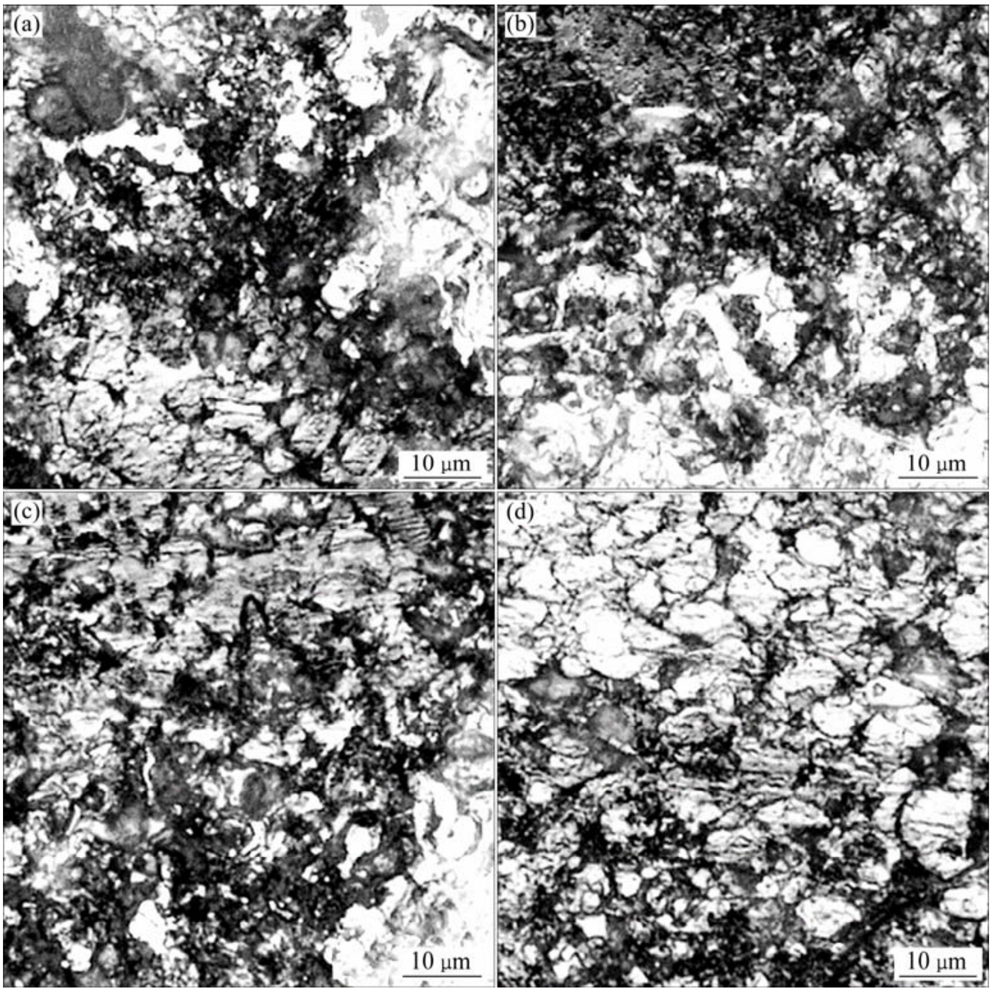

Fig. 14 Optical images of wire surface for pulse on time 4 μs at different wire tensions: (a) 5.88 N; (b) 8.82 N; (c) 11.76 N; (d) 14.70 N

is found to decrease with the increase of wire tension.

3) The longer pulse on time induces higher wear in the wire electrode. On the other hand, higher tension in the wire electrode reduces the wear by providing steady machining.

4) Tapered slots were produced due to progressive wear of the wire electrode. The amount of taper increases with the increase of the electrode wear.

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6061 铝合金的电火花加工

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摘　要：在不同脉冲时间和导线张力下，研究 6061 铝合金电火花线切割加工过程中材料的去除率、切口/狭缝宽度、表面光洁度和线电极磨损，通过改变脉冲时间和导线张力，在电火花线切割加工机床上进行了 8 次实验。结果表明，随着脉冲时间的延长，材料的去除率增加，但导线张力不影响材料的去除率。较高的导线张力有利于促进加工工艺的稳定性，产生较低的线电极磨损和更好的表面光洁度。随着脉冲时间的变化，表面粗糙度没有明显变化。在所有加工条件下，表面外观非常相似。加工后表面包含凝固熔融材料、飞溅材料和气泡。由于热量输入的增加，脉冲时间的延长增大了线电极的磨损。线电极的磨损产生了斜槽，该斜槽正面的切口宽度比底部的宽。较高的电极损耗会产生较高的锥度。

关键词：电火花线切割；6061 铝合金；材料去除率；切口宽度；表面光洁度

(Edited by Xiang-qun LI)