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ORIGINAL ARTICLE

Enhanced debris expelling in high-speed wire electrical discharge machining

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Abstract Surface machined by high-speed wire electrical discharge machining (HS-WEDM) at high energy (average current >8 A) suffers from surface burn and reduced cutting speed increase-rate, a major problem which is investigated in this paper. According to the study, the debris is mainly expelled out of the inter-electrode gap by the liquid medium. When machining at low energy, the gap is full of water-based medium, and the debris is mainly expelled by this medium. However, at high energy the medium in the gap is enormously vaporized and is then reduced due to a thermal load at high energy. Thus, the debris cannot be removed from the gap in time, resulting in its deposition and eventually leading to the surface burn. To overcome this limitation, it is suggested that within a range of discharge energy levels, the erosion products of the HS-WEDM process should be driven by a medium carrier with a higher melting point and vaporization point to ensure that there is sufficient liquid medium in the gap at high energy to carry and expel the debris out of the machining zone. Experiments were conducted by increasing the JR1A (traditionally used dielectric medium) -to-water ratio to increase the content of high-melting-point medium, thus validating the theory. Based on the experimental results, a new type of dielectric medium, JR1H, was formulated to ensure that there is still sufficient liquid medium to expel the debris at large energy machining. A greater threshold of stable cutting speed (more than 330 mm^2/min) was achieved with the machining current of 15 A using JR1H, which is a significant breakthrough in higher efficiency HS-WEDM.

Keywords High-speed reciprocating traveling · WEDM · Surface burn · Debris expelling

1 Introduction

Owing to its high performance-to-cost ratio, high-speed wire electrical discharge machining (HS-WEDM) has become an indispensable process in modern manufacturing industries such as die and mold making, evident from its growing usage and continuous progress [1–4]. Due to the advancements in pulse power supply and wide application of compound dielectric fluid recent years [5], the highest cutting speed of HS-WEDM can now reach up to 250 mm^2/min. However, the practical cutting speed at which the process can maintain stable performance is only about 120 mm^2/min. In attempt to achieve higher machining efficiency, the stability of HS-WEDM process decreases and the probability of wire breakage increases with the increase of input discharge energy. Wang et al. [6] found out that the surface machined by HS-WEDM exhibits surface burn once the working current is more than 6.5 A. According to their study, the surface burn is mainly resulted from the fact that a large amount of dielectric medium vaporizes due to thermal effect so that the debris cannot be removed effectively and ultimately re-melts on the machined surface. Once the surface burn takes place, an increase in the input energy results in a very slow or no increase in the cutting speed. At the same time, the stability of the HS-WEDM process decreases and the probability of wire breakage increases significantly.

The primary goal in this technique is to achieve higher machining efficiency and endurable machining process of HS-WEDM within the lifespan of wire electrode [7]. Under the existing machining conditions, however, dielectric fluid between the two electrodes is not sufficient to efficiently expel

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the debris from the machining gap at higher energy. This poses a serious limitation towards obtaining better efficiency and surface quality. Therefore, this paper aims to improve the cooling, cleaning and debris removal property in the machining process by providing a better discharge environment via dielectric medium modification. This study is a major breakthrough in achieving higher efficiency of HS-WEDM process mechanism.

2 Experiments

2.1 Experimental conditions

The experiment was conducted using the HF320 HS-WEDM (actual picture shown in Fig. 1).

The parameters of the material used and the wire electrode are listed in Table 1. In this experiment, two kinds of working fluid with different JR1A-to-water ratio (1:20 and 1:5) were used to investigate the effect of dielectric fluid on the machining performance. The machining parameters of pulse power supply are listed in Table 2.

2.2 Results

2.2.1 Effect of dielectric fluid concentration on the cutting surface

Figure 2a, b shows the surfaces machined using the dielectric fluid with concentration of 1:20 and 1:5, respectively. Figure 2a suggests that when the dielectric medium (JR1A)-to-water ratio is 1:20, the cutting surfaces are smooth and bright without alternate black stripes (surface burn) at low energy (average current ≤6 A). As the average current increases to 8 A, the machined surfaces clearly exhibit surface burn. In addition, the burn stripes are larger amount of burn substance re-melts onto the machined surface as the discharge energy rises. On further increasing the average current to 12 A, short circuit occurred more often, leading to an extremely unstable state of the HS-WEDM process. In addition, the specimen cut from the workpiece could not be removed easily as they were sintered to the base material.

Fig. 1 Photograph of the experimental equipment

Table 1 Parameters of material and wire electrode

Item	Parameter
Material	Cr12, thickness = 50 mm
Wire electrode	Molybdenum wire, diameter = 0.18 mm, length = 380 m, traveling speed = 12 m/s

While using the dielectric fluid with the dielectric-to-water of 1:5 at the same current, the surface quality significantly improves. Figure 2b reveals that the cutting surfaces are quite smooth and bright without burn even when the current rises up to 10 A. When the current reaches 12 A, slight burn appears on the machined surface whereas the surface machined at 14 A shows obvious and severe burn.

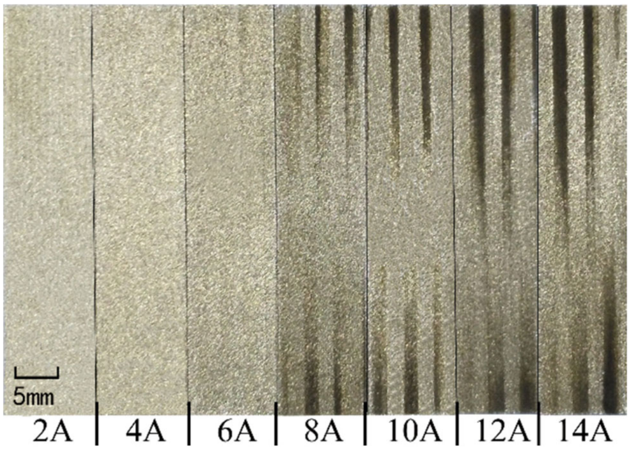
2.2.2 Effect of dielectric fluid concentration on the cutting speed

Figure 3 illustrates the relationship between the cutting speed and average current under different dielectric fluid concentrations. As seen from the figure, both curves can be divided into three zones in terms of average current which is analyzed as follows.

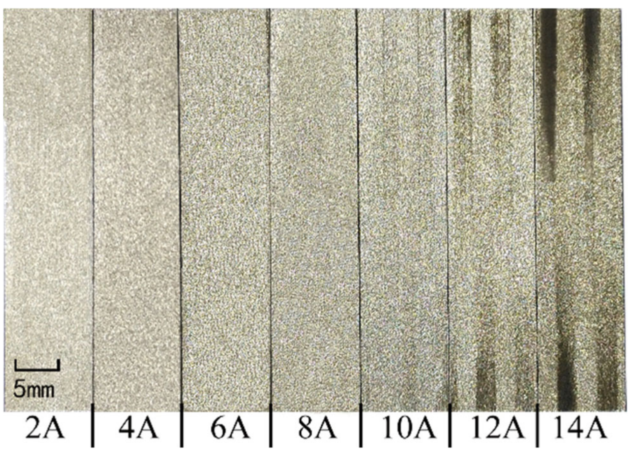
First, we will analyze the case when the working fluid concentration is 1:20. The first zone under this condition is the region where the current varies from 2 to 6 A with the cutting speed from 50 to 152 mm^2/min, which indicates a proportional rise of cutting speed with increasing average current. The second zone is the region where the average current varies from 6 to 12 A. In this area, although the cutting speed

Table 2 Parameters of pulse power supply

Pulse-on time (μs)	Duty ratio	Number of MOS tube	Average current (A)
40	1:8	2	2
40	1:9	7	4
40	1:6	7	6
40	1:4	7	8
40	1:3	7	10
40	1:3	9	12
40	1:3	11	14



(a) Cutting surfaces under dielectric fluid concentration of 1:20



(b) Cutting surfaces under dielectric fluid concentration of 1:5

Fig. 2 Cutting surfaces under different dielectric fluid concentrations. **a** Cutting surfaces under dielectric fluid concentration of 1:20. **b** Cutting surfaces under dielectric fluid concentration of 1:5

still increased with increasing current, the rate of increase was much lower, suggesting that the discharge state in the gap deteriorates. Then, it is the last zone where the current is more than 12 A. Adverse discharge especially short circuit occurred frequently and so the process was extremely unstable, ultimately resulting in the decrease of overall cutting speed. Therefore, the last zone was completely unsuitable for machining.

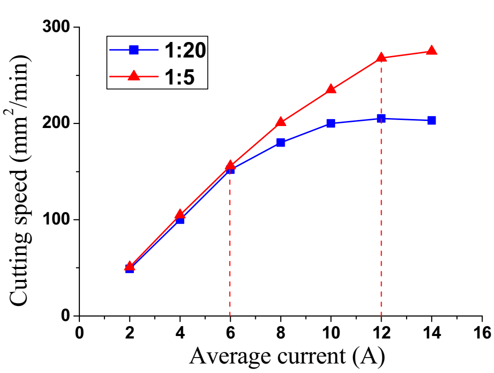


Fig. 3 Relationship between the cutting speed and average current under different dielectric fluid concentrations

For the fluid concentration of 1:5, when the machining energy is low, average current ≤6A, cutting speed behaves similar to the 1:20 counterpart indicating that the first zones of both cases are identical. However, the second zone exhibits a different trend where the cutting speed still maintains proportional increase although at a lower rate with the increasing current. Therefore, the machining gap in this region maintains a favorable state of cleaning, debris removal and deionization although it is worth mentioning that the ability of expelling debris gradually decreases slightly. In the third region where the average current is over 12 A, the cutting speed increases at a much lower rate.

It can be concluded from Figs. 2 and 3 that the discharge environment in the machining gap had deteriorated and the cutting surface began to suffer from burning when the cutting speed increased at a much lower rate. Moreover, as the fluid concentration increases, the occurrence of deterioration of inter-electrode discharge state would be delayed on the discharge current zones, that is, discharge state deterioration emerges only when the current increases up to a threshold. Both the surface quality and the cutting speed are better at higher energy as the concentration increases, indicating that increasing the fluid concentration can greatly improve the gap condition.

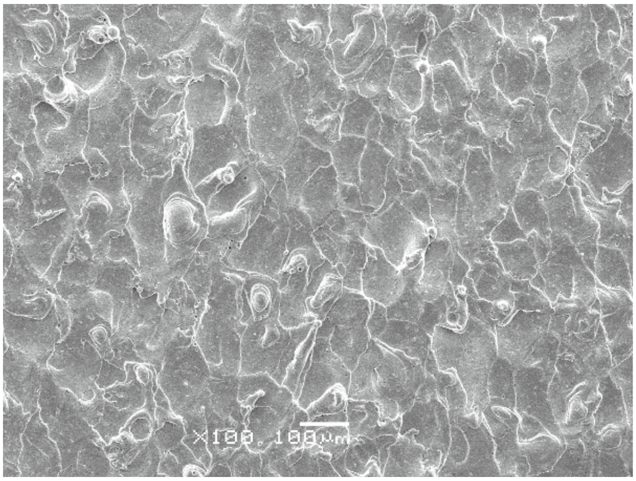
3 Analysis of debris expelling

3.1 Analysis of morphology and content of the machined surface

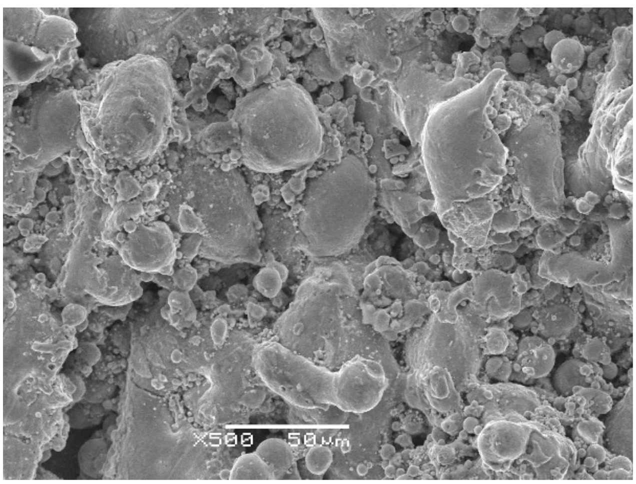
To further investigate the condition of the machining gap, the machined surfaces were analyzed using scanning electron microscopy (SEM). Figure 4a shows the micrograph of the normal cutting surface without burn stripes at the average current of 4 A, and Fig. 4b, c are the micrographs of the burned surface machined at 14 A under the fluid concentration of 1:20 and 1:5, respectively. Comparing the three graphs, it can be noted that the discharge craters on the normal surface are uniformly scattered and have clear shapes and outlines, only few residuals exist on the flange bulge of the craters, and the surface is glossy smooth. However, the discharge craters on the burned surface have fuzzy boundaries and the surface is covered by substantial re-melted debris.

The three surfaces were analyzed by energy-dispersive spectrometer (EDS) after ultrasonic cleaning for 1 min each and the energy spectrum analysis is shown in Fig. 5. The surface elements and contents are listed in Table 3.

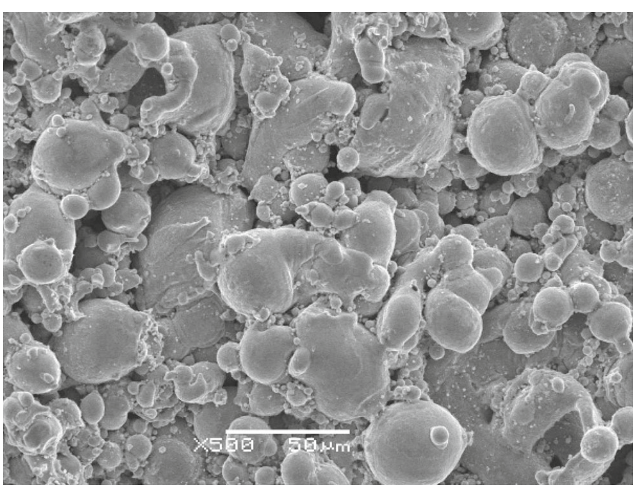
Figure 5 and Table 3 show that the elements of the three surfaces are the same, but the C and O contents on the burned



(a) Microstructure of the normal surface (4 A)



(b) Microstructure of the burned surface machined under the fluid concentration of 1:20 (14 A)



(c) Microstructure of the burned surface machined under the fluid concentration of 1:5 (14 A)

◀ **Fig. 4** Microstructures of the cutting surface. **a** Microstructure of the normal surface (4 A). **b** Microstructure of the burned surface machined under the fluid concentration of 1:20 (14 A). **c** Microstructure of the burned surface machined un-der the fluid concentration of 1:5 (14 A)

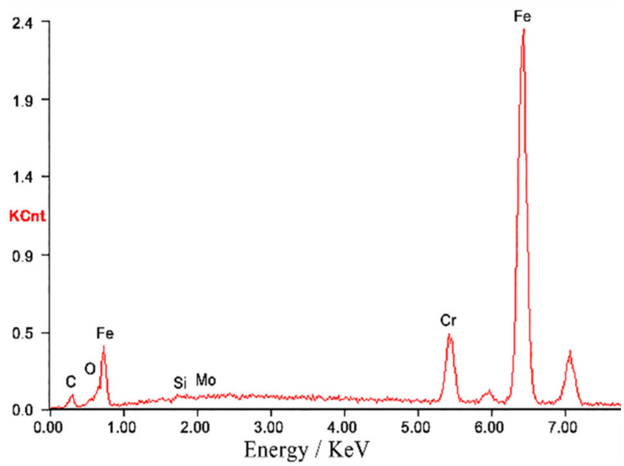
surfaces apparently increase. In addition, both C and O contents on the burned surface machined under the dielectric fluid concentration of 1:20 are higher than that on the burned surface of 1:5, indicating that there are more residual compounds containing C and O on the burned surface of 1:20, so the surface burn was worse. In HS-WEDM, when the discharge energy is high, the base oil added in the dielectric medium produces thermal cracking and polymerization under the continuous high temperature in the machining gap, eventually generating black vicious substances. When the ratio of JR1A to water is 1:20, these substances cannot be effectively expelled out of the machining gap. As a result, these black products intensively accumulate on the machined surface. Therefore, the content of C and O of the surface substantially increases. While the ratio of JR1A to water is 1:5, due to the increase of the vaporization temperature of dielectric fluid and the improvement of cooling and cleaning properties, the products of base oil cracking and polymerization can be easily expelled out of the machining gap. Therefore, the content of C and O under 1:5 is lower than that of the surface machined under 1:20.

Furthermore, the mass percent of Mo on the normal surface is only 1.26% while it reaches up to 4.18 and 1.45% on the two burned surfaces, respectively. Therefore, the element Mo, which comes from the wire electrode may adhere to the machined surface, but the amount of Mo adhered to the machined surface can be reduced with the increase in fluid concentration, in turn reducing the wire electrode wear accordingly. The results and analysis above prove that the discharge condition can be improved by increasing the dielectric fluid concentration.

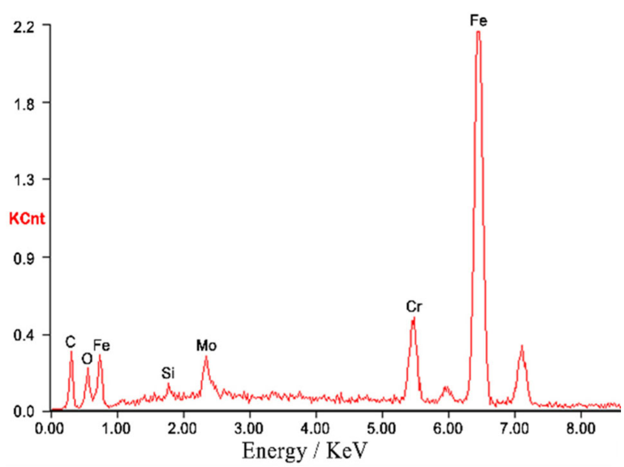
3.2 Effect of the gap condition on the cutting speed and the machining stability

In the process of HS-WEDM, discharge waveforms can monitor the electrode gap condition and reflect the stability of the machining process [8, 9]. Figure 6a, b illustrates the waveforms of continuous discharge current and voltage during the experiment conducted at the same energy (current 12 A, pulse-on time 40 μs) under different fluid concentration of 1:20 and 1:5, respectively. On comparing the two figures, we observed that most of the waveforms of discharge voltage have no

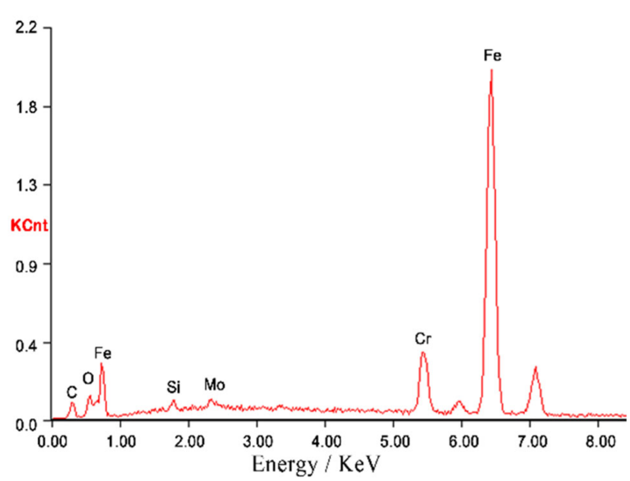
Fig. 5 Energy spectrum analysis of the three surfaces. **a** EDS of the normal surface. **b** EDS of the burned surface machined under the fluid concentration of 1:20. **c** EDS of the burned surface machined under the fluid concentration of 1:5 ▶



(a) EDS of the normal surface



(b) EDS of the burned surface machined under the fluid concentration of 1:20

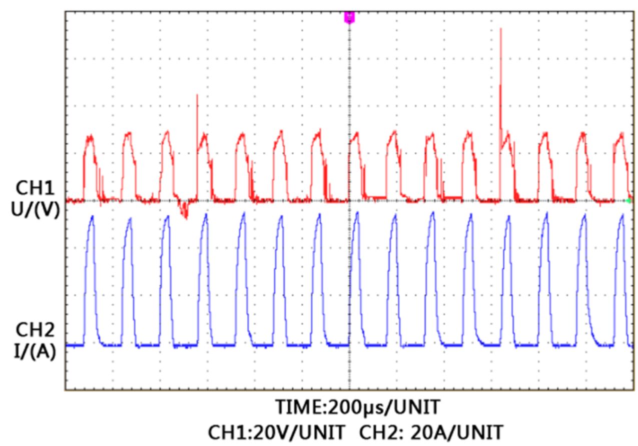


(c) EDS of the burned surface machined under the fluid concentration of 1:5

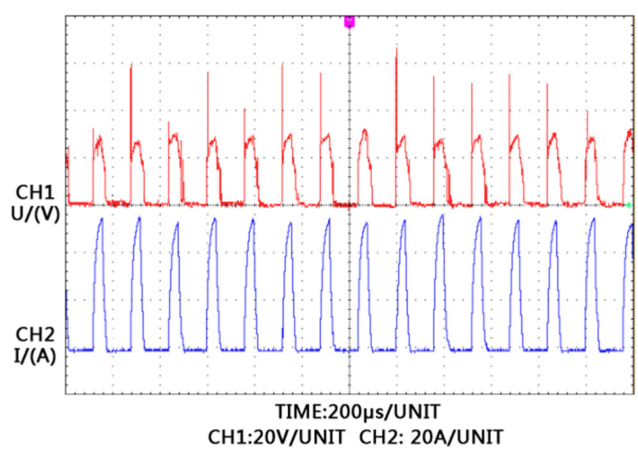
Table 3 Elements and contents of the surfaces

Surface		(a)	(b)	(c)
Elements and mass percent (wt%)	Fe	82.74	67.77	78.37
	Cr	9.21	8.26	8.59
	C	4.91	15.76	8.4
	O	1.46	3.42	2.35
	Mo	1.26	4.18	1.45
	Si	0.42	0.61	0.84

breakdown time delay when the fluid concentration is 1:20, while almost all of the waveforms have delay time when the



(a) Waveforms of continuous discharge under the fluid concentration of 1:20

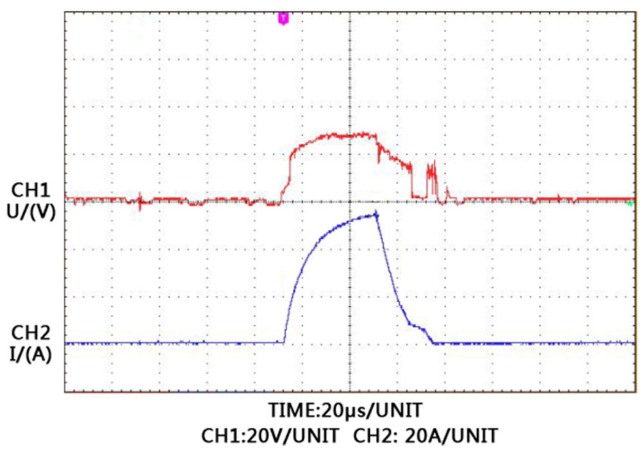


(b) Waveforms of continuous discharge under the fluid concentration of 1:5

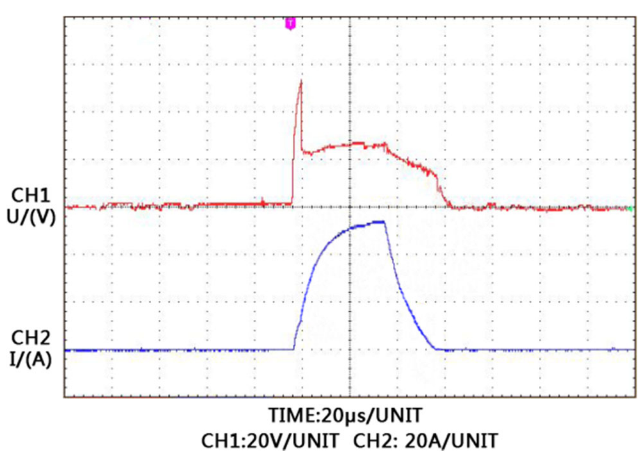
Fig. 6 Waveforms of continuous discharge under different fluid concentrations (current 12 A, pulse-on time 40 μs). **a** Waveforms of continuous discharge under the fluid concentration of 1:20. **b** Waveforms of continuous discharge under the fluid concentration of 1:5

fluid concentration is 1:5. The breakdown time delay can reflect the condition of the inter-electrode working medium. If the voltage waveform has breakdown time delay, then the machining gap is full of dielectric fluid, which needs time to be ionized to form plasma channel. On the other hand, when the waveform has no discharge delay, the physical state of the working medium deteriorates, and the accumulation of the erosion products results in partial temperature being very high, which is close to the loose conduction state [10]. Consequently, the pulse energy utilization ratio is greatly reduced and the cutting speed increases at a reduced rate or may even decrease.

Figure 7a, b shows the single pulse discharge waveform acquired at the same energy (current 12 A, pulse-on time 40 μs) under different fluid concentrations of 1:20 and 1:5, respectively. As clearly seen from Fig. 7a, with 1:20 fluid concentration, the inter-electrode discharge waveform of voltage has no breakdown time delay, micro short circuit emerges at the very beginning of the spark, the maintenance voltage keeps rising, and the waveform fluctuates unstably when the pulse is turned off. Moreover, the falling time of the current waveform is prolonged, indicating that the machining debris is not removed effectively and accumulated debris blocks the cooling and recovery of dielectric. In contrast, as shown in Fig. 7b, when the dielectric fluid concentration is 1:5, the inter-electrode discharge waveform of voltage has breakdown time delay, and the current waveform is normal with proper falling time, which reflects that the debris in the gap is removed effectively, the discharge condition is favorable, and the dielectric fluid was cooled and deionized completely.



(a) Single pulse waveform under the fluid concentration of 1:20



(b) Single pulse waveform under the fluid concentration of 1:5

Fig. 7 Single pulse waveform under different fluid concentrations (current 12 A, pulse-on time 40 μs). **a** Single pulse waveform under the fluid concentration of 1:20. **b** Single pulse waveform under the fluid concentration of 1:5

3.3 Analysis of debris expelling

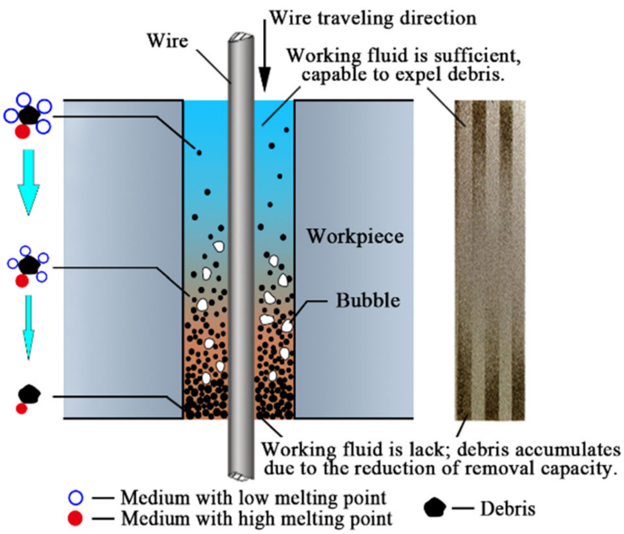
It can be concluded from the analysis above that the primary cause of surface burn and reduced rate of increase behavior of the cutting speed at large machining energy is the deficiency of working fluid, needed to expel debris in the gap. In other words, the erosion products are not removed out of the machining gap in time due to the reduction of the chip removal capacity of the working fluid. Consequently, to reduce or avoid the surface burn, it has to be guaranteed that there is always sufficient working fluid existing in the gap at large machining energy.

Currently, the most commonly used dielectric medium JR1A contains about 20% medium with high melting point. The contents of these mediums in the whole working fluid when JR1A is mixed with water by the ratio of 1:20 and 1:5 are listed in Table 4.

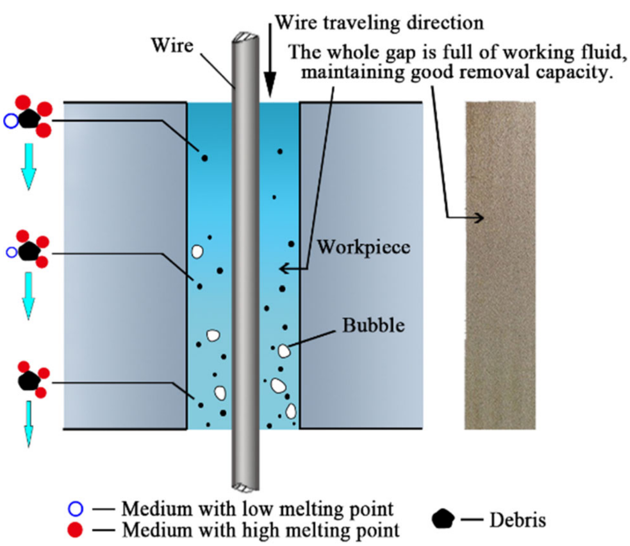
Figure 8 shows the schematics of inter-electrode debris expelling condition at high energy (average current 8–12 A). When the ratio of JR1A to water is 1:20, the working fluid is mostly comprised of the medium with low melting point, especially water. Due to the low viscosity of this water-based medium, it can completely fill the gap. Therefore, the erosion products can be easily and quickly driven out of the machining gap by both the wire electrode and the water-based medium. Hence the cutting speed exhibits a proportional increase as the machining energy increases. However, this medium would rapidly and substantially vaporize under the influence of the high discharge energy as the machining current increases[11], resulting in the decrease of the debris removal capacity (arrows shown in Fig. 8). As a consequence, the machining

Table 4 Content of medium with high melting point

Dielectric medium	Ratio to water	Content of medium with high melting point (%)
JR1A	1:20	1
	1:5	4



(a) Inter-electrode debris expelling condition (ratio to water of 1:20)



(b) Inter-electrode debris expelling condition (ratio to water of 1:5)

Fig. 8 Schematics of inter-electrode debris expelling condition under different ratios of JR1A to water. **a** Inter-electrode debris expelling condition (ratio to water of 1:20). **b** Inter-electrode debris expelling condition (ratio to water of 1:5)

debris would easily aggregate in the machining gap, which would inevitably result in abnormal discharges and the debris would re-melt on the machined surface, which is known as the surface burn. The intensive debris accumulated in the gap especially at the outlet along the wire traveling direction, would severely impact the cooling process of the wire electrode, thus the wire electrode wear will be intensified significantly and the probability of wire breakage increases.

When the ratio of JR1A to water is 1:5, the working fluid possesses higher vaporization temperature since it contains more medium with high melting point and vaporization point. The trend of the cutting speed as the current changes at low energy resembles that when the ratio is 1:5 (the first zone in Fig. 3). Although medium with low melting point still rapidly vaporizes due to the heat, the increased medium with high melting point is ample to efficiently drive the debris out of the gap. Given the increase of medium with high melting point, the viscosity of the whole working fluid increases, so the cutting speed increases more slowly as the average current increases, yet this trend can be maintained at higher energy. In addition, due to the increase in active ingredients of the fluid, a thicker and denser film is formed around the wire to alleviate the bombardment by the positive ions during the discharge. Therefore, the wire electrode wear is greatly reduced and the lifespan of the wire is prolonged.

In summary, enhancing the content of medium with high melting point can enormously improve the cooling, cleaning and debris removal performance, providing the normal condition for discharge at large energy and meanwhile significantly decreasing the wire wear.

Table 5 Chemical composition of JR1A and JR1H

Content (%)	JR1A	JR1H
Vegetable oil	5	12
Oleic acid	5	12
Metal antirust preventives	10	16
Surfactant-assisted	20	20
Potassium hydroxide	3	3
Industrial purified water	allowance	allowance

4 New dielectric medium specialized for high efficiency HS-WEDM

Based on the theory analyzed above, a new type of dielectric medium, JR1H, was designed to increase the content of medium with high melting point to 40%. Compared to the widely used dielectric medium JR1A, JR1H contains the same kinds of substances but with different contents, especially for the medium with higher melting point such as vegetable oil,

Table 6 Experimental parameters

Item	Parameter
Pulse power supply	Pulse-on time = 40 μs, duty ratio = 1:3, average current = 15 A
Material	Cr12, thickness = 50 mm
Wire electrode	Molybdenum wire, diameter = 0.18 mm, length = 380 m, traveling speed = 12 m/s
Dielectric fluid	JR1H, ratio to water = 1:10

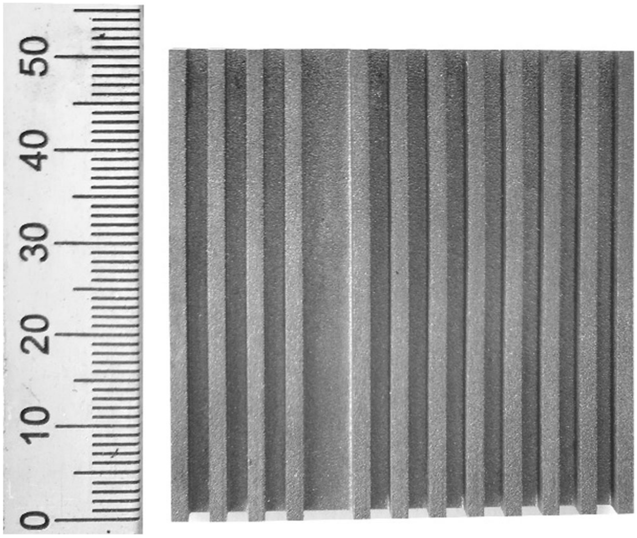


Fig. 9 Surface machined using JR1H

antirust preventives and oleic acid. The chemical composition of JR1A and JR1H is listed in Table 5.

The JR1H medium was tested in coherence with the previous investigations and the experimental parameters are listed in Table 6. In this test, the ratio of dielectric medium JR1H to water is 1:10 and the reservoir volume is 35 L, so that the proportion of high melting point medium in the entire volume is up to 10%. The machined surface is shown in Fig. 9. The cutting speed is 330 mm^2/min with the surface roughness (Ra) of 7.3 μm. In addition, the cutting area reaches up to 90,000 mm^2 when the wire electrode wear is 0.01 mm (from initial 0.18 to 0.17 mm of the diameter).

Figure 9 and the related results mentioned above demonstrate that selecting proper dielectric medium such as JR1H as the working fluid is a big leap towards solving the current problems in machining efficiency of HS-WEDM at high energy. JR1H can ensure that the cutting process maintains normal discharge condition even at large energy, thus better machining efficiency and surface quality can be obtained along with significantly diminished wire electrode wear. Therefore, long-time continuous and stable machining at large energy can be achieved.

5 Conclusions

1. The primary cause of surface burn and lower increase rate of the cutting speed at high machining energy is the deficiency of working fluid in the gap, leading to the failure to expel debris from the machining gap in time. Eventually the un-expelled debris would accumulate and re-melt on the machined surface.
2. By increasing the ratio of medium with high melting point and vaporization point in the working fluid, it can be guaranteed that there is still sufficient working fluid in the gap to effectively expel debris from the machining zone, thus improving the cutting efficiency at large energy.
3. Based on the analysis of the theory proposed in this study, a new type of dielectric medium specialized for HS-WEDM capable to obtain higher cutting efficiency was developed, and relative experiment was conducted. The result showed that the stable machining efficiency was more than 330 mm^2/min when the average current is 15 A.

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