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THE COMPARATIVE EFFECT OF WIRE ELECTRODES ON WIRE BREAKAGE FREQUENCY AND CUTTING RATE IN WEDM OF INCONEL 706

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Abstract
Non-traditional machining methods like wire electric discharge machining (WEDM) appear to be an ideal choice for machining high strength super alloys like Inconel 706, because of their capability to generate intricate profiles with high accuracy. However, wire breakages are a common problem in the WEDM process and adversely affect the productivity, accuracy, and surface quality. Therefore, the aim of this work is to investigate and comprehend the phenomenon of wire breakage using Inconel 706 as work material and brass wire, diffused brass wire, and zinc-coated brass wire as electrode materials. Six process parameters—pulse-on time, pulse-off time, peak current, spark gap voltage, wire feed rate, and wire tension—have been varied experimentally to determine their effect on the frequency of wire failure. According to the findings, the zinc-coated brass wire breaks with the lowest frequency when compared to the other two. Additionally, an ideal range of input variables has been proposed for efficient WEDM of Inconel 706 without unexpected wire breakages. This range can also be utilized for further research work related to modeling and optimization in WEDM of Inconel 706.

Keywords:
Inconel 706, WEDM, Wire breakage frequency, Cutting rate

1 INTRODUCTION

Inconel 706, a nickel-base high-performance superalloy, is known for its high-strength, high temperature resistance, high rupture strength, excellent creep, and fatigue strength. The superior mechanical properties combined with excellent resistance to oxidation and corrosion, even in extremely aggressive environments makes it a reliable choice for applications involving combustion and chemical reactions such as turbine rotors, components in jet engines, compressor blades, nuclear reactors, rocket engines [1]. Due to its tendency to get work-harden, Inconel 706 is extremely difficult to machine using traditional methods. As a result, it becomes important to machine Inconel 706 using unconventional methods. To produce complex and intricate shapes in superalloys such as Inconel 706 with exact tolerances and surface finish requirements, a WEDM process is used [2], [3]. A small diameter wire (0.15-0.3 mm), commonly made of plain brass, diffused brass, and zinc-coated brass, serves as the tool electrode and the workpiece is mounted on a computer numeric-controlled worktable. To decrease the likelihood of generating erroneous parts, a mechanical positioning mechanism is employed to maintain tension on the wire. A fresh wire electrode is fed continuously to the workpiece and a constant gap of in the range of 0.025–0.05 mm between the wire electrode and workpiece is maintained [4], [5]. The wire electrode is a crucial factor that contributes to the performance of WEDM process. The wire electrodes should possess, a high electrical conductivity to minimize the energy loss, sufficient tensile strength to support the required tension while maintaining great dimensional correctness. Wire breakage occurs in numerous industrial applications of WEDM [6]. The performance of WEDM, specifically the prevention of the wire electrode from breaking, is found to be one of the most critical concerns because the WEDM machine runs constantly without attention of the operator. The operator is always concerned about re-fixing the electrode wire in case the wire breaks in the middle of the cut for whatever reason. The wire cannot be repositioned at the same spot. Consequently, profile machining accuracy declines. Breaking of wire causes substantial harm to the WEDM machining process [7].

2 REVIEW OF RELATED WORK

Plain brass wire is the most popular and commonly used electrode in WEDM machining for the past 50 years. The brass electrode provides great combination of high tensile strength, high electrical conductivity, and decreased cost, in comparison to copper, which has lesser tensile strength. Therefore, wire electrodes used in WEDM are primarily made of brass and its derivatives, such as diffused brass wire and zinc-coated brass wire [8], [9]. The frequent breakage of wire is critical issue that has a significant impact on the cutting rate, part accuracy, surface quality and overall machining operation efficiency [10], [11]. Shoda [12]and cabanes [13] in their studies, identified the key indicators such as ignition delay, peak current and discharge energy to monitor development of instability in the process that leads to wire breakage. They concluded that wire breakdown happens whenever there is a significant amount of spark discharges at a specific location. Several authors found in their investigations that likelihood of wire breakage is increased due to many factors such as high wire tension, high pulse-on duration, low pulse-off duration, ineffective removal of material debris, high sparking frequency, decrease in wire feed rate and rise in temperature of the wire electrode due to inefficient flushing, low tensile strength of the wire electrode [14]–[16]. Rajurkar et al [6] noticed that a sudden rise in sparking frequency result in wire failure during WEDM of a steel workpiece and suggested a monitoring and control approach which maintained the sparking frequency at constant value in real time to avoid the breakage of wire. It was determined by Patil and Brahmankar [17] that wire breakages proved to be detrimental to the cutting rate of composite materials. Wire ruptures can however be reduced by maintaining higher flushing pressure, appropriate servo reference voltage and suitable pulse-off time. According to Antar et al [9] the use of copper core wires (coated with zncu50 and Zn rich brass) can considerably boost the productivity of WEDM process, minimize recast layer thickness, and residual stresses as compared to brass wire under the same machining parameters. Shandilya et al [18]examined the impact of the pulse-on time, pulse-off time, servo voltage, wire feed rate and % of sic in mmc on the frequency of wire breakage during WEDM of sicp/6061 aluminium metal matrix composites using a diffused brass wire. The authors concluded that to reduce the frequency of wire breakage, lower values of pulse-on time and servo voltage, as well as greater values of pulse-off time and wire feed rate, should be used. It was also mentioned that presence of non-conductive sic particles in MMCs directly impact the frequency of wire breakage.

Increased stagnation of debris in the gap and high wire vibration lead to more wire rupture, low material removal rate and poor shape accuracy [19], [20]. Traditionally, debris is flushed out from gap with the help of dielectric jet from nozzles. Flushing of debris is more efficient with a high flow rate from the nozzles, however this result in more wire breakage [21]. A Okada et al [22] investigated the effect of nozzle jet flushing on wire breakage. It was found that the increase in the wire deflection due to jet flushing and accumulation of debris near short kerf length leads to more frequent breakage of wire. Luca et al[23] compared the machining performance of zinc-coated brass wire and uncoated brass wire during WEDM of Inconel 718. When compared to uncoated brass wire, the experimental results proved that zinc-coated copper wire performed better. Zhi Chen et al [24] proposed a novel wire electrode (SMWE) for improving the machining characteristics of WEDM and compared its performance with that of zinc-coated wire and brass wire electrodes. SMWE considerably increased the surface quality and machining efficiency. Sampath Boopathi et al [25] used the molybdenum wire tool and water-mist (dielectric in plasma phase) during WEDM of Inconel 600 alloy to predict cutting speed (CS) and surface irregularity (SI) utilizing input parameters such as current (K), pulse-duration (PD), pulse-pause time (PP), and flow rate (FR) of mixed tap water. CS and SI are found to increase by pulse length and current, whereas the CS and SI are decreased by PP. The maximum flow rate of tap water results in the highest CS and SI. Abhilash P. et al [26] examined impact of discharge energy and debris-accumulation on wire break failure and surface integrity issues during WEDM of Inconel 718. Four different wires materials such as hard zinc-coated brass, half-hard zinc-coated brass, hard uncoated brass, and half-hard uncoated brass were used. The geometric accuracy of the machined components is significantly influenced by the selection of wire material. Hard wires have been reported to machine the surfaces with the highest level of accuracy. Das S. et al [27] extensively reviewed the research work on several facets of wire-electrode erosion such as the impact of heat produced in spark plasma, wire rupture process, wire fatigue and thermal stresses. The authors systematically depicted the causes of wire breakage, suggestions for improving wire life and control & monitoring systems for wire health. It gives practical guidelines for the effective usage of the WEDM process by addressing the root reasons of wire failure.

As per survey of the research work reported above, it has been found that most of investigations are related to WEDM of superalloys and MMCs using brass wire or zinc-coated brass wire. Some researchers have also tried other wire materials such as molybdenum, copper core (with zinc-coating) and zinc-coated brass (varying hardness). Although some authors have reported on comparative performance of different wire materials for WEDM of superalloys, there is little or no work on comparative performance of different wire electrodes for WEDM of superalloy such as Inconel 706. This paper presents the impact of process parameters on wire breakage frequency and cutting rate (CR) using

Three different wire electrode materials (brass, diffused brass, zinc-coated brass) for WEDM of Inconel 706. The main purpose of this work is to; (i) identify the best wire out of three to perform further experimentation so as to develop the model for WEDM of Inconel 706 and (ii) determine the range of process parameters such as pulse-on time (Ton), pulse-off time (Toff), peak current (IP), spark gap voltage (SV), wire feed rate (WF), and wire tension (WT) in order to minimize the risk of wire breakage.

3 EXPERIMENTAL PROCEDURES

In this work, an electronic sprint cut ELPULS 40A DLX, WEDM machine tool has been used for all investigations. The wire electrode each of diameter 0.25 mm namely brass wire, diffused brass wire and zinc-coated brass wire have been used. In recent times, Inconel 706 has replaced Inconel 718 as the preferred super alloy for turbine wheel applications. Inconel 706 is selected as work piece material for its extensive range of applications in the nuclear power industry, rocket engines, extrusion dies, hot work tools, medical devices, and casting dies. Table 1 displays the elemental details of the selected work material confirmed by an electron probe micro-analyzer (EPMA). The range of parameters, given in table 2, for conducting experiments were chosen based on machine capability. The de-ionized water was used as dielectric. The height and width of workpiece is 25 mm. The length of cut was 15 mm in all experiments. The experiments were performed using one-factor-at-a-time (OFAT) approach in which one factor was changed at a time while the remaining input parameters were held constant at the midpoint of their respective ranges. Wire breakage frequency was calculated by dividing the number of wire breakages during cutting by total cutting time for a particular length of cut. A stopwatch with the least count of 0.01s was used to measure cutting time. The experimental results for wire breakage frequency corresponding to six process parameters are listed in tables 3 to table 8. The cutting rate is directly noted from the WEDM machine. As a result of this initial testing, only those input parameter ranges that allowed successful WEDM cutting were bracketed for further study. The figures show impact on wire breakage frequency and cutting rate for these bracketed range only. The further study to investigate effect of input parameters on performance measures such as cutting rate (CR), surface roughness (SR) and recast layer thickness (RLT) was conducted using these bracketed ranges of parameters.

Tab. 1: Chemical composition of Inconel 706

Element	Ni	Fe	Cr	Nb	Mn	C	Co	Al	Si	Ti	Cu
	40.38	38.08	15.37	2.87	0.26	0.042	0.43	0.23	0.18	1.89	0.108

Tab. 2: The range of WEDM parameters selected based on machine capability

Process Parameter (Symbol)	Units	Minimum value	Maximum value
Pulse on time (Ton)	µs	0.4	1.65
Pulse off time (Toff)	µs	8	50
Peak current (IP)	A	60	230
Spark gap voltage (SV)	V	16	50
Wire feed rate (WF)	m/min	1	14
Wire tension (WT)	g	400	2000

Tab. 3: Frequency of wire breakage vs pulse on time

Pulse-on time (µs)	Plain Brass wire	Diffused brass wire	Zinc-coated brass wire
0.45	0.04	0	0
0.65	0.08	0.05	0.04
1	0.18	0.13	0.1
1.35	0.25	0.19	0.14

1.55	0.3	0.24	0.2

Tab. 4: Frequency of wire breakage vs pulse off time

Pulse-off time (μs)	Plain Brass wire	Diffused brass wire	Zinc-coated brass wire
10	0.34	0.28	0.24
16	0.24	0.19	0.15
27	0.17	0.12	0.08
38	0.09	0.05	0.02
44	0.05	0	0

Tab. 5: Frequency of wire breakage vs peak current

Peak Current (A)	Plain Brass wire	Diffused brass wire	Zinc-coated brass wire
80	0	0	0
105	0.07	0.05	0.04
150	0.17	0.14	0.12
195	0.23	0.19	0.15
220	0.3	0.24	0.2

Tab. 6: Frequency of wire breakage vs spark gap voltage

Spark gap voltage (V)	Plain Brass wire	Diffused brass wire	Zinc-coated brass wire
18	0.26	0.22	0.2
30	0.18	0.14	0.13
50	0.13	0.1	0.07
70	0.05	0.04	0.03
82	0.02	0	0

Tab. 7: Frequency of wire breakage vs wire feed rate

Wire feed rate (m/min)	Plain Brass wire	Diffused brass wire	Zinc-coated brass wire
2	0.31	0.23	0.18
4	0.24	0.2	0.14
7	0.18	0.14	0.07
10	0.12	0.08	0.02
12	0.03	0	0

Tab. 8: Frequency of wire breakage vs wire tension

Wire tension (g)	Plain Brass wire	Diffused brass wire	Zinc-coated brass wire
400	0.03	0.02	0
600	0.05	0.05	0.02
1000	0.11	0.08	0.05
1400	0.16	0.13	0.1
1600	0.21	0.15	0.12

4 EXPERIMENTAL OUTCOMES

4.1 Effect of process parameters on wire breakage frequency

It is clear from figure 1a that for three types of wire materials, wire breakage is observed to zero at minimum pulse on time while the frequency of wire breaking rises steadily with increase in the pulse on time. The increase in pulse on duration increases the discharge energy/pulse. The root cause is that volumetric material removal increases due to rise in discharge energy/pulse [28], [29]. This leads to rise in molten metal constituents in the dielectric medium present in the gap. The degradation of dielectric thus leads to unusual arcing in place regular sparking. As a result, the wire gets soften and loses its tensile strength which causes the wire to break. Therefore, it is recommended to use the moderate values of pulse-on time [30], [31]. Figure 1b show that wire breaking is minimum (or zero) at the highest value of pulse off time regarding all wire electrode materials. However, the frequency of wire breaks consistently rises as the pulse-off time falls. This could be explained by the fact that the sparking frequency decreases with increase in pulse-off time, causing lower molten debris in the gap. Also, dielectric fluid cools down the wire and cleans the gap of debris with an extended pulse-off time. As a results wire breakage happens rarely. Hence, extended pulse off time is preferred [30] – [32]. It is evident from figure 1c that for all three-wire materials, the rate of wire breakage rises steadily as peak current rise. As stated earlier the consistent rise in wire breakage is due to fact that discharge energy rises with increase in peak current. Consequently, optimal values of peak current must be adopted [33], [34]. Figure 1d indicates how the spark gap voltage affects the frequency of wire breaks. Spark gap voltage establishes the distance between the workpiece and the wire electrode's leading edge. None of the three-wire materials experience wire breakage when the gap voltage is maintained at its maximum value. The figure1d shows that when the gap voltage falls, the frequency of wire breaks rises. This is because low gap voltage narrows down the distance between the wire electrode and the workpiece, allowing some of the discharge energy to be transferred to the wire electrode. As a result, the electrode's temperature rises, triggering a wire break. Moreover, the narrower distance makes it difficult for molten metal to flush out, and ultimately leading to erroneous arcs and wire breaks. To resolve this issue, a suitable servo gap voltage should be used [33] – [36]. Figure 1e depicts how wire feed rate influences the frequency of wire breaks. The speed at which the fresh wire electrode is continually fed to the machining zone is known as the "wire feed rate.” The chart clearly reveals that in all three-wire materials, the frequency of wire breaks reduces as the wire feed rate rises. This could be explained by the fact that slowing down the wire feed reduces the wire electrode's ability to endure excessive discharge energy/time, thereby leading to wire breaking. Also, a slower feed rate causes the wire to spend more time in the gap, which results in more craters along its length, that eventually breaks the wire. So larger feed rates must be employed to prevent frequent wire breaks [17], [18], [37]. The term wire tension is defined as the gram-equivalent load to keep the continually fed wire under tension. Figure 1f displays how wire tension relates to the frequency of wire breaks. The wire failures are lowest for lower wire tension values however, it keeps rising with rise in wire tension for all three-wire materials. It can be a due to the simple reason that higher wire tension holds the wire in a tighter position, making it more likely to break under the pressure of spark discharges. Also, the wire breaks when the tension becomes higher than the wire's tensile strength. Increased wire tension improves the precision of intricate products and reduces wire vibration amplitude. To achieve high precision and decrease wire breakage rate, a suitable range for wire tension should be specified [18], [38].

4.2 Effect of process parameters on cutting rate

Figure 2a shows the relationship between cutting rate and pulse duration for Inconel 706, demonstrating that cutting rate increases as pulse duration increases for all three-wire materials[39] – [41] . However, the zinc-coated brass wire achieved a greater cutting rate for Inconel 706 as compared to the diffused brass wire and brass wire within the bracketed range of pulse on time. Figure 2b displays the variation in cutting rate with change in pulse off time, illustrating that cutting rate falls steadily with increase in pulse off duration for all three-wire materials [39], [40]. While zinc-coated brass wire demonstrated the best performance when compared to the other two wires, diffused brass wire has proven superior to brass wire. Figure 2c reveals the impact of peak current on cutting rate, depicting that cutting rate increases with an increase in peak current for all wire materials [39], [40]. Comparing the three wires, the zinc-coated brass wire performed the best. The variation in cutting rate with change in spark gap voltage is evident in figure 2d and it is indicated that the cutting rate improves as we decrease the spark gap voltage for all three-wire materials [39] – [41]. Compared to diffused brass wire and brass wire, zinc-coated brass wire obtained a higher cutting rate. The correlation between cutting rate and wire feed rate can be seen in figure 2e and cutting rate declines with an increase in wire feed rate for all three-wire electrodes, but this decline is relatively flat as compared to previous parameters such as pulse on time, pulse off time, peak current, and spark gap voltage. Figure 2f presents the relationship between cutting rate and wire tension, and no clear trend is observed between cutting rate and wire tension across all wire materials [42] . It is pertinent to note that the cutting rate varied within very narrow range for each wire electrode. The zinc-coated brass wire produced a significantly higher cutting rate in comparison to the other two wire electrodes within the range of wire tension.

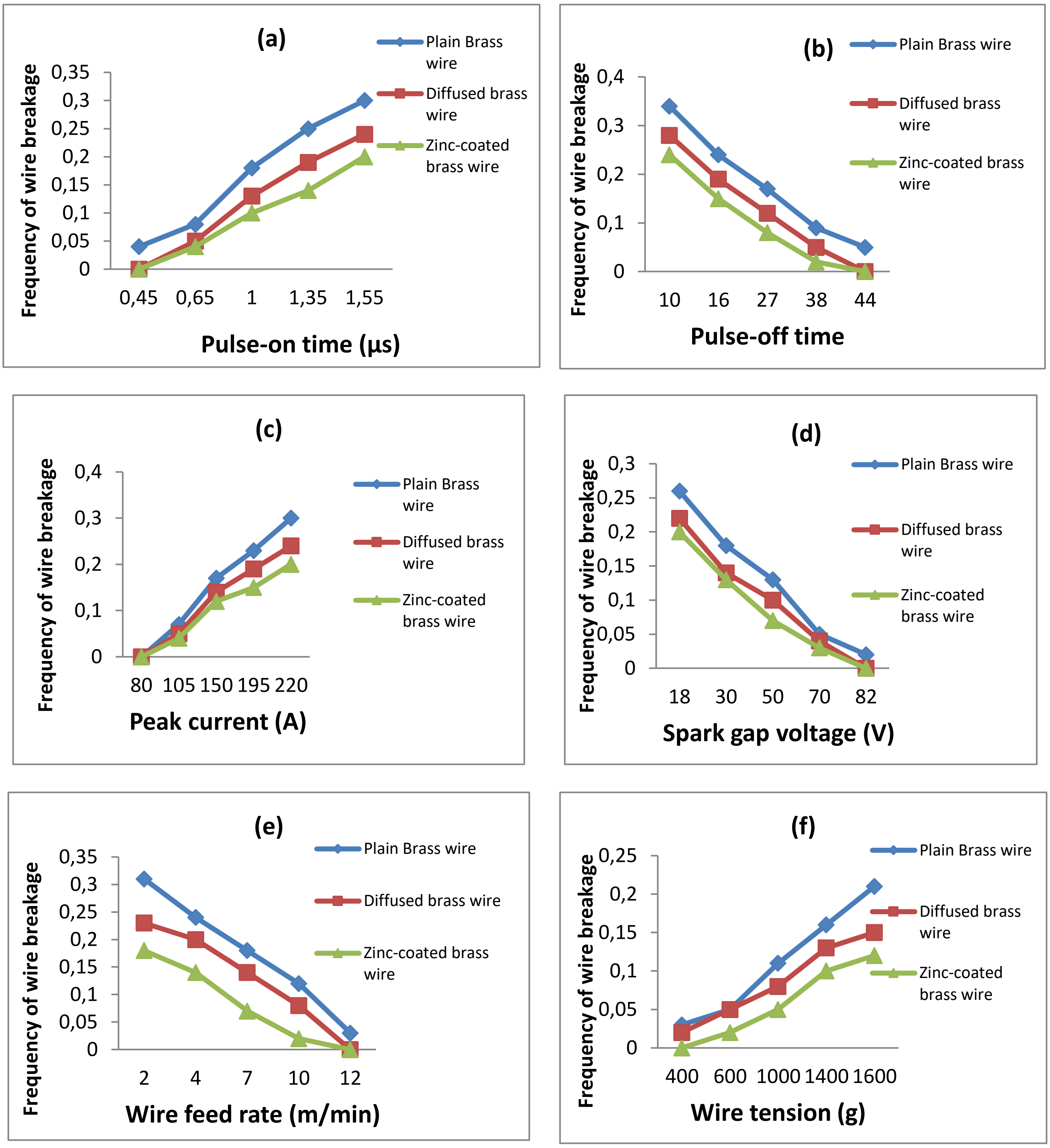

Fig. 1 (a) Effect of pulse on time, (b) pulse off time, (c) peak current, (d) spark gap voltage, (e) wire feed rate, and (f) wire tension on frequency of wire breakage.

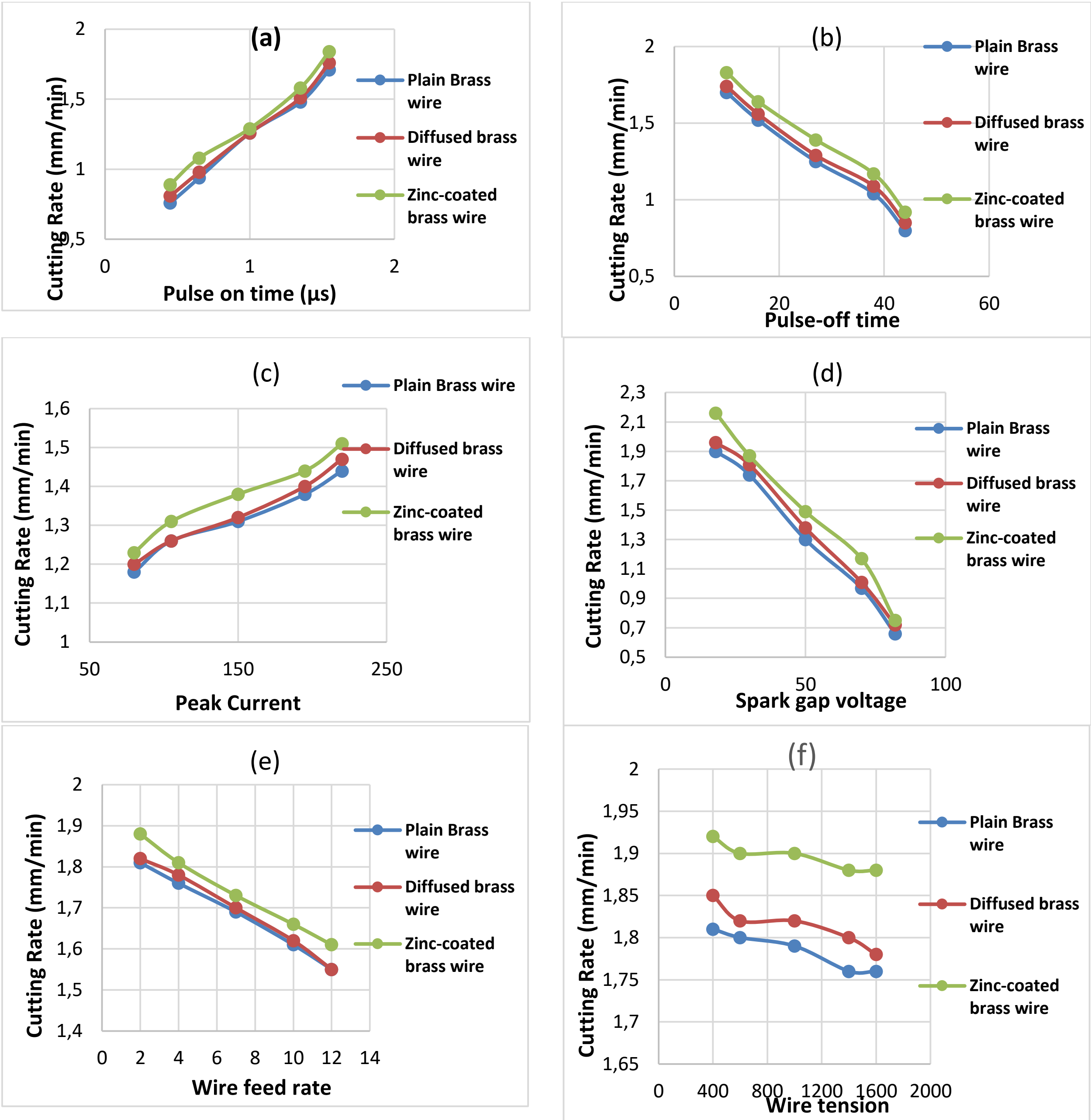

Fig. 2 (a) Effect of pulse on time, (b) pulse off time, (c) peak current, (d) spark gap voltage, (e) wire feed rate, and (f) wire tension on cutting rate.

5 ANALYSIS AND DISCUSSION

The comprehensive evaluations of graphical charts (shown in figures 1a to 1f) clearly exhibits that zinc-coated brass wire electrode has the lowest frequency of wire breakage when compared to plain brass wire and diffused brass wire electrodes for all process parameters. The possible reason for this may be the poor gap conductivity of brass wire, which results in poor flushing conditions. Adding more zinc to the brass electrode does not improve the situation either, as it creates issues during fabrication and drawing. Thus, to solve this issue, zinc is usually plated on brass. Because the zinc particles possess a low melting point and evaporate easily, they assist to increase the gap's conductivity and, as a result, improve flushing. Additionally, the zinc particles' ability to "boil off" assists in cooling the wire, thereby decreasing the likelihood of wire breakage [9]. Further, the in-depth evaluations of charts (in figures 1a to 1f) proposed the variable ranges that can be utilized efficiently during WEDM of Inconel 706 using zinc-coated brass wire with the minimum risk of wire breakage. The minimum and maximum values for each process parameter have been decided after meticulously reviewing the trends of every graph. The one extremity (minimum or maximum) for each process parameter has been selected corresponding the point at which the frequency of wire breaking is minimum or zero. Likewise, the opposite extremity for that process variable has been identified, corresponding to the point where the frequency of wire breaks is one or more in a single cut. Table 3 lists the ranges for these parameters. The complete analyses of the charts (in figures 2a to 2f) confirmed that zinc-coated brass wire produced a significantly higher cutting rate in comparison to brass wire and diffused brass wire electrodes for WEDM of Inconel 706. Table 9 reveals that the WEDM of Inconel 706 using zinc-coated brass wire becomes impractical when the pulse-on time is greater than 1.55 us, the pulse-off time is less than 11 us, the peak current is greater than 220 a, the spark gap voltage is less than 18 v, the wire feed rate is less than 2 m/min, and the wire tension is greater than 1600 g.

Tab. 9: The successful machining range of WEDM process parameters

Process Parameter (Symbol)	**Units**	**Minimum value**	**Maximum value**
Pulse-on-time (Ton)	μs	0.45	1.55
Pulse-off-time (Toff)	μs	10	44
Peak current (IP)	A	80	220
Spark-gap-voltage (SV)	V	18	44
Wire-feed-rate (WF)	m/min	2	12
Wire-tension (WT)	g	400	1600

6 CONCLUSIONS

Based on experimental results and analysis of WEDM of Inconel 706 using three different wire electrode materials, the following conclusions have emerged.

1. An appreciable rise in the frequency of wire breakage with a rise in Ton, IP, and WT and a decline in Toff, SV, and WF was observed for three wire electrodes such as brass wire, diffused brass wire, and zinc-coated brass wire.
2. Compared to diffused brass wire and brass wire, the zinc-coated brass wire achieved the lowest frequency of wire breakages for WEDM of Inconel 706.
3. Zinc-coated brass wire produced a significantly higher cutting rate in comparison to brass wire and diffused brass wire electrodes for WEDM of Inconel 706.
4. The experimental investigation recommended an ideal range for all process parameters, within which Inconel 706 can be efficiently machined without the drawback of unexpected wire rupture. This selection can be applied to upcoming studies for modeling and optimization in WEDM of Inconel 706.

The results of the present study can be effectively utilized for efficient machining of Inconel 706 using WEDM. An ideal range of input parameters can be utilized to carry out further research work to develop models for response parameters and to optimize the input parameters in WEDM of Inconel 706. The paper summarizes the instructions for preparing an electronic publishing paper for the proceedings of the HSM 2023 International Conference.

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