

Sustainability in wire electrical discharge machining of titanium alloy: understanding wire rupture

A. Pramanik^{1*}, A.K. Basak²

¹Department of Mechanical Engineering, Curtin University, Bentley, WA, Australia

²Adelaide Microscopy, The University of Adelaide, Adelaide, SA, Australia

*Corresponding author, email: alokesh.pramanik@curtin.edu.au, Phone: +61 8 9266 7981, Fax: +61 8 9266 2681.

Abstract

To reduce the machining time and energy, it is important to have uninterrupted machining to make the process sustainable. Understanding the factors and mechanism that affect the wire failure is vital to reduce machining time to preserve resources and improve sustainability. Therefore, the mechanism of wire electrode rupture during electrical discharge machining (EDM) of Ti-6Al-4V alloy has been investigated in this study. To aid the analysis, electrolyte flushing pressure (7, 10, 15, 18 MPa), wire tension (800, 1100, 1400 and 1700 gf) and pulse-on-time (4, 6, 8 and 10 μ sec) were varied to understand the effects of these parameters on wire rupture. The incidents of wire rupture are high at lower flushing pressure and higher wire tension. The influence of pulse-on-time depends on the interaction ns between wire tension and flushing pressure. The wire rupture occurs at instantaneous high temperature due to generation of unwanted arcs when the EDM debris/wastes are not flushed away properly. Higher wire tension may break the wire even at lower temperature in the machining zone. The wire rupture might be very sudden and/or gradual decrease of cross-section of the wire, however, the tips of the broken wire experience necking before fracture which is contributed to associated wire tension and softening by high temperature. The coating of the wire was disrupted and wear-off around the tips of broken wire. Workpiece material was not detected on the tips, however, trace of oxides islands was detected that formed due to high temperature oxidation of wire materials around the broken tips.

Key words: Sustainability; wire EDM; failure process; titanium alloy; surface properties.

1. Introduction

EDM generally occurs in a special fluid, called as electrolyte, where the tool electrode produces the cavity of its shape in the workpiece electrode. Usually, workpiece is sub-merged in the electrolyte to create a favourable environment for electric spark generation. Unlike conventional machining (Gupta, Sood et al. 2017, Mulyana, Rahim et al. 2017), a direct contact is not made between electrodes during material removal in EDM process (Pramanik 2014). Spark erosion in EDM takes place in the vicinity of two electrodes and produces desired two and three dimensional profiles according to input parameters. Wire EDM (WEDM) becomes different

from conventional EDM, due to thin wire electrode (0.05–0.3 mm of diameter) which moves continuously through the machining zone (Maher, Sarhan et al. 2015). High frequency electric pulses pass through the gap between the workpiece and wire, and material removal takes place in front of moving wire by spark discharges (Tosun and Cogun 2003). WEDM does not require operator assistance all the time where the machine operator manually adjusts the parameters when abnormal situation is detected (Cabanes, Portillo et al. 2008). The process is used for hard-to-machine materials to fabricate complex shapes and to obtain better surface quality with respect to traditional machining (Gamage and DeSilva 2016, Garg and Lam 2016). It is not easy to machine complex shape in hard materials due to very high tool wear in traditional machining. Wire electrode rupture during the operation is very common which make the whole process unstable and considered as a major problem (Dekeyser, Snoeys et al. 1985). This undesirable circumstances reduces machining efficiency, sustainability and induce surface damage in the workpiece (Wang and Rajurkar 1992). Environmental consequences of the EDM process are important as this process requires huge amount of thermal energy (Gamage, DeSilva et al. 2016, Garg and Lam 2016). Gamage and DeSilva (Gamage and DeSilva 2016) noted that wire failure substantially raised (48%) the impact value of consumed energy based on the environmental impact study. The time of wire rethreading is a complete waste of resources as well as energy as most of the sub units of the EDM machine continue to consume energy. The energy consumption rate of EDM depends on the machine tool and machining variables where the chillers/water coolers and the pumps consumed highest energy (Gamage, DeSilva et al. 2017). Therefore, wire failures are not only slowing down the process and gives poor quality output, but also cause increased energy and environmental implications which is detrimental to production economics and sustainability. Therefore, understanding of wire failure and prevention is highly essential to achieve higher productivity with sustainable production in wire EDM.

To address the above mentioned issue, researchers have constructed an equivalent circuit model to monitor the location of discharge (Shoda, Kaneko et al. 1995, Lauwers, Kruth et al. 1998, OBARA, ABE et al. 1999). Adaptive control optimization (ACO) may also improve the wire rupture problem (Snoeys, Dauw et al. 1983). The complex and often unstable atmosphere during EDM operation, and higher ratio between machining and total production times, justify the efforts to consider adaptive control optimization (ACO) principles (Dekeyser, Snoeys et al. 1985) as the thermal load on the wire is assumed as a leading factor in describing wire rupture (Jennes, Snoeys et al. 1984). Kinoshita *et. al.* (Kinoshita, Fukui et al. 1982) noted that the pulse incidence of gap voltage increases sharply and continues for roughly 5-40 ms afore the rupture of wire. Based on this, a regulator and monitor scheme was developed where the pulse creator and servo arrangement were turned off instantaneously at the abrupt increase of pulse occurrence to avoid rupture of wire, however, the pulse occurrence of the gap voltage will rise rapidly when the power of the pulse generator is resumed which requires another power shut down. The repeated on/off of the power reduces the efficiency of machining. Further, the method was not appropriate for workpieces thinner than 20 mm which will increase the frequency of power on/off. Similar to Kinoshita *et. al.* (Kinoshita, Fukui et al. 1982), Rajurkar and Wang (Rajurkar,

Wang et al. 1991) also suggested a approach to prevent wire rupture while EDM of steel by regulating the spark incidence at a fixed level where the cutting speed is proportionate to the sparking incidence and lesser sparking incidence reduces the rate of material removal. Jennes *et. al.* (Jennes, Snoeys et al. 1984) developed a model to investigate the comparative effect of different input variables on the thermal stress of the wire electrode. It was noted that temperature is the greatest influential feature that induces rupture of wire. The rupture of wire occurs when the immediate rate of energy surpasses a certain border dependent on the thermal characteristics of the wire electrode. Shoda *et. al.* (Shoda, Kaneko et al. 1992) noted that the discharge concentration at high sparking frequency breaks the wire because of high local temperature. Therefore, Liao *et. al.* (Liao, Chu et al. 1997) developed an adaptive control approach to avoid wire rupture by reducing the spark energy. Pramanik *et. al.* (Pramanik and Basak 2016) explored the role of various input variables on the degradation of wire electrodes when machining aluminium based metal matrix composites (MMCs) reinforced with different sizes of SiC particles. The available researches on WEDM of MMCs are focused on the influence of input variables (Pramanik, Basak et al. 2015, Pramanik 2016), wire tension and spark energy on the wire rupture (Cabanes, Portillo et al. 2008, Gamage and DeSilva 2016), surface finish of the machined parts (Lal, Kumar et al. 2013, Habib and Okada 2016), materials removal rate along with the theory and experimental authentication of crater generation on the workpieces (Kinoshita, Fukui et al. 1982, Jennes, Snoeys et al. 1984).

Wire EDM involves multi-performance characteristics, wire fails normally at sever machining condition when the material removal rate is high (Maher, Sarhan et al. 2015). Therefore, wire failure hinders the high productivity and product quality associated with sustainable production and low energy consumption. Literature review indicates that the EDM process has been applied to machine diverse range of materials such as, titanium alloy, aluminium alloy, steels, metal matrix composites etc. (Huang, Shih et al. 2006, Pramanik, Basak et al. 2015, Pramanik 2016, Joshi, Ananya et al. 2017, Mandal, Dixit et al. 2017, Singh, Sarma et al. 2017, Pramanik, Basak et al. 2018). The information presented above indicates that there are some investigations on the control and prevention of wire rupture during wire EDM of monolithic materials which is relevant to this study as this study have used monolithic material as workpiece. In fact, so far no research has ever tried to understand the failure mechanism. This is the first report on details of wire failure. Therefore, no literature of exactly on this point is available. However, there are lots of investigation to prevent wire failure without much understanding about the failure mechanism and morphology of the broken wire. At this situation, this study was an effort to understand the failure of wire which may help the prevention of failure. This addresses the mechanism or nature of wire break which opens an avenue to understand wire break which guides to deeper understanding of prevention of wire break. Definitely further research is required to connect these two facts for the cleaner production. Therefore, it is imperatively needed to underpin the current understanding of wire rupture during wire EDM and reveal the physical mechanisms of wire rupture. This present study investigates the complex interconnectivity among wire rupture, frequency of wire rupture and

© 2018. This manuscript version is made available under the CC-BY-NC-ND 4.0 license <http://creativecommons.org/licenses/by-nc-nd/4.0/> morphology of broken wire for a range of electrolyte flushing pressure, wire tension and pulse-on-time during wire EDM grade 5 titanium (Ti-6Al-4V) alloy. In this case, the wire rupture is a single occurrence of rupture but the term “frequency of wire rupture” indicates how often the wire rupture occurs. The outcomes of this research will be beneficial to the researchers as well as industry community towards better understanding of wire ruptures during WEDM process.

2. Materials and methodology

A series of WEDM of Ti-6Al-4V alloy were carried out by FANUC ROBOCUT α -0iD machine. Typical properties and chemical composition of this alloy are given in tables 1 and 2 respectively. During WEDM process, the following fixed parameters were employed: 10 l/min flushing rate, 44 V servo voltage, 10 m/min wire speed, 85 V open circuit voltage and 12 mm hole-diameter. Zinc coated brass wire of 0.25 mm diameter was used as wire electrode. Experiments were performed by changing flushing pressure, pulse-on-time and wire tension to study the influence of those parameters on rupture of wire. Details of the experiment parameters are given in table 3. The machining parameters were chosen based on the information in the literature (Patel, Pandey et al. 2008, Pramanik, Basak et al. 2015) and the facilities available in the laboratory. A slot of 9 mm long and 12 mm diameter cylinder were generated on 137×42×9 mm³ titanium alloy plate in individual experiment.

Table 1: Mechanical properties of Grade 5 Ti Alloy (Granta Design Software 2015).

Tensile strength (MPa)	Young's modulus (GPa)	Elastic limit (MPa)	Density (kg/m ³)	Melting point (K)	Max service temperature (K)
1200	114	910	4420	1933.15	690

Table 2: Chemical composition of Grade 5 Ti Alloy (Granta Design Software 2015).

Elements	C	N	O	Cr	Fe	V	Al	Ti
% Composition	0-0.1	0-0.5	0-0.2	0.021	0-0.4	3.5-4.5	5.5-6.75	88-91

Table 3: Details of experimental parameters

Flushing pressure	Test no.	Wire tension (gf)	Pulse-on-time (μ sec)	Flushing pressure	Test no.	Wire tension (gf)	Pulse-on-time (μ sec)
7 MPa	1	800	4	15 MPa	19	800	4
	2		6		20		6
	3		8		21		8
	4	1100	4		22	1100	4
	5		6		23		6
	6		8		24		8
	7	1400	4		25	1400	4
	8		6		26		6
	9		8		27		8

10 MPa	10	800	4	18 MPa	28	1400	8
	11		6				
	12		8				
	13	1100	4		29	1700	8
	14		6				
	15		8				
	16	1400	4		30	1400	10
	17		6				
	18		8				

After the experiments, the morphology of broken wires was investigated with the help of field emission scanning electron microscope (FE-SEM) equipped with energy dispersive x-ray (EDX) analysis system (Quanta 450, FEI).

3. Results and discussions

3.1 Wire rupture incidences

The wire starts to degrade as soon as the WEDM process starts and continue as the wire enter inside the workpiece till comes out from the bottom. The shape and surface morphology of wire changes during the process due to tension, high temperature and transfer of materials. The electric sparks not only remove workpiece material but also contributes towards plastic deformation and vaporisation of wire electrode. All these changes the original circular cross-section of the wire to oval shape, regardless of the type of workpiece material. This is permanent deformation of the wire due to the interaction in the severe environment around it during the material removal process as reported in details in our previous communication (Pramanik 2016).

Table 4 reports the incidents of wire rupture for each experiment considered in this study. For certain machining conditions, the rupture of wire is very common and frequent. Wire rupture occurs at lower flushing pressure (7 MPa) and at every pulse-on-time (4, 6 and 8 μ sec) when the wire tension was higher (1400 gf); however, it broke only at pulse-on-time of 6 and 8 μ sec when the wire tension was medium (1100 gf). Most of the wire break incidents were noticed at low flushing pressure, high wire tension and medium pulse-on-time.

Table 4: The incidents wire rupture.

Flushing pressure	Test no.	Wire tension (gf)	Pulse-on-time (μ sec)	Wire break incident	Flushing pressure	Test no.	Wire tension (gf)	Pulse-on-time (μ sec)	Wire break incident
7 MPa	1	800	4	0	15 MPa	19	800	4	0
	2		6	0		20		6	0
	3		8	0		21		8	0
	4	1100	4	0		22	1100	4	0
	5		6	1		23		6	0
	6		8	9		24		8	0
	7	1400	4	5		25	1400	4	0
	8		6	11		26		6	0

	9		8	2		27		8	0
10 MPa	10	800	4	0	18 MPa	28	1400	8	0
	11		6	0					
	12		8	0					
	13	1100	4	0		29	1700	8	0
	14		6	0					
	15		8	0					
	16	1400	4	0		30	1400	10	0
	17		6	0					
	18		8	0					

The typical situation in the machining zone can be represented in Fig. 1 which shows that the EDM debris or wastes contributes to form additional arcs around the wire. These generate localized high temperature zone and reduce the strength of the wire. If the wire tension at that situation is high enough to generate stress higher than the strength of the soften wire material, the wire fails. Therefore, the whole process depends on the wire tension, wire material and cleanliness in the machining zone. The cleanliness in the machining zone in turn depends on the flushing ability of the electrolyte and other machining parameters that contributes to the rate of debris or waste generation.

The flushing pressure of electrolyte controls the flow of the fluid which affects its ability to remove debris and replace the fluid from the machining zone. It is likely that at low flushing pressure the debris did not remove very efficiently. Efficient removal of debris is important as the buildup of conductive particles in the gaps generates electrical shorts resulting in arching in the case of low flushing pressure. It is preferred to avoid arc formation as much as possible, as it results in formation of large gouges or craters (surface flaws) due to high amount of energy transfer and affect the workpiece as well as increase wire rupture incidents (Kumar, Kumar et al. 2013). On the other hand, dielectric fluid flushed at a lower pressure has lower flowrate through the machining zone. This lower flowrate reduces heat transfer rate between these large gouges or craters and the electrolyte. In addition, it takes longer to replace the electrolyte in the cutting zone with fresh electrolyte. Therefore, low flushing pressure reduces the cutting speed (Yan, Tsai et al. 2005).

Longer pulse-on-time induces more heat and removes material faster at a cost of higher debris production. It affects the gap conditions in two ways: firstly by holding the high temperature for longer time and secondly, by facilitating the buildup of conductive particles in the gaps. Wire rupture is associated to poor gap conditions. Therefore, longer pulse-on-time breaks the wire electrode when other parameters are in favorable values. With the increase of pulse-on-time, spark frequency increases which results in abnormal increase of sparks. This in turn increase the thermal density of the wire (Huang, Liao et al. 1999). Temperature rise in wire electrode causes its tensile strength to be reduced and can result in wire not remaining straight. Both larger heat production and temperature rise due to excessive thermal load stimulate wire ruptures (Jennes, Snoeys et al. 1984).

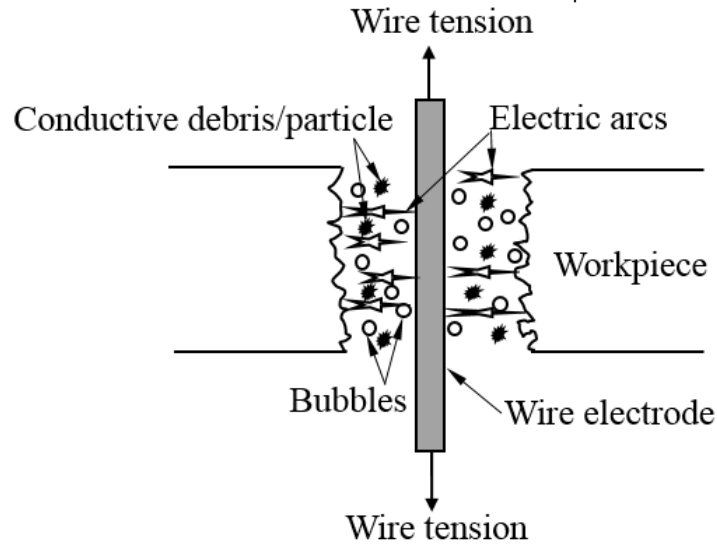


Fig. 1: Machining zone during WEDM process (Habib and Okada 2016).

Wire ruptures has seen to occur at high tension and thin diameter (due to worn out) despite of the gap condition. The wire rupture tendency at high wire tension increases as the ability of wires to sustain discharge energy reduces. The unused wire surface and broken wire tip are given in Fig. 2. The wire diameter diameter closer to the broken tip reduces which is very similar to that of necking effect of specimens during tensile testing. This indicates that, the tensile strength of the wire is low enough at sudden instantaneous high temperature. Therefore, necking starts in wire at this situation at the applied wire tension. Then the ductile failure occurs in the wire electrode finally. The diameter of the broken tips were seen to vary which is influenced by combination of process parameters. The further details of this can found in the authors' previous work as presented in (Pramanik and Basak 2016). Higher flushing pressure and lower wire tension cause vibration of the wire that result in geometrical error of machined components. The complex nature of vibration of the wire is due to the variation in direction and magnitude of acting forces on the wire and stochastic nature of sparks.

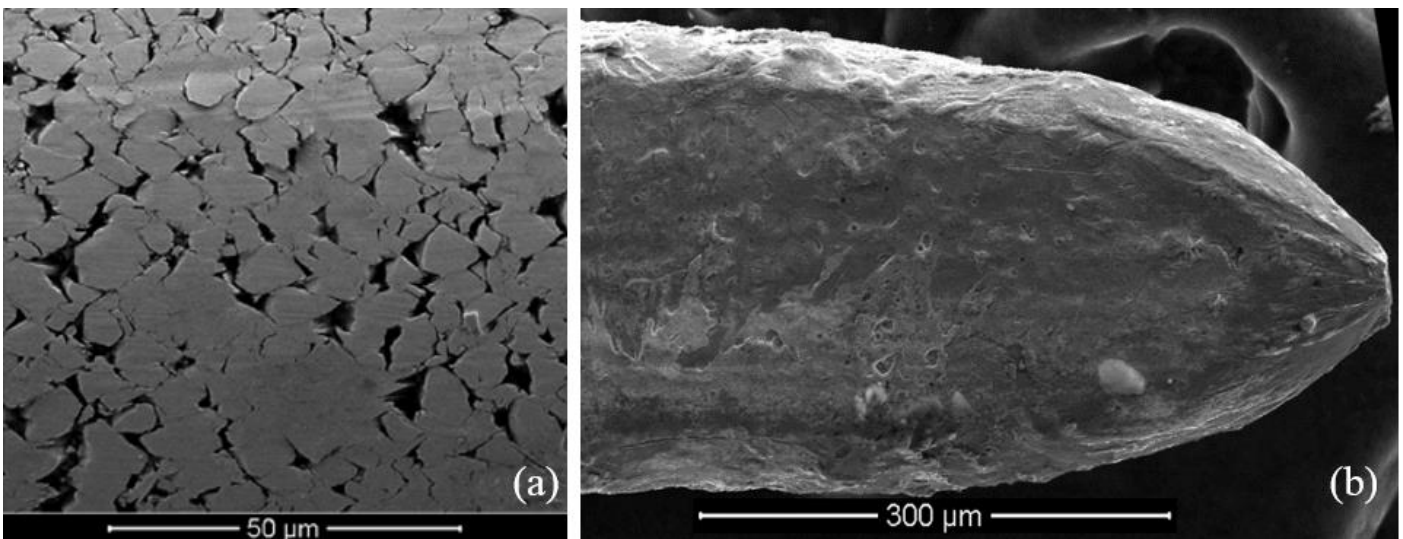


Fig. 2: SEM micrograph of (a) unused wire surface and (b) tip of a broken wire during WEDM process.

Banding on the surface of machined specimen, where wire rupture took place, occurred as shown in Fig. 3. Banding occurs in the form of strips of contrasting color on machined surface. The wire rupture did not occur for all the holes. This banding only noticed when there was wire rupture. Sudden generation of high temperature for a very small duration of time during EDM at the time of wire rupture caused localised melting and materials removal of the workpiece. This might be the possible explanation of banding formation on the machined surface. This occurred only when the wire rupture took place, which supports the phenomena of instantaneous generation of high temperature facilitates the wire rupture. This further deteriorates the finish of the machined surface. Generally, wire rupture has been associated with poor dielectric pressure, high wire tension, electrical discharge and thermal load. The rupture follows as the developed stresses in wire exceed its strength.

3.2 Morphology of broken wire

It is already proven that the initial circular wire electrode deforms to an oval shaped during WEDM process (Pramanik and Basak 2016). The primary indication of this is that the measured diameter of the wire after machining had varying values. Some measurements gave too low values and some measurements gave too high values compare to that of unused wire diameter. In fact, the higher values gave the measurement of bigger diameter of the oval section and lower values gave the measurement of smaller diameter of the oval section. However, in certain situations, the wire diameter decreases all around over a certain length just before failure. Fig. 4 represents the tips (4a, 4c, 4e, 4d) of the broken wires as well as bodies (4b, 4d, 4f, 4h) of the corresponding broke wires just before the failure occur during machining under following parameters: flushing pressure of 7 MPa, wire tension of 1100 gf and pulse-on-time of 8 μ sec. It is clear from the figure that in few instances (figure 4b and 4d) the cross section of the wire decreases gradually over a longer length. This generates sharper broken tips. However, in some cases (figure 4f and 4h) a minor decrease of wire cross section is noted and then it breaks suddenly leaving a blunt tip (4e, 4f, 4g, 4h). This indicates that the severe condition to break the wire develops gradually in some cases (4a, 4b, 4c, 4d) and may as well develop abruptly (4e, 4f, 4g, 4h). The wires also experience crack formation normal to the longitudinal direction on the surface which may be due to the thermal shock.

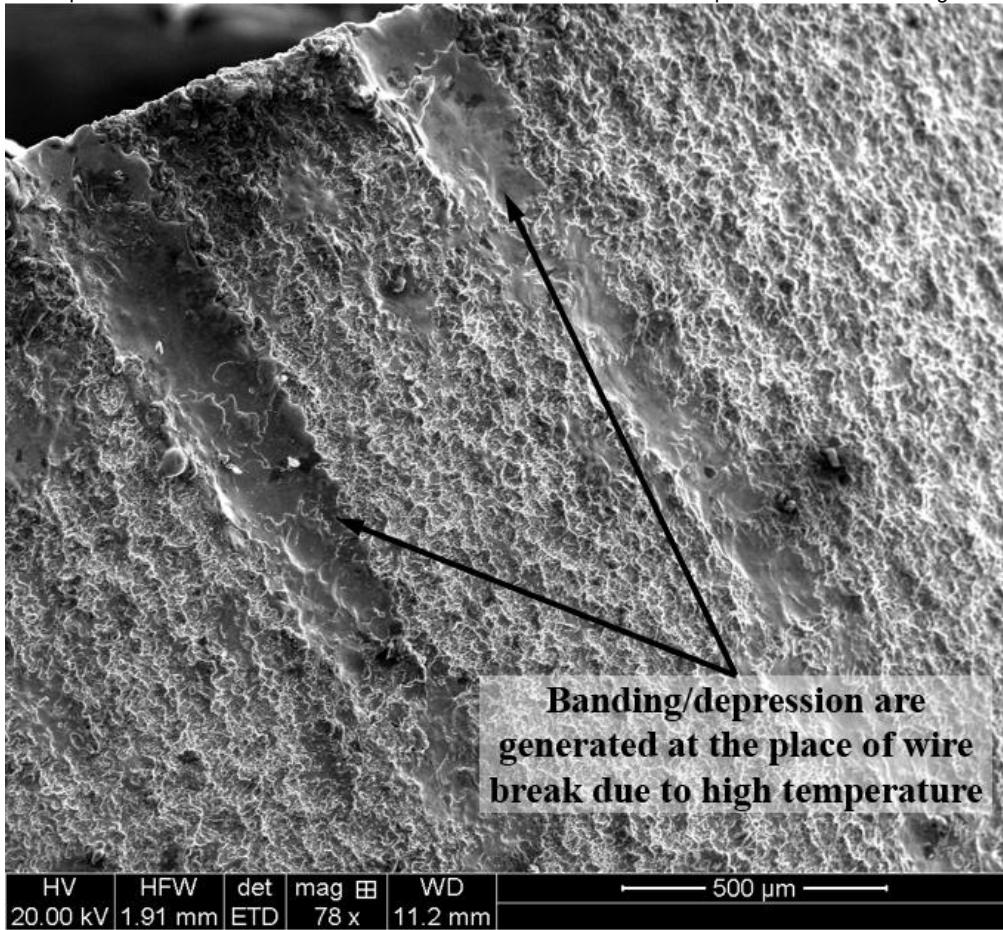


Fig. 3: Banding on machined specimen during WEDM process.

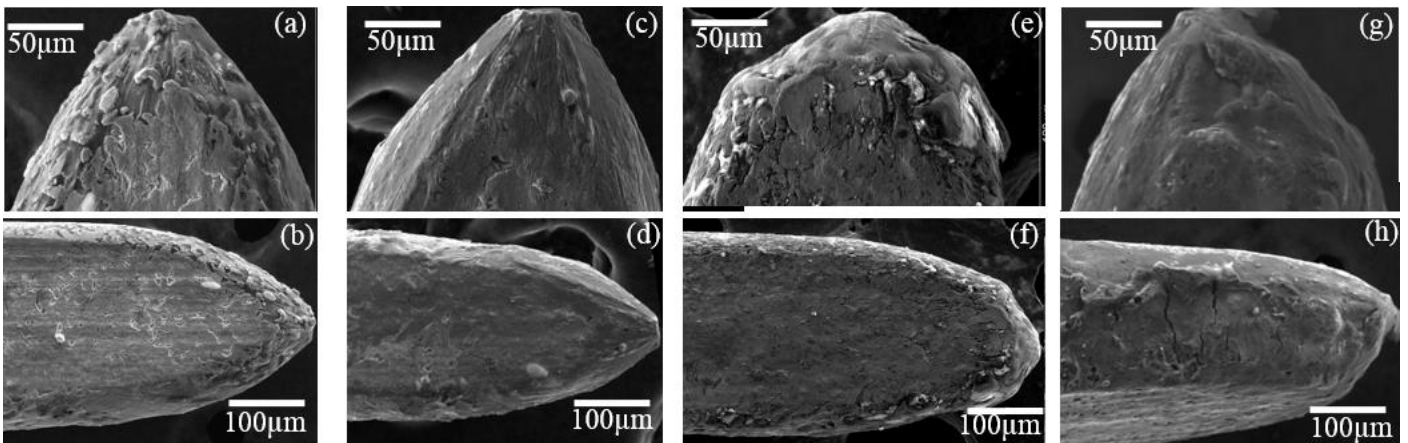


Fig. 4: SEM micrograph of broken wire tips (top row a, c, e, g) and corresponding wire bodies (bottom row b, d, f and h) during WEDM process at 7 MPa flushing pressure, 1100 gf wire tension and 8 μsec pulse-on-time.

The tips of the broken wires in figures 4a, 4c, 4e and 4f show volcano-mouth like appearance where the material is melted and washed away. A symmetric trend of material erosion is clearly visible in the case of sharper tips (4a, 4b, 4c, 4d) but the material erosion is very uneven in case of blunt tips. The temperature generation, ion formation and concentration of debris are not similar in every instant of machining and every spark. Therefore, different geometries of ruptured wire are seen in figure 4. A closer view of the broken wire

© 2018. This manuscript version is made available under the CC-BY-NC-ND 4.0 license <http://creativecommons.org/licenses/by-nc-nd/4.0/> tips are presented in Fig. 5. The zinc coating was disrupted though existed around the tips of the broken wire. It seems that the brass was squeezed out through the disrupted zinc coating which reduced the cross-section area of the wire. Fig. 6 shows the scratches on the broken wire near the tip which are most likely occurred by the debris clogged in the spark gaps at high temperature state.

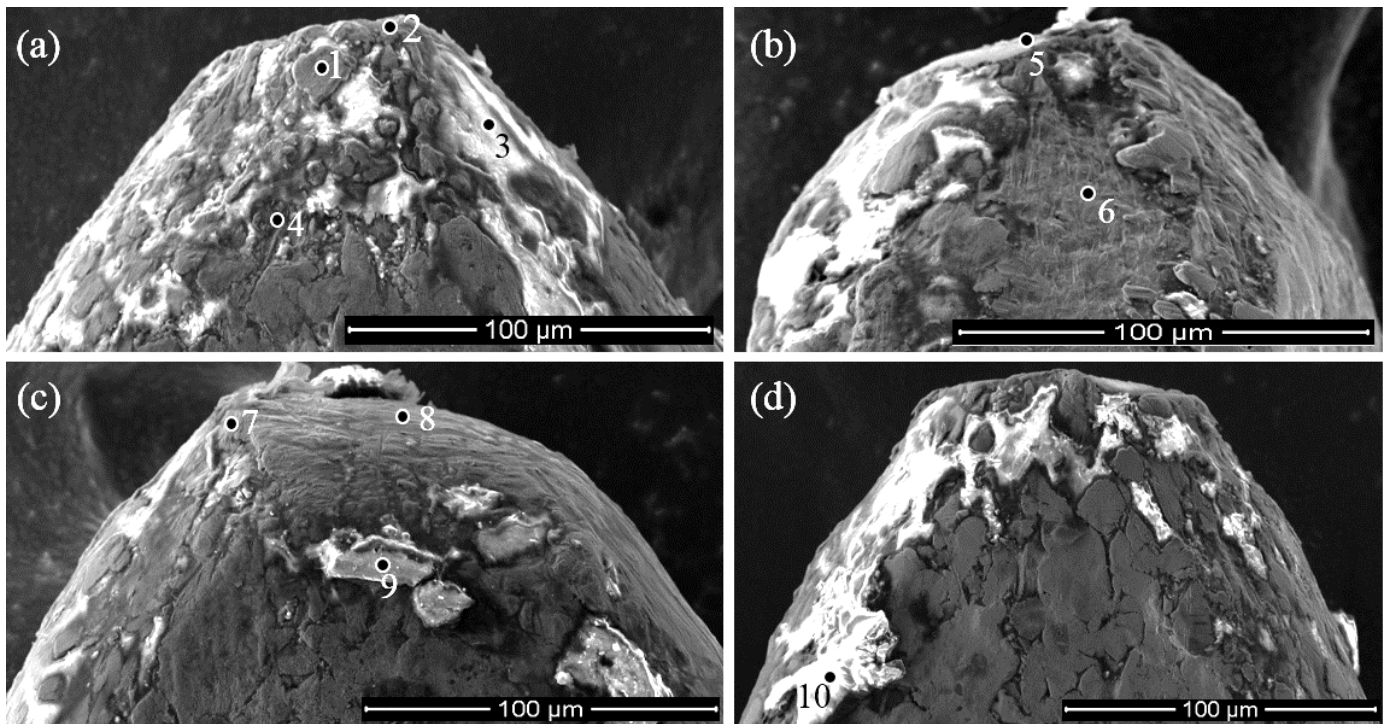


Fig. 5: SEM micrograph of broken wire tips during WEDM process operated at flushing pressure of 7 MPa, wire tension of 1400 gf and pulse-on-time of 8 μ sec.

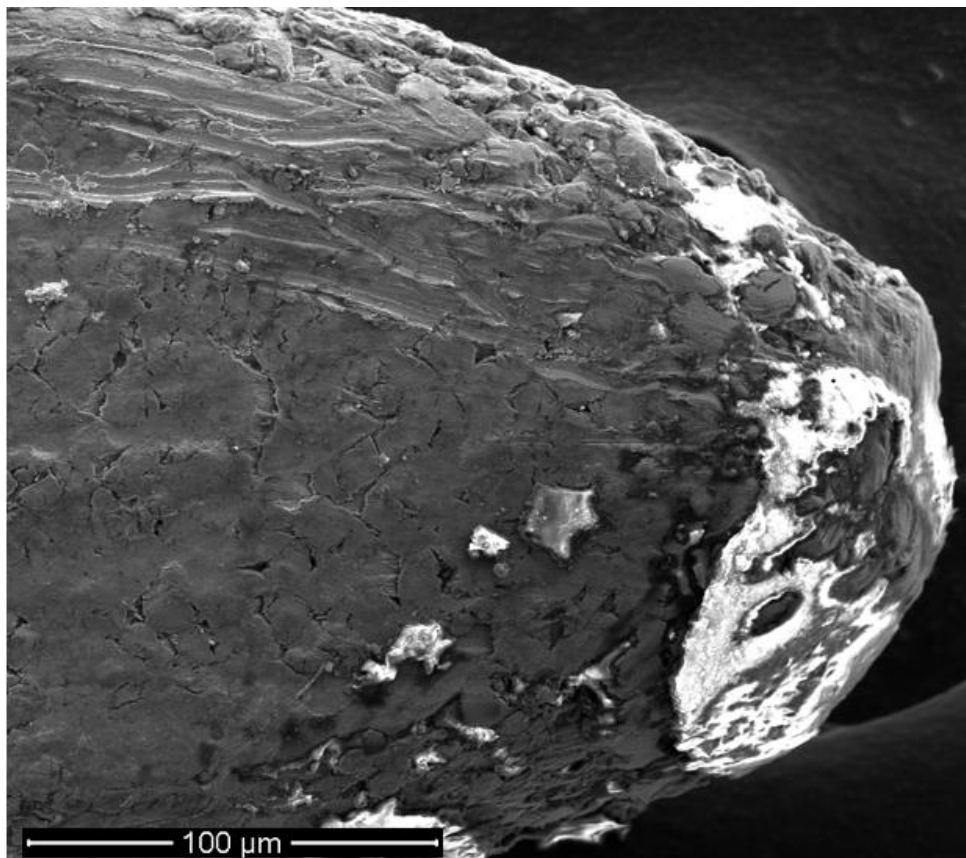


Fig. 6: SEM micrograph of broken wire tip during WEDM process operated at flushing pressure of 7 MPa, wire tension of 1400 gf and pulse-on-time of 6 μ sec.

The EDX analysis at different positions on the broken wire were performed to understand the wear rupture mechanisms. These positions were marked by numerical numbers (1 to 10) in Fig. 5. The EDX results of these positions are presented in Fig. 7. It is important to note that, carbon (C) peak in EDX spectra (Fig. 7) is from the carbon tape which was used to stick the wires in SEM stub and should not be counted during the analysis of EDX results. However, deposition of carbon on wires may also take place due to the thermal decomposition of electrolyte as reported by Kuneida *et. al.* (Kunieda, Lauwers et al. 2005). The wire electrode is brass that is made of copper (Cu) and zinc (Zn) where the proportions of zinc and copper can be varied to create a range of brasses with varying properties. The atoms of these two constituents in brass replace each other within the same crystal structure. It delivers a powerful combination of low cost, reasonable conductivity, high tensile strength and improved flush ability (Dhale and Kulkarni 2015). Brass wire electrodes are extensively used on account of their ability to generate stable discharge in spite of their somewhat limited electrical conductivity. The melting point of brass (900-940 °C) is higher than that of zinc (419 °C) but less than that of Cu (1085 °C). The addition of zinc coat on the surface of brass wire improves the performance of the wire electrode by stabilizing electrical discharge properties (Maher, Sarhan et al. 2015).

The above mentioned facts indicates that the presence of Zn and Cu will dominate the EDX results everywhere as shown in Fig. 7. Point 1 in Fig. 5a is a Zn island as confirmed in Fig. 7 and indicate that Zn coating is disrupted though still adhere till the end of wire fracture. The EDX result in point 2 indicates presence of Cu which came out from the brass of the wire. Therefore, the islands of the coating material are sitting on the top of core material of the wire electrode. The snowy glacier type materials (point 3 in Fig. 5a) on the wire is mainly oxides (such as CuO and ZnO) that form due to the oxidation of wire electrode materials which is foreseen due to the involvement of high temperature during the process. Thus it is clear that the high temperature generated at the time of wire failure decomposes the electrolyte as well as form oxides that deposits abruptly around the islands of Zn coating on the tips of broken wires. The presence of Na at some points (point 4 in Fig. 5a) may also come from electrolyte decomposition. The broken tip (point 5) in Fig. 5b consist of C and brass (Cu + Zn). The exposed area on the wire where the coating is disappeared (point 6) in Fig. 5b contains brass (Cu + Zn). Again on the tips (points 7 and 8) of the broken wire in Fig. 5c the elements are mainly C and brass (Cu + Zn). Snowy glacier material on the broken wire is mainly oxides in points 9 and 10 of Fig. 5c, 5d which is similar to that detected in point 3 as mentioned above.

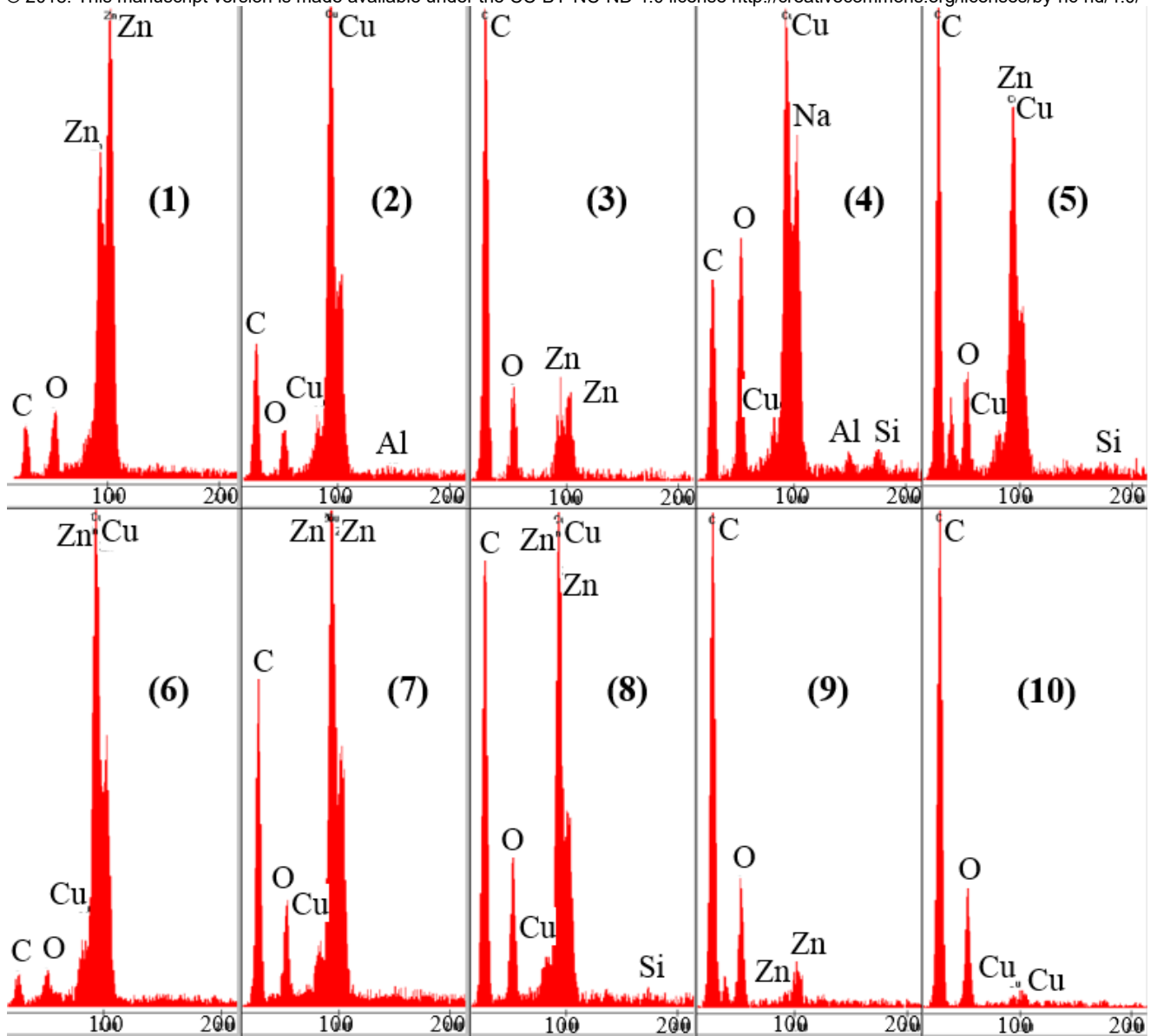


Fig. 7: EDX results on different locations of broken wire indicated in Fig. 5.

The adhesion of workpiece material on the wire generally occurs during sparking due to spattering of molten metal (Pramanik 2016). In addition, the occurrence of electric spark is non-uniform and inconsistency, which causes non-uniform presence of workpiece material on the wire electrode (Pramanik and Basak 2016). The used wire surface shows presence of residual of debris, a number of craters due to spark and re-deposition of solidified workpiece material (Anish K, 2013). However, no such materials are detected around the broken wire tips. This may be because of high temperature in that region which facilitate vaporization of the workpiece materials from the wire surface as well as due to flushing pressure of the electrolyte.

3.3 Mechanisms of wear rupture

A number of factors can lead to wire rupture, as mentioned before, such as the generation of short circuits, inefficient removal of erosion debris as well as other types of stochastic phenomena that appear during the cutting process. The concentration of successive discharges at one point of the wire can generate high flux. All these stimulate to exceed threshold temperature that contribute towards wire rupture. The wire is

© 2018. This manuscript version is made available under the CC-BY-NC-ND 4.0 license <http://creativecommons.org/licenses/by-nc-nd/4.0/> mechanically stressed to satisfy high requirements of geometrical accuracy. Rectilinear accuracies of 0.003 mm over 50 mm were achieved. When the mechanical stress exceeds the tensile strength of the wire, rupture occurs. The thermal load and the erosive impact of electrical discharges significantly influence the tensile strength. Therefore, the power dissipation in the working gap, the thermal load on the wire and wire tension are closely related to wire rupture (Snoeys, Dauw et al. 1983).

Two types of wire breaking phenomena are observed: (i) sudden rise of the sparking frequency and (ii) slight increase of sparking frequency with the increase of arcs and short-circuits ratio (Liao, Chu et al. 1997, Liao and Woo 1997). The complete rupture occurs in three stages based on the deformed shape of the wire electrode during EDM process. At stage one, the circular cross-section of wire starts to change to oval shape where the diameter in one direction is bigger than that of initial diameter and in other direction is smaller than that of initial diameter. This is due to simultaneous effect of high temperature, motion of the wire in two direction and tension in wire during the process. At stage two, the wire cross-section remains oval shaped however both diameters of the oval cross section decrease. At stage three, the wire cross-section becomes circular again but with a significantly smaller diameter than the initial diameter.

In general, the pulses in WEDM process are four types, namely open, normal, arc and short. Each kind of pulse has its own influence on wire electrode and workpiece and, occurs at particular situations. Concerning the effect on the material removal rate, normal is the best pulse, arc is the next best one, while short and open are the worst. Therefore, in certain situations the wire material wears out very rapidly in addition to the wear of workpiece material which reduces both diameters of oval cross-section of the wire. As the area of the wire cross-section reduces, the wire elongates suddenly due to wire tension when the stress in the wire exceed the strength of the wire. In this situation the diameter of the wire reduces significantly and the cross-section of the wire becomes circular. At the end of this stage three, wire rupture takes place at the point of minimum cross-section area. Researchers noticed that an excess of short pulses accelerate wire rupture process, whereas the effects of other pulses remained unknown (Liao, Chu et al. 1997).

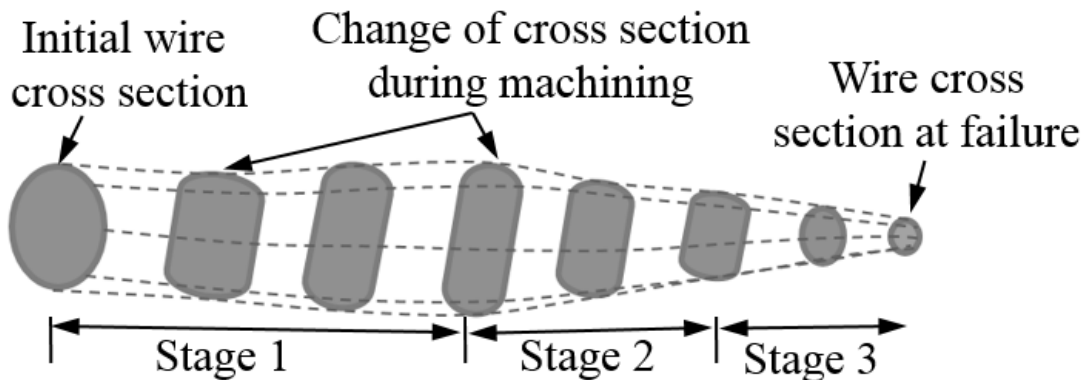


Fig. 8: Schematic diagram towards the deformation of wire electrode cross-section leading ultimate wire rupture.

4. Conclusions

To improve the sustainability of wire EDM process, the present paper investigate the combined effect of wire tension, electrolyte flushing pressure and pulse-on-time on wire rupture incidents during electrical discharge machining of Ti-6Al-4V alloy. Detail investigation of the morphology and composition of broken wire tips was carried out. Based on the outcomes of present research as well as the knowledge available in literature, following conclusions can be made:

- (a) The incidents of wire rupture depends on the condition of spark gap. Presence of too much debris in the spark gap generates unwanted arcs which generates additional temperature. The additional temperature further soften the wire electrode which can break easily at higher wire tension. The low flushing pressure of electrolyte is unable to refresh the spark gap and promotes the unwanted sparks; therefore increases the incidents of wire rupture. To prevent wire rupture at higher pulse-on-time higher flushing pressure and lower wire tension are effective as the higher pulse-on-time generates more debris.
- (b) The wire rupture takes place in a very narrow window of the time frame compared to the whole process. In some cases, it is very sudden where the reduction of wire cross-section is very sharp and in other cases wire cross-section decreases gradually before fracture. The tips of the broken wires have an appearance of ductile fracture which experience necking. This is due to high ductility of the wire material which allows severe plastic deformation due to applied wire tension.
- (c) The zinc coating on the wire was disrupted and took the island like form on the brass core just before fracture. In some places the coating was disappeared around the tips of broken wire. No workpiece material was detected on the tips because of high flushing pressure. The high operation temperature cause the decomposition of electrolyte to deposit carbon on the wire surfaces as well as facilitates oxides formation which is favourable to form in that conditions. The oxides appear as white glacier like materials in SEM images and distributed discontinuously only around the tips of broken wire.
- (d) Deformation of the wire takes place in three stages before complete fracture. Initially the round cross-section of the wire deforms to oval shaped followed by gradual decrease in overall area of the cross-section and finally necking takes place where the oval shapes cross-sections reduced to a point just before complete failure.

References

- Cabanes, I., E. Portillo, M. Marcos and J. Sanchez (2008). "An industrial application for on-line detection of instability and wire breakage in wire EDM." Journal of materials processing technology **195**(1): 101-109.
- Dekeyser, W., R. Snoeys and M. Jennes (1985). "A thermal model to investigate the wire rupture phenomenon for improving performance in EDM wire cutting." Journal of Manufacturing Systems **4**(2): 179-190.
- Dhale, S. and M. Kulkarni (2015). "Effect of Electrode Coatings in Wire Electrical Discharge Machining of Inconel-718." IOSR Journal of Mechanical and Civil Engineering **13**(4): 53-59.
- Gamage, J. and A. DeSilva (2016). "Effect of wire breakage on the process energy utilisation of EDM." Procedia CIRP **42**: 586-590.

© 2018. This manuscript version is made available under the CC-BY-NC-ND 4.0 license <http://creativecommons.org/licenses/by-nc-nd/4.0/>

Gamage, J. R., A. K. DeSilva, D. Chantzis and M. Antar (2017). "Sustainable machining: Process energy optimisation of wire electrodischarge machining of Inconel and titanium superalloys." Journal of Cleaner Production **164**: 642-651.

Gamage, J. R., A. K. DeSilva, C. S. Harrison and D. K. Harrison (2016). "Process level environmental performance of electrodischarge machining of aluminium (3003) and steel (AISI P20)." Journal of Cleaner Production **137**: 291-299.

Garg, A. and J. S. L. Lam (2016). "Modeling multiple-response environmental and manufacturing characteristics of EDM process." Journal of Cleaner Production **137**: 1588-1601.

Gupta, M. K., P. K. Sood, G. Singh and V. S. Sharma (2017). "Sustainable machining of aerospace material–Ti (grade-2) alloy: Modeling and optimization." Journal of Cleaner Production **147**: 614-627.

Habib, S. and A. Okada (2016). "Experimental investigation on wire vibration during fine wire electrical discharge machining process." The International Journal of Advanced Manufacturing Technology **84**(9-12): 2265-2276.

Huang, C. A., C. L. Shih, K. C. Li and Y.-Z. Chang (2006). "The surface alloying behavior of martensitic stainless steel cut with wire electrical discharge machine." Applied surface science **252**(8): 2915-2926.

Huang, J., Y. Liao and W. Hsue (1999). "Determination of finish-cutting operation number and machining-parameters setting in wire electrical discharge machining." Journal of Materials Processing Technology **87**(1): 69-81.

Jennes, M., R. Snoeys and W. Dekeyser (1984). "Comparison of various approaches to model the thermal load on the EDM-wire electrode." CIRP Annals-Manufacturing Technology **33**(1): 93-98.

Joshi, K., A. Ananya, U. Bhandarkar and S. S. Joshi (2017). "Ultra thin silicon wafer slicing using wire-EDM for solar cell application." Materials & Design.

Kinoshita, N., M. Fukui and G. Gamo (1982). "Control of wire-EDM preventing electrode from breaking." CIRP Annals-Manufacturing Technology **31**(1): 111-114.

Kumar, A., V. Kumar and J. Kumar (2013). "Parametric effect on wire breakage frequency and surface topography in WEDM of pure titanium." Journal of Mechanical Engineering and technology **1**(2): 51-56.

Kunieda, M., B. Lauwers, K. Rajurkar and B. Schumacher (2005). "Advancing EDM through fundamental insight into the process." CIRP Annals-Manufacturing Technology **54**(2): 64-87.

Lal, S., S. Kumar, Z. Khan and A. Siddiquee (2013). "An investigation on effects of wire electrical discharge machining parameters on surface roughness of newly developed hybrid metal matrix composite." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture: 0954405413506703.

Lauwers, B., J.-P. Kruth, P. Bleys, B. Van Coppenolle, L. Stevens and R. Derighetti (1998). Wire rupture prevention using on-line pulse localisation in WEDM. Proceedings of the 12th International Symposium for Electromachining.

Liao, Y., Y. Chu and M. Yan (1997). "Study of wire breaking process and monitoring of WEDM." International Journal of Machine Tools and Manufacture **37**(4): 555-567.

Liao, Y. and J. Woo (1997). "The effects of machining settings on the behavior of pulse trains in the WEDM process." Journal of Materials Processing Technology **71**(3): 433-439.

Maher, I., A. A. Sarhan, M. M. Barzani and M. Hamdi (2015). "Increasing the productivity of the wire-cut electrical discharge machine associated with sustainable production." Journal of Cleaner Production **108**: 247-255.

Maher, I., A. A. Sarhan and M. Hamdi (2015). "Review of improvements in wire electrode properties for longer working time and utilization in wire EDM machining." The International Journal of Advanced Manufacturing Technology **76**(1-4): 329-351.

Mandal, A., A. R. Dixit, S. Chattopadhyaya, A. Paramanik, S. Hloch and G. Królczyk (2017). "Improvement of surface integrity of Nimonic C 263 super alloy produced by WEDM through various post-processing techniques." The International Journal of Advanced Manufacturing Technology: 1-11.

Mulyana, T., E. A. Rahim and S. N. M. Yahaya (2017). "The Influence of Cryogenic Supercritical Carbon Dioxide Cooling on Tool Wear during Machining High Thermal Conductivity Steel." Journal of Cleaner Production.

OBARA, H., M. ABE and T. OHSUMI (1999). "Control of Wire Breakage during Wire EDM-1st Report: Monitoring of Gap Signals According to Discharged Location." International journal of electrical machining **4**: 53-58.

Patel, K., P. M. Pandey and P. V. Rao (2008). "Understanding the role of weight percentage and size of silicon carbide particulate reinforcement on electro-discharge machining of aluminium-based composites." Materials and Manufacturing Processes **23**(7): 665-673.

Pramanik, A. (2014). "Developments in the non-traditional machining of particle reinforced metal matrix composites." International Journal of Machine Tools and Manufacture **86**: 44-61.

Pramanik, A. (2016). "Electrical discharge machining of MMCs reinforced with very small particles." Materials and Manufacturing Processes **31**(4): 397-404.

Pramanik, A. and A. Basak (2016). "Degradation of wire electrode during electrical discharge machining of metal matrix composites." Wear **346**: 124-131.

© 2018. This manuscript version is made available under the CC-BY-NC-ND 4.0 license <http://creativecommons.org/licenses/by-nc-nd/4.0/>

Pramanik, A., A. Basak, A. Dixit and S. Chattopadhyaya (2018). "Processing of duplex stainless steel by WEDM." Materials and Manufacturing Processes: 1-9.

Pramanik, A., A. Basak and M. Islam (2015). "Effect of reinforced particle size on wire EDM of MMCs." International Journal of Machining and Machinability of Materials **17**(2): 139-149.

Pramanik, A., A. Basak, M. N. Islam and G. Littlefair (2015). "Electrical discharge machining of 6061 aluminium alloy." Transactions of Nonferrous Metals Society of China **25**(9): 2866-2874.

Rajurkar, K., W. Wang and R. Lindsay (1991). "On-line monitor and control for wire breakage in WEDM." CIRP Annals-Manufacturing Technology **40**(1): 219-222.

Shoda, K., Y. Kaneko, H. Nishimura, M. Kunieda and M. Fan (1992). Adaptive control of WEDM with on-line detection of spark locations. Proceeding of 10th International Symposium for Electro-Machining (ISEM-10): 410-416.

Shoda, K., Y. Kaneko, H. Nishimura, M. Kunieda and M. Fan (1995). "Development of Adaptive Control System to prevent EDM wire breakage." EDM technology **3**: 17-22.

Singh, M. A., D. K. Sarma, O. Hanzel, J. Sedláček and P. Šajgalík (2017). "Machinability analysis of multi walled carbon nanotubes filled alumina composites in wire electrical discharge machining process." Journal of the European Ceramic Society.

Snoeys, R., D. Dauw and J.-P. Kruth (1983). "Survey of adaptive control in electro discharge machining." Journal of Manufacturing Systems **2**(2): 147-164.

Tosun, N. and C. Cogun (2003). "An investigation on wire wear in WEDM." Journal of materials processing technology **134**(3): 273-278.

Wang, W. and K. Rajurkar (1992). "Monitoring sparking frequency and predicting wire breakage in WEDM." Sensors and Signal Processing for Manufacturing, PED **55**.

Yan, B. H., H. C. Tsai, F. Y. Huang and L. C. Lee (2005). "Examination of wire electrical discharge machining of Al 2 O 3 p/6061Al composites." International Journal of Machine Tools and Manufacture **45**(3): 251-259.