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18th CIRP Conference on Electro Physical and Chemical Machining (ISEM XVIII)

Effect of wire breakage on the process energy utilisation of EDM

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Abstract

Optimum energy utilisation is a major concern during machine tool design, as not only is energy consumption an environmental impact/sustainability indicator; it also affects the production economics. Most electrodischarge (EDM) machines have a high degree of automation allowing better coordination of energy consuming subunits for a given machining parameter. The purpose of this study is to analyse the variation of energy consumption with unexpected wire breakages during machining. An industrial CNC wire EDM operation of aluminium and steel plate cutting is studied. A time study and an energy study are performed involving all sub units of machining operation. Results are presented and justifications are made for the fluctuations in total energy consumption during wire breakages. Further, an environmental impact study comparing wire EDM with and without unexpected wire breakages is presented drawing insights for machine tool design and operating practices.

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Keywords: Wire EDM; wire breakage; Energy; Sustainability

1. Introduction

Although categorised as an unconventional machining process, the recorded first observation of metal erosion with spark discharges was by Joseph Priestley in 1768 [1]. However, commercial level EDM has been there since 1950s [2]. EDM refers to material removal of electrically conductive materials by thermal energy generated through electrical sparks between workpiece and tool-electrode immersed in a non-conductive dielectric fluid (deionised water in the case of WEDM). The process is used to machine hard to cut materials with complex shapes and to obtain better surface quality compared to traditional machining. Over the years the technique has evolved incorporating computer numerical control to facilitate more autonomous and precise machining. Optimum machining parameters are developed to reduce operator dependency and improve quality of machining using variety of approaches such as for example Grey-Taguchi method [3].

There are several studies on wire breakage issue during WEDM. Controlling the pulse frequency at a constant level through online monitoring of sparking frequency during machining has been proposed to avoid wire failure [4]. A

computer-aided pulse discrimination system based on characteristics of voltage waveform has identified two symptoms of wire failure, excess of arc discharges and sudden rise of sparking frequency [5]. A finite element modelling approach is taken to predict thermal distribution in the wire and thus optimising system parameters to prevent wire breakage [6]. Apart from the spark characteristics and temperature distribution, the effect of mechanical strength of wire on wire rupture mechanism has also been studied using a stress analysis model [7].

Motives behind preventing wire failure are reported as high machining time or low productivity, diminished accuracy, poor machined surface quality and reduced machining efficiency [4–6,8]. However, studies on the effect of wire breakage on total process energy are limited. EDM process is found to be at least 1000 times more energy intensive than conventional machining as the material removal rate (MRR) is very low compared to traditional machining [9]. Once broken, the rethreading time is a non-value adding activity while background activities consume a considerable amount of energy. Therefore, this study focuses on the impact of wire failure on process energy with justification for supply power fluctuations during WEDM. Furthermore, the analysis is

extended to the environmental implications of wire failure compared to fail-free machining.

2. Approach

Experiment based approach is taken to monitor the wire breakages. Experiments were carried with KingSpark® wire cut CNC EDM machine - manufacturing year 2007. Elcomponent® SPC data logger is used to log current data of supply power during machining. Two work materials, 6 mm thick plate of Aluminium alloy (3003) and 11mm thick plate of tool steel (XW 41) are chosen. In both cases 0.2 mm brass wire is used as the tool. Two video cameras are used for time study and to locate the exact time of wire breakages. Video data is then tallied with the logger data to identify points of wire breakages.

Power data of individual subcomponents of the machine are examined and recorded before the experiments for subsequent justification of total supply power variations. The subunits are rapid water fill pump (0.85 kW), filter pump (2.7 kW), ion exchange and auxiliary water fill pump (1.14 kW), water cooler (5.8 kW), servo (0.35 kW), and controller unit (0.16 kW). The power ratings are adjusted for pump efficiencies where applicable. The 6 mm thick aluminium alloy plate was used to cut a gear wheel of 44 mm PCD and a square profile (10×10 mm) with steel as shown in Fig. 1.



Fig. 1. (a) Gear profile with Al alloy (b) Square profile with steel

The material and shape were selected to give diversity and complexity of machining conditions. Aluminium alloy has relatively low electrical/thermal properties than steel which affects discharge quality and the gear profile gives a challenging contour for the machine than a straight cut. These factors have contributed to few wire failures during machining. On the other hand, the second experiment performed using steel (XW41) to cut a square shape, allowing for straight cuts that did not produce any wire failures.

The machining parameters used for case studies are listed in Table 1. The twofold values indicated under Case I, represent the initial setting and final adjusted setting to prevent wire failure. There were four wire breakages and each time manual adjustments were made by the operator to prevent repeated failure. There were more than one adjustment to find a working combination and the second value is the final version which worked fine. The material removal rates (MRR) are not a preset parameter but the resultant values for each case which are calculated experimentally. It can be noticed, for example, that the initial wire tension is reduced from 9 to 6 as a consequence of wire breakage. Pulse ON/OFF times and wire feed values are also amended as can be seen from the table.

Table 1. Machining parameters used for the case studies

Parameter	Case I Al- Alloy	Case II Steel
Tool/work material	Brass/Al	Brass/Steel
Pulse ON (µsec)	7/5	8
Pulse OFF (µsec)	12/14	13
Wire tension (g)	9/6	7
Wire feed (m/min)	6/5	5
Servo feed (mm/min)	57/62	50
Gap voltage (V)	63	64
Resultant MRR (mm ³ /min)	7.58	11.82

For the assessment of environmental impact, three types of data: energy, resources and emissions are required as represented in Fig. 2. Energy data are obtained using the data logger. A time study is performed to map each phases of machining. Machining phases are setting up phase (includes work clamping, part geometry uploading, programme selection, tank filling), machining phase, standby and wind-up phases. Resource data refers to consumed wire, use of deionised water, proportionate consumption of deionising resins and water filter materials. Solid and liquid forms of emissions are considered same as input. However, airborne emissions are omitted considering the practicality of industry setup to capture the emissions.

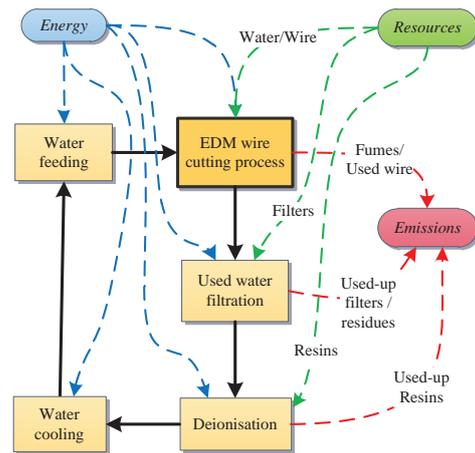


Fig. 2. Trace of impact sources of WEDM process [10]

3. Supply power variation

The experiment with aluminium alloy plate made a few frequent wire brakages. The machine is equipped with an automatic wire rethreading mechanism wich should ideally rethread the wire within about 57 seconds. However, at the time of the experiment the pneumatic rethreading mechanism was out of order hence it was manully rethreaded. Manual rethreading time varies each time but averages to 5.24 minutes which is far greater than automatic rethreading. Resulting power consumption data with manual rethreading is analysed to develop the total process power utilisation during machining.

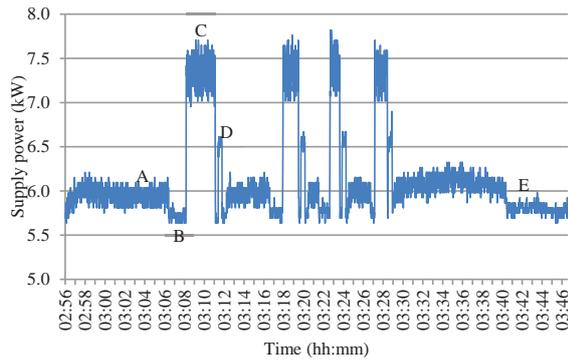


Fig. 3. Fluctuations of supply power with wire breakages – Al alloy

Figure Fig. 3 shows a window of total power variation during WEDM capturing points of wire failure. Four similar fluctuations can be noticed. The tallied video and logger time data proves that these fluctuations maps to wire failure points. The power level of around 6 kW as shown in region 'A' denotes the power consumption during actual discharging. Number of sub units, including generator, servos, auxiliary pump and cooler are contributing to this rate of power consumption. The drop of about 0.3 kW from region 'A' to 'B' is the point that wire failure takes place. This clearly shows the stoppage of discharging and servos. Machine operator then have to manually rethread the wire after draining the tank.

The region 'C', which consumes a peak power of 7.3 kW with a rise of about 2.6 kW from level 'B' may be due to the filter pump (2.7 kW) operating to filter out drained water. The time taken for rethreadings has slight variations due to manual operation. The narrow sub optimum spike shown with 'D', just after 'C', is due to tank re-filling. On average 24 seconds of operation is noticed here for the feed pump with a 0.8 kW rise which is roughly the same as the feed pump power. Once the tank is filled then the machining command is set again and it is reflected again in the graph with 6 kW power value. This variation pattern is repeated for each time wire breaks. Region 'E' shows the standby mode power consumption after machining is completed. Even in standby mode there is a consumption of over 5.2 kW to run background non-machining but supportive operations. These could be mainly the water cooler, deioniser and the controller unit. However, exact contribution from each sub unit cannot be calculated unless individual loggers are attached to each sub unit.

The graph can be used to calculate the total time and energy lost due to wire failure. In this case, 15 minutes of machining time have been lost due to wire failures which amounts to 30% of total machining time. This has caused a waste of 1.7 kWh of electrical energy which is over 23% of total machining energy (Fig. 4). Time taken to resume machining after each wire failure is non-productive and has adverse implications on process energy utilisation. The machine tool algorithm triggering the operation of sub units after a wire failure could be optimised to make it more intelligent to avoid wire breakages and thus saving potential waste of energy.

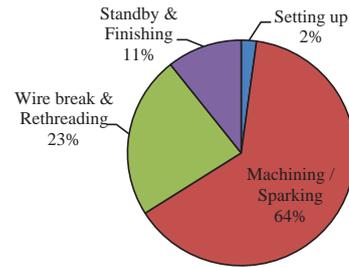


Fig. 4. Process energy utilisation during each phase of machining

The figure Fig. 5 presents the power profile during WEDM of steel. Region from start up to about 11 minutes is the machine starting up phase with two distinct hikes reflecting pump triggering and standby power level of about 5.6 kW (Region 'P'). This is similar to the previous experiment's standby power value shown in region 'E' of Fig. 3. The region 'Q' starting from 11 minutes to 22 minutes is the continuous machining period with an average power value of 7.42 kW with no wire failure.

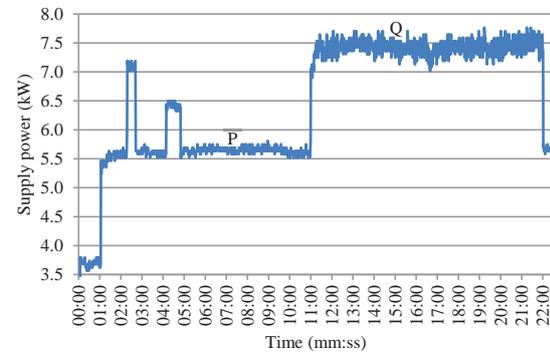


Fig. 5. Fluctuations of supply power of WEDM – Steel

Based on the set machining parameters, the area under power curve gives an idea of energy consumption. So wire failures at higher power values could lead to increased waste of energy. The machine operators normally amend the machining parameters such as, wire feed, wire advance and sparking frequency to avoid further wire failures after first instant. This was observed in the first case study to keep the process going without failing. However, this slows down the process further and thus adversely affecting the energy consumption.

4. Environmental implications

This section discusses the influence of wire failure on environmental performance of WEDM process. A comparison of Al-alloy machining with and without wire failure is made in terms of factors affecting environmental impact as shown in Table 2. Only the machining phase is considered here for clear understanding of wire failure effect by excluding energy or resource consumption in starting up and shutting down phases.

Table 2. Life cycle inventory for energy and resources with and without wire failure

Description	Without wire failure	With wire failure
Machining time (minutes)	35	50
Electrical energy (kWh)	3.5	5.2
Deionised water (ml)	881	1259
Deionising resins (g)	15.6	22.2
Lubricant oil (ml)	43	43
Used-up wire (g)	62.01	64.82
Work material removed (g)	0.72	0.72

Resources that require periodic replacement, such as deionised water and resins, are allocated for the duration of machining based on life hours according to WEDM maintenance guidelines [11]. These guidelines may differ for each individual machine tool manufacturer. However, for LCI purposes, it is assumed that the general maintenance guidelines are followed by the operators. The extended time due to wire failures and standby are also considered as machining time for resource ageing and replacement purposes.

Environmental impact is assessed using LCI data presented in Table 2. SimaPro® 8 LCA software with Ecoinvent data base version 3 [12] is used for the assessment. The impact assessment is performed using ReCiPe [13] Endpoint (H) V1.11/ Single score method. The method produces a single score of three endpoint categories of environmental mechanism - damage to human health, ecosystem and resource availability. A ‘point or person- equivalents’ in the single score method represents the normalised endpoint score which denotes the amount of annual environmental load of an average person [14]. It is usually expressed in units of thousandth (milli-points- mPt) for better representation of smaller impact values.

Fig. 6 depicts the environmental impact for each impact source with and without wire failure. The significance of the impact of wire failure on process energy is again reflected in the figure showing over 300 mPts of impact for electrical energy which is a 48% increase compared to fail-free machining. The highest impact is caused by the wire material (brass) which shows a slight increase of about 5% impact due to wasted wire resulted from rethreading.

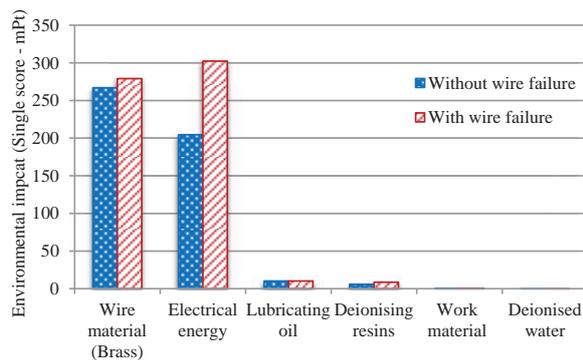


Fig. 6. Environmental comparison with and without wire failure

Energy consumption during starting up and shutting down processes are excluded here on purpose to keep the focus only on the machining process. If included, it will increase the impact value further as discussed under Fig. 4. The total increase in environmental impact due to wire failure is 23% compared to fail-free operation. The impact from other resources, lubricating oil, resins, work material and deionised water is marginal compared to the aforementioned key contributors. The resources which have no effect from wire failure are also included in the LCI to assess the comparative significance on environmental impact. It should be noted that even if the wire material and work materials are changed the impact of electrical energy consumption due to wire failures will remain significant.

5. Discussion

It is important to understand the machine’s reaction to unprecedented events. It is observed that once the wire is broken the machine is programmed to drain out the water from the work tank and start a cycle of filtering and deionising. This drastically increases the energy consumption during rethreading process. Apart from that, other background processes such as, for example the water cooler with high power rating, continue to operate irrespective of productive or non-productive time. In summary, as most of the energy consuming sub units remain consuming energy, the wire rethreading time is a total waste of energy and resources. In addition to that the operators take remedial actions after the initial wire failure by manually altering the operating parameters. This adds up to the delays and affects the quality of cut.

The results could be improved by incorporating the automated rethreading mechanism as oppose to manual rethreading, as manual rethreading times are not consistent. During rethreading periods the machine keeps consuming energy as it waits in standby mode for the operator to attend. Tracing individual energy consuming sub units, with dedicated data loggers for each subunit, could have made a clearer and precise justification as how the wasted energy is shared among sub components.

6. Conclusion

Implications of wire breakage on process energy utilisation and environmental impact are studied using two case studies. Significant waste of energy is reflected with wire failure. The energy utilisation in an event of wire failure will depend on the machine tool control algorithm to restore machining in order.

The environmental impact study reflects a significant increase (48%) in the impact value of utilised energy due to wire failure. It further uncovers the significance of wire material to the total impact figure despite the main focus on process energy. 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.

Further research is underway with different machine tools and different work materials. Generating individual job level energy consumption reports, possibly including excess energy usage due to wire failures and other unexpected events could be a direction for further research. This will increase the awareness of all stakeholders, especially machine tool builders and operators, to take remedial action to prevent higher energy consumption and subsequent environmental damages. Research on wire manufacturing considering improved mechanical properties to prevent wire failure without compromising quality or machining speed would be another potential area for further research.

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