OPTIMISATION OF EDM FAST HOLE-DRILLING THROUGH EVALUATION OF DIELECTRIC AND ELECTRODE MATERIALS

Fábio N. Leão
School of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK
epxfnl@nottingham.ac.uk

Ian R. Pashby
School of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK
Ian.Pashby@nottingham.ac.uk

Martyn Cuttell
Rolls-Royce PLC, Wilmore Rd. Gate 6, Derby, DE24 9BD, UK
Martyn.Cutttell@rolls-royce.com

Peter Lord
Rolls-Royce PLC, Wilmore Rd. Gate 6, Derby, DE24 9BD, UK
Peter.Lord@rolls-royce.com

Abstract. *Electrical discharge machining (EDM) fast hole-drilling is a highly developed technology used for making holes in parts such as turbine blades, fuel injectors, cutting tool coolants, hardened punch ejectors and plastic-mould vents. Hole sizes generally vary between 0.3 and 3mm, with a length to diameter ratio of over 150:1. EDM fast hole-drilling is a key manufacturing technology for gas turbine components, and Rolls-Royce currently operates over fifty machines using brass electrodes and deionised water dielectric in a range of factories. The process, however, leads to high production costs, mainly due to the high consumption of electrodes. Using fractional factorial and response surface design, a series of studies have been carried out with the purpose of optimising the drilling process through the evaluation of a water-based dielectric and an electrode material different from the standard materials of deionised water/brass, through analysis of drilling time, electrode wear, surface integrity and dimensional accuracy. The results showed that it is possible to obtain good drilling rates and achieve a reduction in electrode wear of nearly fifty percent.*

Keywords: *Electrical discharge machining, fast hole-drilling, optimisation, dielectric and electrode material*

1. Introduction

Electrical discharge machining (EDM) is a process in which removal of workpiece material is achieved by sparks between the workpiece and a tool electrode, with high temperatures causing melting and vaporisation. The workpiece and the electrode are covered in a dielectric fluid and are connected to a generator delivering periodic pulses of energy. There is no physical contact between the workpiece and the electrode and the small gap separating them is maintained under servo control.

There are different variations of EDM processes including die sink EDM, wire EDM and EDM fast hole drilling. The main difference between fast hole drilling and other processes lies in the use of a high pressure (70 – 100 bar) dielectric pump. The combination of the high pressure dielectric fluid, the rotation of the tubular electrode and the high electrode feed rate (controlled by a fast response servo) make it possible to produce holes at a very *fast* rate.

Hole sizes produced by EDM fast hole drilling are generally between 0.3 and 3mm, with a length-to-diameter ratio of over 150:1. The process is used for making holes in parts such as turbine blades, fuel injectors, cutting tool coolant holes, hardened punch ejector holes, plastic mould vent holes and other operations.

EDM fast hole drilling is a key manufacturing technology for gas turbine components. Rolls-Royce currently operates over 50 machines using brass electrodes & deionised water dielectric in a range of factories. EDM drilling is probably the only practical method for producing deep holes with very small diameters in turbine blades. However, the process leads to high production costs, mainly due to the high consumption of electrodes. As reported in a previous study (Dünnebacke, 1992), this aspect may be related to the type of dielectric fluid used.

The dielectric fluid performs an extremely important function, having an effect on overall productivity and on the final quality of the machined parts. There are four functions of a dielectric liquid for electrical discharge machining: electrical insulation; restriction of the spark area; flushing and cooling.

The dielectric must *insulate* the electrode from the workpiece so that there is a suitable gap between them. The precise size of the gap depends on the dielectric strength of the dielectric liquid. For a given voltage applied, greater dielectric strength allows for a smaller gap and a faster and more accurate machining (BP, 1982). Dielectric strength depends on a number of factors, including the size and shape of electrodes, the material from which they are made, the frequency and duration of the applied voltage, and the temperature, pressure, contamination and molecular structure of the dielectric (Dakin, 1990; Permain and Clegg, 1993; Gallagher, 1975).

If the sparks between the electrode and the workpiece were produced in the air, the erosion effect would be very small because the electrical discharge would spread through the gap, losing its energy. One of the most important functions of the dielectric liquid is to *restrict the spark area*, i.e. to concentrate the discharge in a narrow channel so as to produce a high energy-density, thus concentrating heat energy over a small area of metal. This increases the metal removal effect of each discharge (BP, 1982; Weller, 1984).

The dielectric is expected to carry the impurities away from the gap, preventing short circuits which would impair the machining performance. *Flushing* is especially important for the removal of coarse debris and carbonaceous particles resulting from the breakdown of oil-based dielectrics. However, fine impurities (which are too small to be removed by filtration) are beneficial for the process as they facilitate the ionisation and formation of discharge channels (Erden, 1980).

The dielectric must *cool* both the electrode and the workpiece. Overheating of the electrode and the workpiece would lead to excessive production of gas and vapour, resulting in dimensional inaccuracies (Storr, 1992).

A number of dielectric materials can be used in EDM, including hydrocarbon oils, deionised water, silicone fluids (Scheucher, 1978), hydrocarbon oil combined with conducting powders (Chow et al, 2000), aqueous solutions / emulsions of organic compounds (König and Jörres, 1987), oxygen (Kunieda and Yoshida, 1997), nitrogen and inert gases such as helium and argon (Kunieda and Furuoya, 1991). However, the most widely used in fast hole drilling are deionised water and hydrocarbon oils.

A painstaking review of the performance of deionised water, water-based dielectrics and gaseous dielectrics has recently been published (Leão and Pashby, 2004). It reported that an emulsion of water with glycerine resulted in higher material removal (40%) and lower relative wear (90 %) when compared with hydrocarbon oil. It was also found that a commercial water-based dielectric produced material removal rates up to three times higher than those obtained with oil. However, most of the work cited in the review paper is related to die sink EDM; there is no published work on the performance of dielectric fluids for EDM fast hole drilling. Nevertheless, there are a number of companies producing water-based dielectrics and additives for EDM drilling applications. There is a Japanese patent of a dielectric fluid composed of deionised water and very small quantities (0.2 to 3%) of additives, including colloid graphite powder, sugar, saccharine and glycol (Wijers, 1991).

EDM spark temperatures range from 9,000K to 30,000K and depend on the type of dielectric used (Pillans et al, 2002). Therefore, metallurgical alterations, and as a consequence, changes in the mechanical properties of the workpieces are expected to occur. Two distinct layers are identified in the surface of parts produced with EDM - the white or recast layer and the heat-affected zone (McGeough, 1988). Since dielectrics may have different chemical compositions and thermal conductivities, it is expected that the formation of the two layers and the associated mechanical properties will depend on the type of dielectric used.

The performance of the EDM process depends to a large extent on the material from which the electrodes are made (Zaw et al, 1999). The main requirements for electrode materials are that they have high electrical and thermal conductivity and high melting temperature (Guitrau, 1997). A high boiling point is another important property, as was found recently (Tsai and Masuzawa, 2004). Since in EDM fast hole drilling the electrodes tend to be tubes with very small diameters (0.3 – 3mm) but much greater lengths (300 -500 mm), it is also necessary that the material possess suitable tenacity/rigidity so that the electrode can tolerate the mechanical movements imposed by the electrode feeder / holder without breaking or bending. It is also important for the electrode to have suitable tensile stress so that it is able to resist to high dielectric pressure. A number of electrode materials can be used in EDM, but due to the particular requirements of fast hole drilling, the most common are brass, copper tubes and, to a lesser extend, tungsten wire.

Drilling performance depends not only on the properties of the electrode material but also on the combination of EDM parameters, and especially on the type of dielectric fluid used. The objective of this study is to optimise the EDM fast hole drilling process through an evaluation of dielectric and electrode materials and EDM parameters. In order to ascertain the optimal conditions, statistical methods were used to model the process for each combination of dielectric and electrode material. This paper presents the results obtained with two different dielectric materials and two different electrode materials. The results obtained from testing other materials will be published in a future paper.

2. Experimental procedure

2.1. Equipment, tools and materials

The drilling tests were performed on an Amchem model HSD6 equipped with a high pressure (70 bar) dielectric pump, which supplied dielectric to the gap between the electrode and the workpiece. The machine was also equipped with *Signature Analysis* - an online process monitoring system which uses an encoder to measure the variations in servo velocity and programmed depth (hole depth + electrode wear). So as to be able to determine wear and validate the results achieved with signature analysis, a precision ruler was used to measure electrode length before and after drilling. The diameter of the drilled holes was measured using a KEYENCE VHX-100 digital microscope**.** The holes were drilled using a single point rotating tool electrode holder. The rotation employed was 1200 RPM. The electrode used in the trials was tubular, with external diameter of 0.45 mm and length of 450 mm. The electrodes were made either of brass or copper. The workpiece was made of a nickel-based alloy, cut from the root of the blade and ground to a thickness of 6.3mm. Two different dielectric fluids were used in the experiments: deionised water with an average conductivity of 0.30μS/cm and a water-based dielectric composed of deionised water, alcohols and salts and with an average conductivity of 1900 μS/cm.

2.2. Design of Experiments

Design of Experiments (DOE) is a planned approach for determining cause-and-effect relationships that can be applied to any process with measurable inputs and outputs. DOE provides a statistical means of analysing how numerous variables interact (Anderson and Whitcomb, 2000). The traditional one-factor-at-a-time approach to designing and performing an experiment is inefficient and very often produces misleading results. Since with DOE more than one factor can be varied at the same time, it becomes possible to identify factor interactions, an understanding of which is extremely useful when seeking to optimise processes. Moreover, DOE is more economical than the traditional methods of experimentation. In the present study the experiments were designed and performed in two steps, detailed below. Minitab v14 software was used to design the experiments, analyse the results and model the drilling process.

2.2.1. Screening trials

Screening trials were used in order to identify the most important factors affecting the EDM drilling process. The experimental matrix was designed using fractional factorial resolution VIII (128 run). The factors and coded levels used in the trials are shown in Tab. 1. The dielectric used in level 1 was deionised water. A solution of deionised water with alcohols and salts was used in level 2. The electrode materials in levels 1 and 2 were brass and copper respectively. The specific kinds of alcohols and salts, together with the actual levels of EDM parameters employed in the experiments, constitute proprietary information and therefore cannot be published.

Table 1. Factors and levels

Factor	Level 1	Level 2
Dielectric	-1	+1
Electrode	-1	+1
Servo	-1	+1
Peak current	-1	+1
Duty cycle	-1	+1
Gap voltage	-1	+1
Capacitance	-1	+1
Frequency	-1	+1

2.2.2. Optimisation trials

The optimisation trials were designed using the response surface method, a collection of mathematical and statistical techniques useful for modelling processes in which responses are influenced by several variables and the objective is to optimise the responses (Montgomery, 2001). The response surfaces can be represented by second-order polynomials (shown below) if there is curvature in the system.

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \sum \beta_{ij} x_i x_j + \varepsilon$$

Where,

β:	regression coefficients
x:	factors
k:	number of factors
ε:	approximation error

The method of least squares (Montgomery, 2001) was used to estimate the regression coefficients. Analysis of variance (ANOVA) was performed to test the significance of the obtained coefficients at 10% level of significance. The adequacy of the models was tested by confirmation trials.

One of the fundamental assumptions of the statistical analysis for DOE is that the data must have a normal distribution. Since the drilling time was not a "normal" response, in both the screening and optimisation trials the data were transformed using the Box-Cox method (Montgomery, 2001).

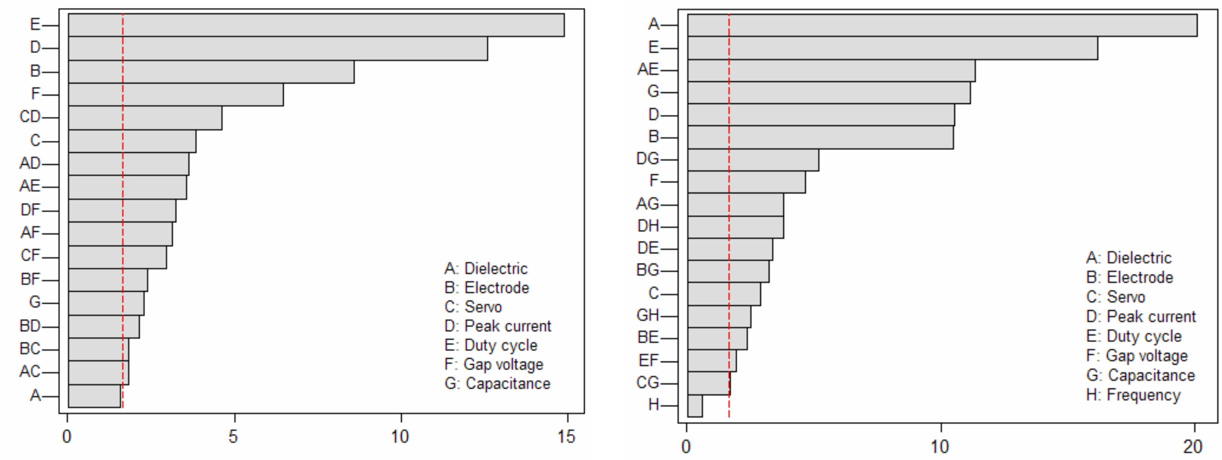
3. Results and discussion

3.1 Screening trials (Fractional factorial design)

Figure 1 shows the Pareto chart of the effects of the design factors on drilling time (a) and electrode wear (b). All the bars which extend beyond the vertical dashed line correspond to effects which are statistically significant, at a significance level of 10%.

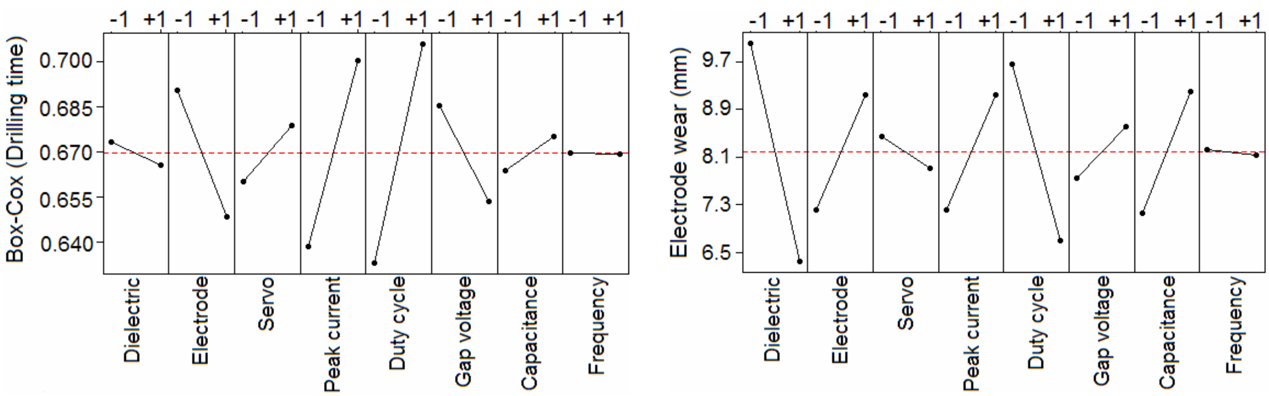
It can be seen in Fig. 1a that duty cycle and peak current were among the factors making a significant contribution to variations in drilling time. Frequency is not present in the Pareto chart because it did not affect the drilling time. Although the dielectric in itself had a small effect on drilling time, its interactions with peak current, duty cycle and gap voltage had an important impact on the results. Dielectric and duty cycle were among the factors which most affected electrode wear (Fig. 1b). Although frequency was not found to be relevant, it could not be excluded from the Pareto chart of electrode wear because it had a significant impact through its interaction with peak current and capacitance.

The effects of the variations of the different factors levels on drilling time (a) and electrode wear (b) are presented in Fig. 2. In order to minimise drilling time and electrode wear, electrode material and gap voltage have to be set at lower levels. For servo and duty cycle, higher levels are conducive to good performance. A “compromise” had to be found between levels of peak current, capacitance and dielectric material, as variations in these factor levels had opposite effects on drilling time and electrode wear. In order to achieve that compromise, optimisation trials using the response surface method were carried out to ascertain optimal operational conditions. The factors which were selected to be used in the optimisation trials were servo, peak current, duty cycle and gap voltage.



(a) (b)

Figure 1. Pareto chart of the effects on drilling time (a) and electrode wear (b)



0.700 = 24.16 seconds
0.640 = 53.77 seconds

(a) (b)

Figure 2. Effect of factor levels on drilling time (a) and electrode wear (b)

Capacitance was kept constant in the optimisation trials because its effect on drilling time was small. Although its effect on wear was significant, it can be seen in Fig. 2b that it is convenient to keep it at constant low level as this ensures lower electrode wear. Since frequency had no effect on drilling time and only a relatively small effect on electrode wear, it was not considered in the optimisation trials in order to have a smaller number of tests to be performed.

3.2 Optimisation trials (Response surface design)

Based on the experimental data gathered, statistical multi-regression analysis was performed in order to establish second order models of drilling time, electrode wear and hole size in the drilling process when operating with brass electrodes, deionised water and the water-based dielectric. The models generated are as follows (in coded units).

Deionised water:

$$DT(R^2 96\%) = 0.02253A + 0.02326B - 0.00046C - 0.01671D - 0.01175A^2 - 0.01005B^2 - 0.01023C^2 - 0.00766D^2 + 0.00982AB - 0.00637AD + 0.00634CD + 0.75783$$

$$EW(R^2 97\%) = -0.2125A + 1.3413B - 0.2008C + 0.1662D - 0.4353B^2 + 0.2091C^2 - 0.1750CD + 6.2185$$

$$HD(R^2 48\%) = 0.00067A - 0.00042B + 0.01008C - 0.00945B2 - 0.01000AB + 0.48120$$

Water-based dielectric:

$$DT(R^2 95\%) = 0.04332A + 0.08947B + 0.04067C - 0.01619D - 0.03345A^2 - 0.06916B^2 - 0.01963C^2 - 0.01634D^2 + 0.07842AB + 0.05326AC - 0.02037BC - 0.02625BD + 0.27479$$

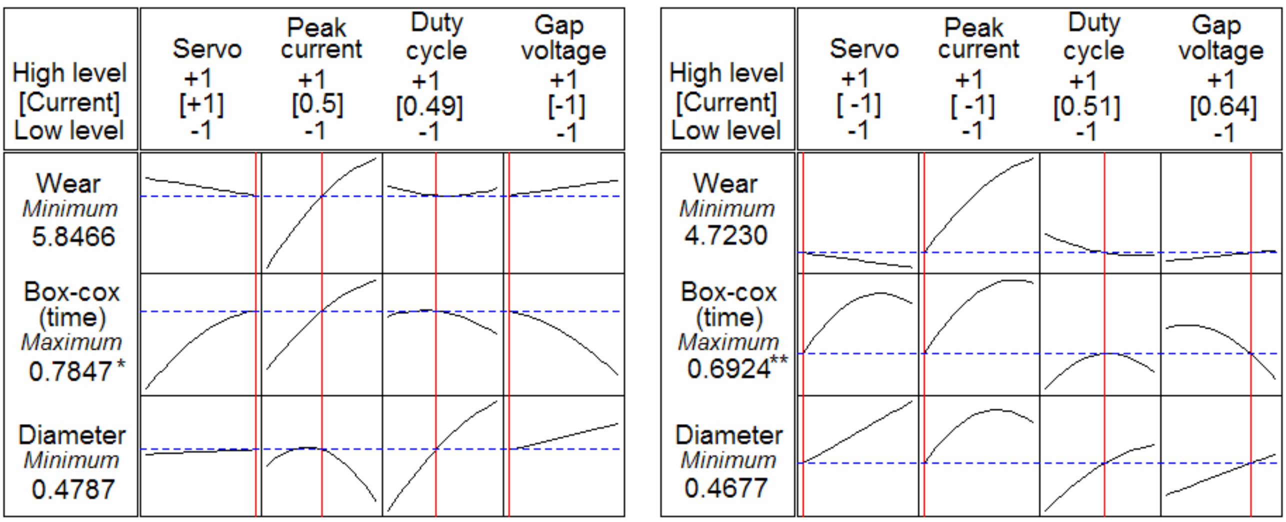
$$EW(R^2 97\%) = 0.02083A + 1.75000B + 0.55000C + 0.02083D - 0.17292A^2 - 0.55417B^2 - 0.14167C^2 - 0.12292D^2 - 4.54374$$

$$HD(R^2 88\%) = -0.017500A + 0.029167B + 0.034583C + 0.011250D - 0.008958C^2 + 0.007292D^2 - 0.010000AC + 0.013750BC + 0.551111$$

Where,

DT:	drilling time	A: servo
EW:	electrode wear	B: peak current
HD:	hole diameter	C: duty cycle
R^2:	multiple correlation coefficient	D:gap voltage

A typical graphical representation of the models showing optimal values of drilling time, electrode wear and hole diameter, with the respective coded values of servo, peak current, duty cycle and gap voltage, is presented in Fig. 3, generated by the Minitab response optimisation tool. The optimal values of electrode wear and drilling time (Fig. 3a) have been obtained for a hole diameter of $0.45^{+0.06\,/\,-0.00}$ mm. Figure 3 b shows how the shape of curves have changed for servo and peak current set at level -1 and gap voltage set at 0.64. The reason for the shape modification is the presence of factor interactions, as shown above in the equation for the models.



* 0.7847 = 7.20 seconds
**0.6924 = 24.61 seconds

(a) (b)

Figure 3. Graphic models of optimal responses for deionised water

It can be seen in Fig. 3 that peak current was the factor which most affected the responses. A higher current (level +1) results in lower drilling time at the expense of higher electrode wear and hole diameter. This is due to the fact that higher currents result in more heat in the gap and as consequence more material is melted and vaporized when the sparks occur. However, since the peak current had a second order effect on the responses, for peak current higher than level +1 drilling time will increase (downward Box-Cox curve) and hole-size will decrease (Fig. 3b). One possible explanation for this is that the metal from both electrode and workpiece melts to the maximum depth, and at that point the heat spreads out without melting more metal and without sustaining the melting temperature at the bottom of the crater (Poco Graphite, 1996), thus decreasing hole size and increasing drilling time.

Duty cycle is the ratio between the pulse *On* time and its sum with pulse *Off* time, so a low *Off* time will result in a high duty cycle. Figure 3 shows that the duty cycle also had a second order effect on drilling time and electrode wear: drilling time was lowest for a medium range of duty cycle. When the duty cycle increased beyond the peak of the curve, drilling time decreased. Shorter pulse duration (*On* time) results in less heat energy in the gap, and as consequence less molten metal (higher drilling time). However, if the pulse duration is too long (high duty cycle), the plasma channel will expand, causing less energy density on the workpiece and decreasing material removal rate (Mohan et al., 2004). There is a specific duty cycle which results in minimum electrode wear. This implies that the pulse duration is high enough for the gas bubbles (in the gap) containing vaporized workpiece material to reach the surface of the electrode, protecting it against wear (Jameson, 2001).

The servo parameter refers to the speed specification the servo motor moves in order to keep the gap size constant. It can be observed in Fig. 3 that if the value of servo is too low, the drilling time and electrode wear will be high possibly due to short-circuits. As servo speed increases, drilling time and electrode wear will decrease. However, if the servo speed is too high (Fig. 3b), due to its interaction with peak current (set at level -1) the drilling time will be higher due to oscillations of the servo head.

Gap voltage had a greater effect on drilling time than electrode wear and hole size. Drilling performance was better for gap voltage set at level -1. Gap voltage is a parameter used to adjust the behaviour of the EDM servo (Amchem, 2000), setting the reference voltage the servo attempts to maintain. If the value is too high, the EDM slide will oscillate and drilling time will increase, but if the value is too low, the electrode will go into short-circuit (Amchem, 2000). Gap voltage also influences the size of the gap itself: a lower gap voltage will produce a narrower gap, which probably explains why drilling performance was best with the lowest gap voltage. With higher gap sizes, more of the spark energy may be lost, thereby adversely affecting the drilling performance. On the other hand, the flushing efficiency (which greatly affects the process performance) increases with gap size, which is particularly important with regard to deep holes. A previous study (Leão, 2003) showed that the drilling time was lower for higher values of gap voltage. The holes in question were double the length of those drilled in the present study.

Confirmation trials were carried out in order to check the accuracy of the models. The parameters used were those predicted for optimal conditions, shown in Fig. 3a. The average error produced by the models was approximately 10%. Figure 4 shows a comparison between the optimal values of electrode wear and drilling time obtained with water-based dielectric and deionised water. It can be seen that drilling time with the water-based dielectric (8.2 seconds) was slightly greater than that with deionised water (6.54 seconds). In contrast, relative electrode wear with the water-based dielectric (47%) was much lower than that with deionised water (92%). This is probably due to the fact that the salts added to the water-based dielectric altered the material removal mechanisms. Anodic dissolution (typical material removal mechanism in electrical chemical machining – ECM) of both workpiece and electrode may have occurred together with melting and vaporisation of the materials (typical material removal mechanism in EDM). This study suggests, therefore, that the drilling operation with the water-based dielectric is a combination of EDM and ECM, in which lower electrode wear (when compared with EDM) is observed.

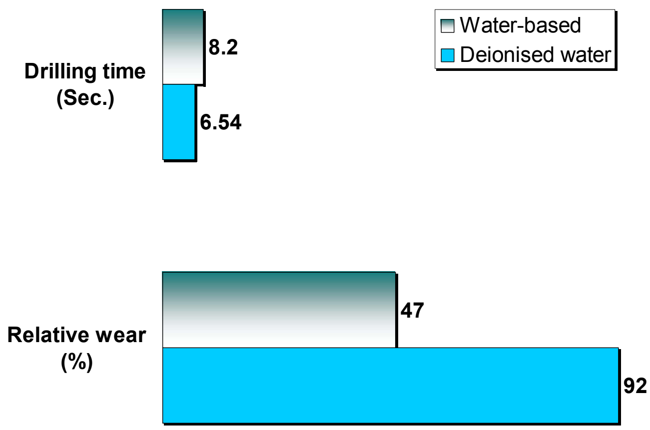
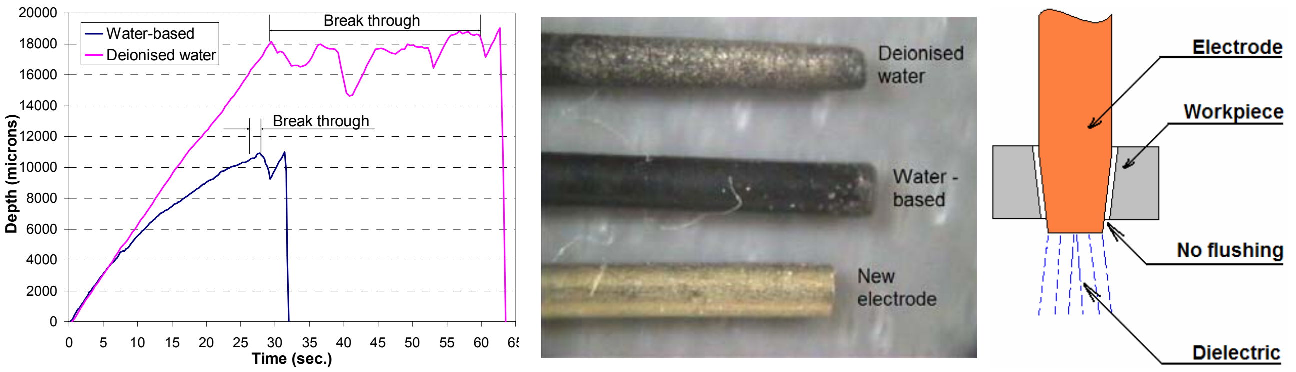


Figure 4. Optimal values of drilling time and electrode wear

One of the main characteristics of the EDM drilling process with deionised water and brass electrodes is the long breakthrough time and this study has shown that the type of dielectric has an important influence on the breakthrough time. It can be seen in Fig. 5a that the breakthrough time obtained with deionised water was much longer than that with the water-based dielectric. This can be attributed to the different types of electrode wear: the electrode assumed a distinctly tapered form when used with deionised water, whereas with the water-based dielectric the wear occurred only on the very top of the electrode (Fig. 5b). The tapering effect increased breakthrough time due to deficiencies in flushing (Fig. 5c), which caused significant oscillations of the electrode throughout the breakthrough phase.

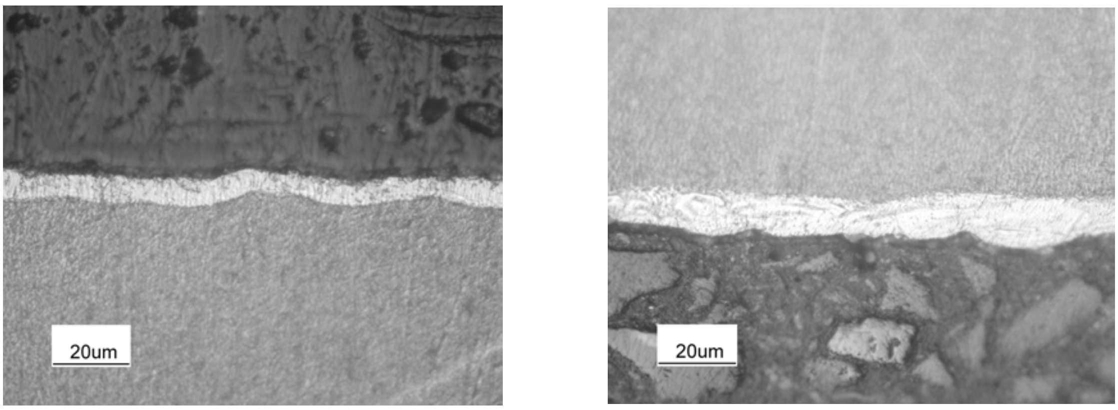
In addition to reducing the breakthrough time, another consequence of the type of wear accompanying the use of the water-based dielectric is that the process is more consistent: there are lower variations in time between each hole drilled. With deionised water, the process during the breakthrough phase is much more unpredictable. Moreover, electrodes which become tapered produce tapered holes with a constriction at the exit end. When EDM fast hole-drilling is used to produce holes in blades, it is not possible to ream the holes to a constant diameter by feeding the electrodes deeper because the excess electrode-length would in many cases provoke back-wall impingement, and as consequence damage the blade.



(a) (b) (c)

Figure 5. (a) Typical signature plots of drilling processes with deionised water and the water-based dielectric (b) Brass electrodes (0.45 mm) after being used with deionised water and water-based dielectric (c) Effect of electrode-tapering on flushing

The dielectric fluids used in the experiment differ in terms of chemical compositions, viscosity and thermal conductivity, and it is therefore expected that the formation of the recast layer will depend on the type of the dielectric employed. Figure 6 shows the recast layer obtained with the water-based dielectric (a) and deionised water (b) when drilling the workpieces using optimal EDM parameters. It can be seen that the recast layer resulting from the use of deionised water (average 13 μ) was thicker than that obtained with the water-based dielectric (average 8μ). If it were necessary when using deionised water to obtain a recast layer of the same size as that produced with the water-based dielectric, the energy employed - i.e. current and duty cycle - would need to be at a lower level, therefore increasing considerably the drilling time.



(a) (b)

Figure 6. Recast layer obtained with the water-based dielectric (a) and deionised water (b)

4. Conclusions

This study has been concerned with optimising EDM fast hole drilling of nickel-based workpieces through an evaluation of dielectric and electrode materials. Two dielectric fluids were used: deionised water, and a solution of water, alcohols and salts. Copper and brass were used as electrode materials. The best combination of dielectric and electrode material was found to be the water-based dielectric with brass electrodes, which produced reasonably good drilling rates and electrode wear 50% lower than that with brass and deionised water.

This study has also shown that the choice of dielectric fluid can have a very significant impact on the type of electrode wear. Whereas with deionised water the electrode assumed a tapered form, with the water-based dielectric the wear occurred only on the very top of the electrode. In the latter case there was a consequent reduction both in breakthrough time and in drilling-time variations.

The average recast layer of parts drilled with the water-based dielectric was 38% thinner than that of parts drilled with deionised water.

5. Acknowledgements

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