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Modelling of surface finish, electrode wear and material removal rate in electrical discharge machining of hard-to-machine alloys

A. Torres, I. Puertas*, C.J. Luis

Mechanical, Energetics and Materials Engineering Department, Public University of Navarre, Campus de Arrosadía, s/n, 31006 Pamplona, Spain

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ABSTRACT

Hard-to-machine alloys are commonly used for industrial applications in the aeronautical, nuclear and automotive sectors, where the materials must have excellent resistance to corrosion and oxidation, high temperature resistance and high mechanical strength. In this present study the influence of different parameters of the electrical discharge machining process on surface roughness, electrode wear and material removal rate have been studied. Regression techniques are employed to model arithmetic mean deviation Ra (μm), peak count Pc (1/cm), material removal rate MRR (mm^3/min) and electrode wear EW (%). All these parameters have been studied in terms of current intensity supplied by the generator of the electrical discharge machine I (A), pulse time t_i (μs), duty cycle η and open-circuit voltage U (V). This modelling allows us to obtain mathematical data and models to predict that the most influential factor in MRR and Ra is the current intensity and in the case of EW and Pc is the pulse time.
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1. Introduction

Hard-to-machine alloys are commonly used for industrial applications in the aeronautical, nuclear and automotive sectors, where the materials must have excellent resistance to corrosion and oxidation, high temperature resistance and high mechanical strength [1,2]. Nowadays, it is accepted that electrical discharge machining (EDM) is one of the non-conventional and most widespread manufacturing processes for manufacturing these parts, due to the possibility of getting parts, which from conventional machining, would be very expensive or even impossible to obtain [3]. Klocke et al. [4] performed an economical and technological comparison between different machining processes (milling, sinking-EDM, wire-EDM and electrochemical machining (ECM)) on two hard-to-machine materials. The results revealed that ECM is the most economical process for large batches of parts while EDM is best for small batches.

In this present study, an INCONEL® 718 Alloy (INCONEL is registered trademark of Special Metals Family of Companies) is studied during die-sinking electrical discharge machining. Due to its good mechanical properties and high resistance to oxidation and corrosion, even in extreme environments, this alloy is commonly used in industrial fields. However, due to its fracture toughness and work hardening behaviour, it is difficult to machine with traditional techniques [5]. Inconel 718 tends to increase its hardness under increasing temperature when cutting temperatures are below 650 °C. This effect causes earlier wear in the cutting tool [6]. Therefore, it is a suitable material to be machined by EDM.

In spite of the suitability of their properties and their wide application range in industry, there has been little research on the EDM of Inconel 718. The available literature includes studies focused on quantifying the influence of the simultaneous variation of some input parameters on pre-defined output parameters. Many of these authors use statistical methods based on design of experiments (DOE). Bharti et al. [1], for example, propose an orthogonal array L36 and two different shapes of cooper electrode in order to quantify the effect of some main EDM parameters on material removal rate, surface roughness and tool wear rate. In a similar study, Ghewade and Nipanikar [7], also based on the Taguchi method, used an orthogonal array L9 not only to analyze some input effects on the machining characteristics but also to predict the optimal choice for each EDM parameter. Their results confirm that current intensity is the most influential factor in the material removal rate, while for electrode wear it is pulse time. In Ref. [8], the parameters are optimized using multi-objective optimization technique of desirability approach. Moreover, fuzzy logic model (FLM) is proposed to optimize machining conditions and reduce costs. FLM shows itself capable of predicting the experimental results with an accuracy of 95%.

The energy density term has been used by some researchers in their studies to explain the EDM process. Thus, Yan et al. [9]

* Corresponding author.
E-mail addresses: inaki.puerta@unavarra.es (I. Puertas), cluis.perez@unavarra.es (C.J. Luis).

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List of symbols

DOE	design of experiments
EDM	electrical discharge machining
EW	electrode wear
I	current intensity
MRR	material removal rate
n	number of cycles
Pc	peak count
R^2	coefficient of multiple determination
Ra	arithmetic mean deviation
Rq	quadratic mean deviation
Rt	total height of roughness profile
Sm	mean spacing of profile irregularities
SR	surface roughness
t_i	pulse time
U	open-circuit voltage
η	duty cycle
ρ_e	energy density
$\Delta\Omega$	total volume of material removed
$\Delta\Omega_p$	volume of material removed from part
$\Delta\Omega_e$	volume of material removed from electrode

indicate that increasing the pulse duration reduces the energy density of the discharge spots by expanding the plasma channel, and consequently MRR decreases and EWR is reduced. Liu et al. [10] study the feasibility of manufacturing micro-holes in the high nickel alloy using micro-EDM. They find that the energy density increases as the discharge current increases. Zhang et al. [11] propose a method of determining the energy distribution and plasma diameter of EDM. In their energy distribution model, they use an equation to calculate the ratio of energy carried off by the debris according to the thermal property of the part material and the volume of debris which was experimentally determined by a metallographic method. On the other hand, Zahiruddin and Kunieda [12] compare micro and macro EDM machining in terms of energy and removal efficiencies.

In EDM machining, the electrodes used are generally made of graphite, copper or copper alloys and tungsten alloys, among many others, because of their electrical and thermal conductivity properties. Many authors have focused on the working tool as an object of study. Mohri et al. [13] evaluate the whole process of electrode wear over time and they consider two stages: the transition state at the beginning of machining, at which stage most of the wear on the edges of the electrode occurs, and the stationary state, a stage in which the deterioration of the electrode is affected by the materials that compound the part. In EDM, machining accuracy is limited by tool wear, which is a consequence of the sparks generated in the process that remove both part and tool electrode [14]. Sohani et al. [15] focus their study on the effect of tool shapes in order to observe the effects on material removal rate (MRR) and tool wear rate (TWR). Their results show that circular-shaped electrode allows greater MRR and lower TWR. However, Pellicer et al. [16] believe that the electrodes with square and rectangular shapes provide greater dimensional accuracy. On the other hand, the triangular shape is inefficient because the electrode edges are worn faster than the flat section. Marafona and Wykes [17] develop a study employing copper–tungsten electrodes. They propose a new method to improve the EDM performance by using the effect of carbon that has migrated from the dielectric to Cu–W electrodes.

Rapid advances in technology and the trend towards miniaturization of products, demand even smaller components with reduced tolerances. Manikandan and Venkatesan [18] optimize the machining parameters for micro-EDM. They point out that the main differences with conventional EDM machining are the size of the tool used, the power supply of discharge energy and the resolution of the *X*-, *Y*- and *Z*-axes movement. They also analyze the influence of the electrode material on the generation of micro holes and try to optimize the influence variables.

All these previous above-mentioned studies confirm the importance of a proper selection of the design parameters in EDM process. In the case of this present study, these are: the current intensity supplied by the generator (I), the pulse time (t_i), the duty cycle (η) and the open-circuit voltage (U). The choice of these parameters will determine the characteristics of material removal rate (MRR), electrode wear (EW) and surface roughness. To carry out the experiments, design of experiments (DOE) techniques have been used, specifically, the factorial design "j^k", where "$k = 4$" is the number of factors and "$j = 2$" is the number of considered levels. This modelling allows us to obtain mathematical data and models to predict that the most influential factor in MRR and Ra is the current intensity and in the case of EW and Pc it is the pulse time.

2. Set-up of the experimentation

This section describes the EDM equipment used for conducting the experiments, as well as the materials used, and it also shows the planning of the experiments carried out. To complete all the experiments, a die-sinking EDM machine ONA Datic type D-2030-S, with a jet flushing system at a pressure of 30 kPa. The dielectric fluid chosen was mineral oil with a flash point of 82 °C. Fig. 1 shows a picture of the equipment used.

An electrolytic copper electrode with rectangular section (12 mm × 8 mm) was used, which was milled before every experiment. As was previously mentioned, the material used in this study

Fig. 1. EDM machine ONA Datic D-2030-S.

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