CIRP Journal of Manufacturing Science and Technology 7 (2014) 11–19

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Experimental optimization of micro-electrical discharge drilling process from the perspective of inner surface enhancement measured by shear-force microscopy

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ARTICLE INFO

Article history:
Available online 16 November 2013

Keywords:
Micro-EDM
Surface quality
Drilling time
Shear force microscopy

ABSTRACT

The micro-electrical discharge drilling process was studied by means of experiments with the twofold objective of increasing the surface quality while minimizing the drilling time. To characterize the inner surface of micro-drilled holes obtained by EDM a specifically conceived scanning probe microscopy technique was used. Discharge current and pulse duration were used as input parameters with the aim of quantifying the effects of applied spark energies on surface characteristics. 150 μm diameter holes were drilled using combinations of process parameters defining spark energies within the range of 3.25 μJ and 15 μJ. Results showed that the surface texture can be characterized by (i) maximum peak-to-valley distance and (ii) periodicity whose dimensions were related to the adopted spark energy. Standard R_q derived from the measured cylindrical surfaces was found to vary between 240 nm and 380 nm. Experiments testified that removal rates higher respect to those commonly used in industry can be adopted when followed by a lateral erosion phase at low energy which reduces R_q of 32% without changing the drilling time.

1. Introduction

In today's manufacturing scenario, electrical discharge machining (EDM) contributes a prime share in the manufacture of complex-shaped dies, molds, and critical parts used in automobile, aerospace, and surgical components with high precision. Micro-EDM (μ-EDM) is capable of machining not only micro-holes and micro-shafts as small as 5 μm in diameter but also complex three-dimensional (3D) micro-cavities as stated by Rajurkar and Yu [1]. Being the discharge duration in the micro- to nano-second range, μ-EDM makes use of negative polarity since fine removal of the workpiece is obtained by electron impact while keeping tool wear to the minimum value. Masuzawa et al. [2] demonstrated the feasibility of micro-parts (pins, nozzles) by μ-EDM while micro-cavities were obtained by Yu et al. [3]. Moreover, μ-EDM is up to now the main process to produce micro-holes in diesel and fuel injection nozzles, Li et al. [4].

As a result, μ-EDM represents a key-point in automotive industry since the reduction of particle formation in fuel engines which should lead to the upcoming EU6 limits is strictly linked to the capability of EDM drilled nozzles to increase atomization of the fuel jet as depicted by Kufferath et al. [5].

The fuel forced through the injection nozzles under high pressure forms a liquid core which is then broken-up and atomized into a spray. The diameter and depth of nozzles (150–200 μm and 250–350 μm respectively) are adjusted to give the desired flow rate, speed and pressure. A proper modulation of μ-EDM parameters determines the quality of the inner surface which should desirably show the lowest roughness as possible to exploit the best performance in terms of jet breaking and atomization of the fuel spray.

Controlling surface finishing by a proper modulation of process parameters then represents a key factor in μ-EDM drilling process so that many studies are devoted to determine performance parameters in electro erosion processing. Jeswani [6] identified the effecting parameters of surface roughness while Uhlmann and Roehner [7] investigated parameters for tool wear factors. Tsai and Wang [8] developed a semi empirical model in which parameters affecting the surface roughness were identified to be discharge duration, maximum current, polarity, input power, material density, conductivity of the material, specific heat capacity, heat

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1755-5817/$ – see front matter © 2013 CIRP.
http://dx.doi.org/10.1016/j.cirpj.2013.10.002

conductivity, melting point, and boiling point of the material. Rebelo et al. [9] investigated parameters for material removal rate and surface roughness when processing of hard copper-berilium alloys. Halkac and Erden [10] performed an experimental study and identified relations between surface roughness and pulse duration.

In order to reduce the surface roughness of electro-eroded surfaces many researchers have recently proposed a hybrid processes (EDM/ECM) which makes use of a final electrochemical etching phase in de-ionized water, as in Nguyen et al. [11]. This technique allows for surface roughness between 50 and 100 nm but has the drawback of rounding the hole edges and decreasing its capability to atomize the fuel jet.

During machining with EDM, the discharge energy produces very high temperatures at the point of spark on the surface of the specimen removing the material by melting and vaporization. The top surface of the workpiece re-solidifies and subsequently cools extremely quickly. Lin et al. [12] discovered the presence of micro-cracks and high tensile residual stresses on the EDM specimen surface caused by the high temperature gradient. Lee and Tai [13] measured the total length of the cracks in the Scanning Electron Microscopy (SEM) photograph and defined a surface crack density to evaluate the severity of cracking. Ramasawmy and Blunt [14] studied the 3D surface topography of the EDM specimen using 3D tip profilometry with a diamond tip. Guu [15] analyzed the three-dimensional images of AISI D2 tool steel machined by the EDM process by means of the Atomic Force Microscopy (AFM) technique. The method used by Peiner et al. [16] to measure surface roughness by inserting a slender tactile sensor inside micro-holes for diesel injection is critical due to the high risk of collision and does not work properly for shorter thicknesses. Quantitative measurements of complete surface profiles along with the evolution of surface texture during drilling over the entire thickness of the hole are rarely available in the literature since they require sectioning the nozzle along its axis and the use of an accurate measuring method able to acquire data from a curved surface confined on a diameter of 100–150 μm.

1.1. Research objectives

Even if μ-EDM is well established in the field of manufacturing injection nozzles, the need for high flow stability and atomization of the jet imposes enhancements in the quality of the machined surfaces along with a reasonable processing time. Concerning holes characterization, the SEM technique allows a rapid survey of large sample areas, but it does not reveal the depth of defects and the 3D surface textures of the electro-eroded material. First objective of the research will be represented by finding out a reliable and robust measuring technique to acquire 3D topography of the drilled surfaces. This characterization will therefore yield a better understanding of the size, shape and distribution of peaks and valleys along with their dependence on the adopted process parameters. Based on the correlation between surface texture and spark energy obtained by the aforementioned experiments, in a final step of the research a drilling strategy will be proposed with the aim of increasing the surface quality keeping processing time at values comparable to those already used in automotive industries.

2. Materials and experimental procedure

2.1. Material

Martensitic AISI440C (pre-hardened and tempered) stainless steel is selected as workpiece material (300 μm thickness) being this material frequently used to produce fuel injection nozzles. Matrices of 150 μm diameter holes are drilled by μ-EDM machine making use of a SARIX SX-200 (Switzerland) pulse generator. Table 1 lists the chemical composition (in weight percent) of the AISI 440C stainless steel.

2.2. Experimental setup and sample preparation

The experimental set-up is shown in Fig. 1. Tungsten carbide electrode of 80 μm is used, while de-ionized water is used as dielectric fluid. Before the hole is drilled an operation of tool flattening, called dressing, is performed. During the dressing step, positive polarity (electrode positive and work piece negative) is used with the aim of removing the electrode tip worn during the previous drilling operation. Thus the lateral wear of the electrode during erosion is compensated and for each hole, machining will begin with the same conditions. Then the polarity is changed, the tool is charged as cathode and work piece as anode for the erosion process. To guarantee good quality at hole exit, the electrode penetrates beyond the end of the hole. Both the dressing and drilling occurs rotating the tool at 800 rpm. The tool is displaced from the axis of rotation of a quantity known as run-out (20 μm). It allows better flushing of the dielectric and to drill hole diameters larger than the electrode diameter.

Generally, in order to satisfy the condition of micromachining, small material unit removal and high precision equipment are required as presented by Masuzawa [17]. In the case of μ-EDM, a small unit removal condition commonly means the discharge energy, W_e [J] induced in the sparking gap during one pulse must be as low as possible, by which:

$$W_e = \int_0^{t_e} u_e(t) i_e(t) dt \quad (1)$$

Being t_e is the pulse duration [s], u_e is the discharge voltage over the sparking gap [V] and i_e is the discharge current [A].

During a discharge, gap voltage u_e is uncontrollable depending on the electrode materials and connecting interfaces. To maintain an efficient discharge, i_e has to be sufficiently large. As a consequence to obtain typically hundreds or tens of nano-Joule (nJ) for W_e, t_e has to be reduced significantly to ns range. In addition, to receive small discharge energies for micro-drilling (μ-drilling) and high surface quality, generators based on capacities, known as relaxation generators, are used. The principle setup of a relaxation generator is a direct current source in combination with RC circuits. The discharge duration, t_e and discharge current, i_e depend on the value of the capacity and cannot be controlled independently. As the relaxation generator is used, it is assumed that peak current and pulse duration are the principal factors of pulse energy which influence the surface morphology and roughness.

Table 1
Chemical compositions of AISI 440C stainless steel.

	Element							
	C	Cr	Mn	S	Si	Mo	Se	Fe
Composition (in wt.%)	0.95–1.2	17.2	1.00	0.015	1.00	0.75	0.20	Remainder