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ORIGINAL ARTICLE

Proposing a new performance index to identify the effect of spark energy and pulse frequency simultaneously to achieve high machining performance in WEDM

Ibrahem Maher[1] · **Ahmed A. D. Sarhan**[2,3]

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Abstract Wire electrical discharge machining (WEDM) is a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks). WEDM demands high cutting rate and high quality to improve machining performance for manufacturing hard materials. The machining performance of computer-controlled WEDM is directly dependent on spark energy and pulse frequency parameters including discharge voltage, peak current, pulse duration, and charging time. In this paper, a new performance index to measure the effects of spark energy and pulse frequency on machining performance is proposed. Moreover, the effects of electric process parameters on performance measures including cutting speed, surface roughness, and white layer thickness are introduced.

Keywords WEDM-CCM · Spark energy · Pulse frequency · Duty factor · Performance index

1 Introduction

Computer numeric controlled (CNC) wire electrical discharge machining (WEDM) is among the more widely known and applied nontraditional machining processes in industry today. In this procedure, improvements to the process mechanism and control have rapidly been taking place. CNC-WEDM can machine harder, electrically conductive (higher strength, corrosive and wear resistant, and difficult-to-machine) materials like tool steel, titanium, metal matrix composites (MMCs), and cemented carbides [1]. Besides machining electrically conductive workpieces, some WEDM work has also been reported on insulating ceramics and non-conductive materials [2, 3]. With WEDM, it is also possible to machine complicated shapes that cannot otherwise be achieved using traditional machining processes, such as turning, milling, and grinding [4, 5].

Productivity and surface quality are the most important performance parameters in CNC-WEDM. In addition, productivity controls the overall cost-effectiveness of the machining process, while quality impacts the functional value of products. Productivity is expressed as cutting speed, while surface quality is expressed through surface roughness and white layer thickness. The importance of these performance parameters is relative and mainly depends on spark energy and pulse frequency parameters [6]. Practically, productivity increases with increasing spark energy (voltage, current, and pulse duration). On the other hand, surface roughness and white layer thickness would increase with increasing discharge voltage, current, and pulse width [7, 8].

Several efforts have been made to find the ideal machining conditions to enhance productivity and achieve high product quality by increasing the cutting rate and decreasing the surface roughness [9, 10]. It has been revealed that cutting speed increases as pulse width increases, and surface roughness decreases as the time between the two pulses decreases. El-Hofy [11] and Levy and Maggi [12] showed that during WEDM, a thin heat-affected zone layer of 1 μm at 5-μJ spark energy to 25 μm at high spark energy is formed. To attain low surface roughness and small white layer thickness, low electrical discharge parameters are required. However, such parameters lower the cutting rate in

✉ Ibrahem Maher
ibrahemmaher@eng.kfs.edu.eg

✉ Ahmed A. D. Sarhan
ah_sarhan@yahoo.com

1 Department of Mechanical Engineering, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh 33516, Egypt

2 Centre of Advanced Manufacturing and Material Processing, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia

3 Department of Mechanical Engineering, Faculty of Engineering, Assiut University, Assiut 71516, Egypt

WEDM. This indicates that a high cutting rate with minimum surface defects is difficult to attain from a single-parameter setting. To achieve efficient machining, mathematical modeling between WEDM parameters and performance characteristics should be available to manufacturers. Two kinds of approaches, theoretical and empirical, are commonly used for WEDM modeling [13]. Owing to the simplified and unavoidable assumptions, the theoretical models yield large errors between the predicted and experimental results. On the other hand, empirical models are limited to specific experimental conditions.

Many efforts to improve process performance have been stated in literature regarding electrothermal concepts. Among these efforts, theoretical [14–16], numerical [17, 18], or empirical methods [19, 20] with different performance parameters and guesstimate results are used to improve the machining process. As previously mentioned, WEDM efficiency mostly depends on the generation and distribution of spark energy within the discharge zone [21, 22]. In practice, efficient WEDM control implies variation of spark energy parameters and pulse frequency parameters, which can be controlled by peak current, pulse-on time, and pulse-off time. However, it is very difficult to study the effect of spark energy and pulse frequency individually on machining performance. This suggests that a high cutting rate with minimum surface defects is difficult to attain from a single-parameter setting. For this reason, in this research work, we proposed a new, simple performance index to study the effect of spark energy in conjunction with pulse frequency at different duty factors on machining characteristics to achieve high machining performance in CNC-WEDM. This can be achieved by weighing the spark energy using the duty factor.

2 Analysis of EDM pulse generator

2.1 Cycle energy

CNC wire electrical discharge machining (CNC-WEDM), sometimes informally also referred to as spark machining, spark eroding, burning, wire burning, or wire erosion, is a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks), while the NC table can make X-Y movements (Fig. 1a, b). Material is removed from the workpiece by a series of rapidly repeating current discharges between the wire electrode and the workpiece, separated by a dielectric liquid, and is subject to electric voltage (Fig. 2a, b) [23].

Figure 3 illustrates the WEDM machine components and a detailed description of the pulse generator used in WEDM. In a pulse generator, the capacitor is charged from a DC source (V_o). As long as the voltage in the capacitor does not reach the breakdown voltage of the dielectric medium under machining conditions (T_{off}), the capacitor (C) continues to charge. Once breakdown voltage (V_d) is reached, the capacitor starts discharging and a spark is established between the tool and workpiece, leading to machining. Such discharge continues as long as the spark can be sustained. Once the voltage becomes too low (V_d^*) to sustain the spark, capacitor charging would continue, as shown in Fig. 4 [11].

During an electrical discharge, the voltage and current impulses vary with time. Electric impulses are determined with the following values: discharge voltage (V_d), pulse duration (T_{on}), pulse-off time (T_{off}), pulse cycle time (T_c), discharge current (IP), pulse frequency (F), and duty factor (DF). The most important WEDM parameters are spark energy and duty factor. The spark energy determines the chip size, and it is the value of electrical energy per one spark, which can be expressed by Eq. (1).

$$E_s = V_d \times \mathrm{IP} \times T_{on} \quad (1)$$

According to Eq. (1), spark energy is influenced by the discharge voltage, discharge current, and pulse duration. The discharge voltage depends on the paired wire electrode and workpiece materials [24]. The discharge current and pulse duration control the spark intensity (Fig. 5a, b). The spark energy determines the spark size and, hence, the chip size. High spark intensity leads to long sparks, thus increasing the cutting speed and chip size but decreasing the surface finish as shown in Fig. 5a [25].

The other most important parameter associated with electrical parameters and that significantly influences WEDM performance is pulse frequency (F) or duty factor (DF). The duty factor determines the weight and number of pulses (Eqs. 2 and 3). The duty factor is a percentage of the ratio of pulse duration to total cycle time. In machines with duty factor settings, the pulse interval is set indirectly by setting the pulse duration and duty factor. Pulse frequency is used to set the pulse interval on some machines and to determine the number of chips per second.

$$F = 1/(T_{on} + T_{off}) \quad (2)$$

$$\mathrm{DF} = T_{on}/(T_{on} + T_{off}) = T_{on} \times F \quad (3)$$

Selecting a spark microsecond cycle time depends on workpiece thickness, flushing condition, and required surface quality. High pulse frequency leads to short sparks and, hence, decreased chip size (Fig. 5b). This condition is consequently recommended to improve surface finish. Low pulse frequency leads to long sparks and, hence, increased chip size (Fig. 5a), so it is recommended for increasing cutting speed [26].

2.2 Cutting speed

The molten crater can be assumed to have hemispherical shape with a radius r that forms due to a single spark