Precision Engineering 51 (2018) 223–231

Contents lists available at ScienceDirect

Precision Engineering

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

Improvement of EDM performance in high-aspect ratio slot machining using multi-holed electrodes

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ARTICLE INFO

Keywords:
EDM
High-aspect ratio slots
Debris
Flushing
Electrode

ABSTRACT

Machining of high-aspect ratio slots is a common operation in industry, particularly in the mold and die and aerospace sectors. Electrical Discharge Machining (EDM) is a competitive technology for this operation, since it does not depend on material hardness and can fulfill strict geometrical requirements. However, due to debris accumulation in the narrow gap, the machining depth for stable machining is limited. The present work includes original findings about the influence of machined holes on flushing efficiency. Different configurations for this basic approach have been proposed and their performance discussed in terms of machining time and electrode wear. A remarkable and original finding is that continuous pockets or open holes are much better than the separated or closed holes. Furthermore, the paper shows that a sudden change in material removal rate occurs when the vacant spaces of the holes are sunk in the slot. A deeper insight into the EDM phenomena has been achieved through a study of discharge parameters, by analyzing discharge frequency, duty factor, discharge delay time and discharge off-time. In this study, using the proposed electrode reduced the process time by as much as 65% in the machining of 10 mm depth slots. Moreover, machining stability can be guaranteed if the flushing pockets machined on the electrode go through the whole depth of the machine.

1. Introduction

Electrical discharge machining (EDM) has become an indispensable technology in the manufacture of high-aspect ratio slots. One of the great advantages of this technology in comparison with conventional manufacturing processes is that in EDM there is no contact between the electrode and work piece, which avoids mechanical stresses, chatter, and vibration problems during machining [1]. Moreover, material hardness is not a limitation, which has implied benefits in comparison with the conventional machining method, particularly in the machining of high-aspect ratio slots in difficult-to-machine materials.

Manufacturing of deep slots is a common operation in industry, with special focus on two sectors: mold and die industry and aerospace industry. In the former, for instance, narrow slots are machined in the mold in order to provide thin strengthening ribs. In the latter, due to the working requirements of turbine engines, high temperature resistant materials are used, such as Titanium-base or Nickel-base alloys. As an example, when it comes to machining the slots used to join the NGVs (*Nozzle Guided Vanes*), EDM is currently regarded as the most competitive solution [2].

However, the EDM machining of high-depth slots is not an easy task. The main drawback is that there is a high concentration of discharges in the bottom section of the electrode, and that as the depth increases debris evacuation becomes difficult or even impossible. As a consequence, the stability of the process becomes affected and the material removal rate decreases [3].

Recent studies can be found in the scientific literature concerning the optimization of the EDM process of high-aspect ratio slots. Much of this work has focused on aerospace applications, mainly due to the high competitiveness of this market, in which the key objective is to reduce the machining time or the total production time.

A number of researchers have explored the effectiveness of choosing different EDM process parameters and electrode material. For instance, Uhlmann and Domingos [4] reduced the machining time of 11 mm depth slots with an electrode of 89.50 mm^2 and the discharge area from 48 min to 21.9 min by adjusting process parameters. Ayesta et al. [5] analyzed the influence of process parameters with a discharge area of 40 mm^2 and depth of 6.5 mm. They concluded that shorter machining times were obtained by a combination of high discharge current, long pulse duration, and low servo voltage. In terms of electrode material,

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http://dx.doi.org/10.1016/j.precisioneng.2017.08.014
Received 24 March 2017; Received in revised form 2 June 2017; Accepted 16 August 2017
Available online 26 August 2017
0141-6359/

Aas [6] compared the machining outputs of two types of graphite qualities. From these experiments, it was concluded that if productivity is a priority, a larger particle grain size is more appropriate.

However, as reported by Klocke et al. [7], due to debris particle concentration in the narrow gap, gap temperature, and ionization conditions of the dielectric fluid, stability of the process cannot be guaranteed. During the early stage of machining, debris evacuation is efficient and as a consequence machining is stable. Nevertheless, when the depth increases, debris particles become stuck in the narrow gap and the process becomes unstable, resulting in a dramatic decrease in the rate at which material can be removed. This phenomenon was also reported by Obaciu et al. [8] when comparing the machining performance of two different work piece materials. They observed that as the erosion depth increases, the material removal rate decreases and the number or short circuits increases. Therefore, the main cause of the increase in process time with the machine depth lies in the accumulation of debris within the narrow gap, which compromises the stability of the process. As a consequence, it is expected that an enhancement of flushing conditions will contribute to the optimization of the process.

Various strategies have been developed in order to improve debris removal from the working gap. Uhlmann and Domingos developed a vibration-assisted EDM-machining technology and they observed improvements in material removal as well as in electrode wear. This technology was validated by machining a 11 mm depth slot; with the optimization of frequency and amplitude, an increase of 11% of the material removal rate was achieved [9]. However, they observed that once the erosion depth exceeded 8 mm the machining performance decreased [10].

A further technology that brings improvement in terms of flushing conditions is the use of jump motion by linear motor equipped machines. Cetin et al. [11] studied the effect of jump motion when using a 10 mm diameter cylindrical electrode. They observed that the electrode jump height is the most relevant factor in machining speed. However, as reported by Liao et al. [12], the work presented in [11] does not take into account the fact that the effectiveness of debris evacuations is related to the geometry. Debris evacuation becomes more difficult when working with thin electrodes than with square section electrodes.

In practice, both vibration-assisted EDM-machining and the use of high-acceleration linear motors require the use of extra equipment, which is not available to many users.

The idea developed in the present research work emerges from the similarities of the problem of EDM of high-aspect ratio slots with a recent application of EDM technology for SiC slicing using foil electrode, which has been described in [13]. They found that if the slicing was conducted by feeding the thin foil electrode in Z direction, the cutting speed was improved by 23% when using an electrode with holes. The improved machining performance was attributed to the chip pocketing effect of holes.

The most important and original findings of the present work are related to the geometry and the position of the holes. A remarkable and original finding is that continuous pockets or open holes are much better than the separated or closed holes. Furthermore, the paper shows that a sudden change in material removal rate occurs when the vacant spaces of the holes are sunk in the slot. In Section 2 the experimental set-up and the test methodology used for obtaining the optimum electrode design is described. In Section 3 a discussion of the results is presented in terms of machining time and electrode wear. A deeper insight into the performance is addressed in Section 4 through a study of discharge parameters, in which discharge frequency, duty factor, discharge delay time, and discharge off-time have been analyzed. A reduced process time as high as 65% in the machining of 10 mm depth slots has been achieved by using the proposed electrode. The results show that machining stability can be guaranteed if the flushing pockets machined on the electrode go through the entire depth of the machine.

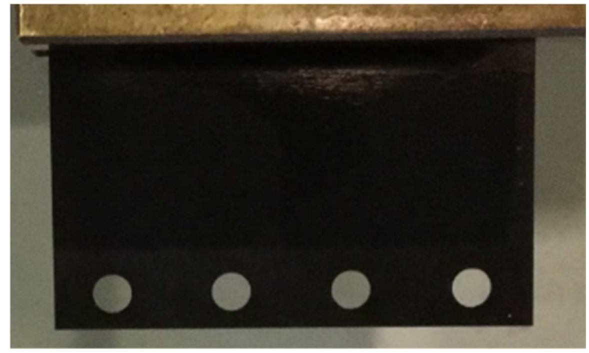

Fig. 1. Specially designed graphite electrode for slot machining.

2. Experimental set-up and test methodology

The objective of the experiments was to assess the improvement in performance, if any, of the EDM process of high-aspect ratio slots when a specially designed electrode is used. The new electrode has a number of holes in its lateral faces that are expected to contribute to effective debris evacuation during the process.

The experiments were carried out under industrial conditions on an ONA CS300 sinking EDM machine. The generator of the machine tool used in the experiments is an iso-energetic generator. This means that during the machining process the generator attempts to maintain discharge current (I) and pulse on time (t_{on}) at constant values. Moreover, in order to avoid inefficient discharges, such as arc and short-circuits, the pulse generator controls the t_{off} value.

The work piece material was F114 structural steel. In this work, POCO EDM3 electrodes were prepared with dimensions of 0.8 mm in thickness and a length of 50 mm. As stated previously, flushing holes were machined on the lateral faces of the electrodes. Fig. 1 shows an example of such an electrode.

Since the objective was to test the efficiency of the new proposal, the conditions of the EDM process were not manipulated during this study. Instead, they were taken from a previous research study [5] in which optimization of process variables for the EDM machining of high-aspect ratio slots was addressed by using Design of Experiments techniques. Therefore, the process conditions have been taken from the above cited reference and they are shown in Table 1. Jump motion has not been used during the experiments.

With the objective of enhancing the flushing condition of the narrow gap, three effects were studied: the effect of flushing holes diameters, positioning of the flushing holes, and geometry of the flushing cavity.

With the aim of studying the repeatability of the process and given that in the industry the same electrode is used for machining a set of slots, in the present work 5 slots were machined for each experimental condition. A detailed explanation of the experimental method for analyzing each effect is presented in the following sections.

2.1. Influence of hole diameter

In order to study the impact of the diameter of the flushing holes on

Table 1
Machining and experimental conditions.

Working fluid	EDM oil
Polarity	+
Open voltage	120 [V]
Discharge current	48 [A]
Discharge duration	89 [µs]
Preset off-time	179 [µs]
Servo voltage	57 [V]