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Experimental investigation of the process behaviour in Mechano-Electrochemical Milling

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ABSTRACT

The increasing demand for high-performance materials, in for example aerospace and biomedical industries, calls for more efficient and capable technologies. This paper describes a new technology, namely Mechano-Electrochemical Milling (MECM), which combines electrochemical machining (ECM) with a mechanical cutting process. The process behaviour has been investigated experimentally based on the machining of two Titanium alloys, Titanium grade 2 and Titanium grade 5. The material removal mechanism was investigated through analysis of the machined surface and removed material. Besides the slightly higher material removal rate in MECM compared to ECM, the MECM process results in more stable process conditions.

1. Introduction

The efficient machining of high performance materials used for example in aerospace and biomedical applications asks for dedicated machining methods. Electro Chemical Machining (ECM) is a common applied machining process for the machining of for example features (pockets, holes, . . .) in Ti-alloys. However, during the ECM process, insulating passivation layers are created on top of the processes surface, burdening the ECM process [1]. In order to cope with these problems, the authors propose a new process, called Mechano-Electrochemical Milling (MECM) [2]. According to Ref. [3], this novel hybrid process combines the principles of electrochemical machining (ECM) and conventional milling in an attempt to benefit from the strengths and minimize the weaknesses of both technologies. The underlying idea of the new MECM technique is to assist ECM by adding a rotating cutting edge. The cutting edge aims to remove the brittle top layer created during the ECM process and not the base material itself. In this way, the complexity of the mechanical machining of the base material (Titanium) should be avoided, while the ECM process might still benefit from the presence of the cutting edge.

There have been similar hybrid processes developed in the past. A typical example is the electrochemical grinding (ECG) process, in which the abrasive grains mechanically remove the oxide layer produced by the electrochemical process [4]. In the material removal mechanism, the electrochemical component is often responsible for 90 to 95% of the total material removal as the mechanical cutting component should only remove the oxide layer on top of the surface [5]. This results in a higher material removal rate (MRR) and a lower tool wear compared to conventional grinding. These benefits could result in significant advantages for the new MECM process compared to pure ECM.

For the purpose of this experimental investigation, a prototype set-up has been built at KU Leuven [2] (Fig. 1). The machining platform consists of three main subsystems to support the following process functionalities: the tool movement (3-axis system), electrical energy and electrolyte flow. A full control of the setup is realized in a LabView® environment. Feed movements can be programmed in a speed range from 0 mm/min to 300 mm/min. A spindle rotation (programmed from 0 to 1000 rpm) is required for the mechanical cutting component in MECM. A controllable power supply allows to control the amplitude (0 to 100 A / 0 to 60 V), frequency (0 . . . 600 Hz range) and shape of the current–voltage profile. The electrolyte, which can be flushed along or through the MECM tool, is being filtered and cooled continuously during machining.

A unique tool concept was developed allowing ECM as well as mechanical cutting (see tool 1, Fig. 2(a)). The mechanical cutting is enabled by mounting a non-conductive cutting insert at the tool end. Based on an initial series of experiments [2], an increase in material

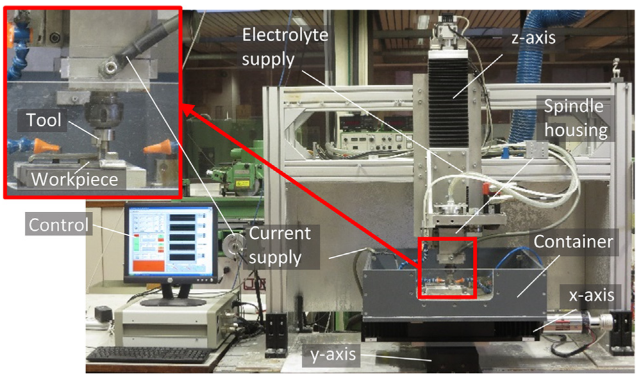

Fig. 1. The Mechano-Electrochemical Milling set-up.

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removal with MECM compared to ECM has been noticed. However, the process seemed to be suboptimal as the tool machined too much of the base material and the machining of slots resulted in hill effects (meaning that the slot is deeper at the side of the tool).

This research aims at the development of a better tool design as well as a more detailed investigation (material removal mechanism, material removal rate, surface quality, . . .) of the MECM process. The process behaviour has been investigated experimentally based on the machining of two Titanium alloys, Titanium grade 2 and Titanium grade 5. In this investigation, it is aimed to solve a few research issues, such as the influence of both, the ECM and the mechanical machining component, on the material removal process, and whether the top layer influenced by the ECM process will be fully removed under the simultaneous effect of both pure ECM and mechanical removal actions.

This could have implications for the efficiency of the ECM process as the milling component in MECM constantly removes the top (passivated) layer and thus averts its negative influence on the ECM process. On the other hand, the ECM treatment of the remaining surface after mechanical machining might have a positive influence on the roughness of this surface.

Section 2 discusses the design and development of a new tool configuration for MECM, complemented by a description of the experimental set-up. This is then followed in section 3 by a process investigation (material removal mechanism, material removal rate, surface quality, . . .) of single track machining. Section 4 discusses the machining of deeper slots by applying the process in a layer-by-layer mode.

2. Tool development for MECM and experimental set-up

Fig. 2(b) shows the new developed tool design. Base material for the tool is stainless steel (316L). A first improvement, compared to tool 1, is the reduction of the tool diameter which makes an average increase in current density (+78%) for the same total current possible. Due to the tool diameter reduction, the commercially used tool inserts (Si_3N_4) has been further ground to its final (smaller) shape (rake angle: 0°; nose radius: 1,2 mm; chamfer angle: 20°). In addition, a nitrile layer was applied on the sides of the tool, in order to minimise current losses via tool sides. The latter is especially important during a layer wise machining to improve the shape of the machined slots. The cross section shape of the new tool (see Fig. 2), has been changed to reduce the hill effect. This hill effect is also described in Ref. [6] and is a result of the unequal distribution of electrical current along the cross section of a slot. Ideally, the tool should have a cross section shape as depicted in the middle of Fig. 2. This (rotating) profile gives an even distribution of the electrons over the machined surface. Due to the practical impossibility to produce such an electrode and the necessity of a flushing hole inside the tool, this theoretical profile was replaced by the profile depicted on Fig. 2(b).

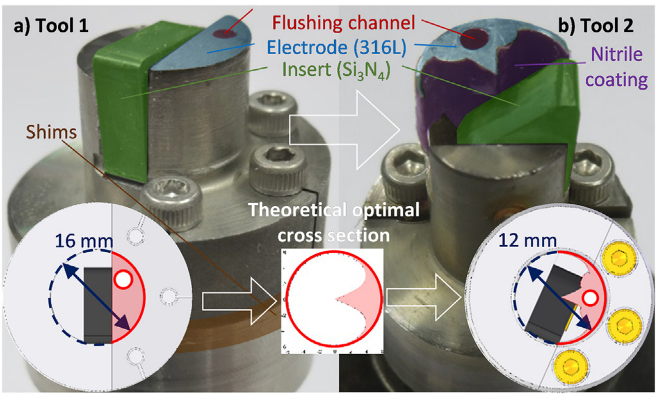

Fig. 2. Tool development – (a) Tool 1 used in Ref. [2], (b) Tool 2 – newly developed tool with increased active area.

Fig. 3 depicts the cross section profiles (measured with a Mitutoyo formtracer CS-3200) in the middle of two slots machined by pure ECM with tool 1 and 2. Due to the use of different tool configurations (difference in diameter and active cross section), different parameter settings had to be selected. The slot machined with tool 2 is smaller in width, (smaller diameter), but does not show the hill effect. Reasons for the profile asymmetry are not fully clear, but could be related to a difference in flushing conditions.

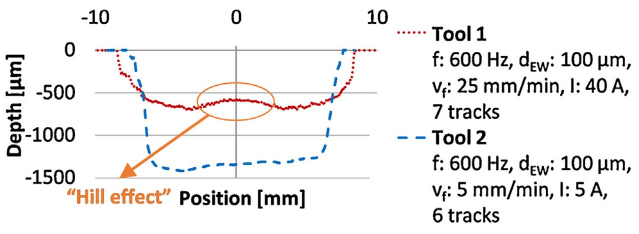

Fig. 3. Cross section profiles of ECM slots with tool 1 & 2.

A series of experiments have been performed in this investigation. In each experiment, one or more tracks (length: 35 mm) were machined on top of each other on ground samples (Fig. 4). This figure also shows an overview of the adjustable distances between electrode and workpiece (d_{EW}) and between the cutting edge and workpiece (d_{CW}). When the cutting edge is located above the electrode surface, the tool is in pure ECM mode.

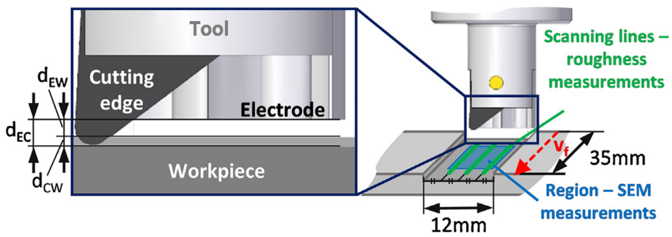

Fig. 4. Tool set-up and related process parameters.

The experimental investigation (Sections 3 and 4) is based on a change of the electrochemical working gap values (d_{EW}: 100 µm; 200 µm) and the spindle rotation (50 rpm, 1000 rpm). The effect of the spindle rotation can be twofold. The presence of a cutting edge can have an influence on the surface characteristics and material removal rate (MRR) for MECM, and in addition, it may influence the flushing behaviour in MECM as well as ECM. An alteration in gap size is expected to have an influence on the electrical resistance of the whole process.

Other process parameters, including current, frequency, electrolyte and electrolyte flow, feed and d_{CW} were kept constant. As for the electrolyte, a sodium nitrate solution has been used (200 g/l). During the single track experiments (Section 3), both the current and voltage were recorded at a frequency of 5000 Hz. In order to exclude the boundary effects, current–voltage profiles in the middle of the track (23 mm = sample length minus tool diameter) are taken into account for further calculations. Machining in this region is considered consistent and relevant for the process in general. The current and voltage profiles are a powerful tool to detect unwanted behaviour such as sparks and to quantify the electrical behaviour in the (M)ECM process. As the generator is current controlled, the voltage measurements are of larger interest.

3. Single track machining

Machining of single tracks has been carried out using both ECM and MECM. To investigate the influence of alloying elements on the process, both Titanium grade 2, or commercially pure Titanium, and Titanium grade 5, or Ti6Al4V have been tested. To investigate the process behaviour, a randomised full factorial two level design of experiments with 3 replicas and 4 factors (material: Titanium

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