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Experimental and numerical investigations in electro-chemical milling

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ABSTRACT

This paper presents experimental and numerical investigations into electro-chemical (EC) milling of simple features such as slots and pockets. Preliminary experimental investigations into the machining of a slot enabled appropriate process parameters to be selected; these were then used to machine a simple square pocket and finally a pocket with a human-being shaped protrusion. These features were machined with tools having circular and square cross-sections. The pocket with the protrusion was machined with tool paths of zig–zag and contour-parallel type. The experimental results indicated that the machining accuracy depends upon, amongst other things, on the tool shape and process parameters. A boundary element of the EC machining process was used to predict the shape of the pockets and in most cases, the predicted shapes compared favourably with the actual machined features.

Introduction

Demand for parts made from high strength, heat and corrosion-resistant materials such as titanium and Inconel, is increasing because of their use in fields such as automotive, medical and aerospace parts. Conventional processes are not really suitable to machine these difficult-to-cut materials because the cutting tools have to be made of a material that is harder and stronger than that of the workpiece.

The disadvantage of having to use harder and stronger cutting tools can be overcome by resorting to non-conventional processes such as electrical discharge machining (EDM), laser beam machining and electrochemical machining (ECM). In EDM and laser beam machining, the stock is removed by using high thermal energy to melt the material. Although in these processes the material is removed without the tool coming into contact with the workpiece, heat-affected zone, residual stresses, and sometimes even surface cracks, are present in the workpiece.

On the other hand, ECM has the advantage that there is no heat-affected zone or residual stresses in the machined workpiece. Material is removed by electrolysis wherein the anode (workpiece) undergoes dissolution at a rate that is largely dependent on the current density. ECM has the advantage of machining materials irrespective of their hardness and toughness; the only requirement is that the material must be conducting. There is a temperature increase within the electrolyte gap due to Joule heating; however, the majority of this heat is conducted away by the bulk of the electrolyte, resulting in a very small amount of heat being conducted into the anode (workpiece).

The common applications of electro-chemical machining are drilling and die sinking. In the latter, a complex 3D shape of the cathode (tool) is reproduced in the workpiece by an axial movement of the tool. In electro-chemical drilling, the shape of the tool is axisymmetric whereas in die sinking, the shape of the tool is similar, but not identical, to that of the workpiece. A considerable effort is required to design the tool for die sinking and it is usually done by trial and error. The time and effort required to design and fabricate the tool for design is reflected in the cost of the workpiece. The difficulties of tool design in EC sinking can be mitigated to a large extent if the die could be electro-chemically machined using a tool of very simple geometry (*i.e.* having a rectangular, spherical or cylindrical cross-section), as in conventional milling, over the workpiece surface.

There has been very limited research in electro-chemical milling, both at the micro and macro scale. At the micro level, most researchers use pulsed machining and Kozak, Rajurkar and Makkar [1] were one of the first to demonstrate pulsed EC micro milling. They milled a simple slot in several axial passes using a cylindrical tool of diameter 280 μm. They also attempted to model the process analytically but were able to do so for only one pass. Use of a cylindrical tool resulted in the sidewalls of the machined feature to become tapered. Kim et al. [2] were able to overcome this disadvantage by using a disc-type electrode; they electro-chemically milled a micro open pocket the sidewalls of which

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were almost square to the base face. Micro features have also been milled using the recently developed electro-chemical jet process. Hackert-Oschätzchena et al. [3] electro-chemically milled slots 200 μm wide and 60 μm deep with a jet diameter of 100 μm. More recently, Zeng et al. [4] used electro-chemical milling to improve the surface of a feature previously machined by EDM. They deployed electro-chemical milling to remove the 5 μm thick re-cast layer.

At the macro scale, Kozak et al. [5] investigated the milling of flat and cylindrical surfaces, both convex and concave, with a ball-ended electrode, which they referred to as a universal tool. The main purpose of their experiments was to verify the results predicted by their analytical model. Instead of using a ball-ended cutter, Ruszaj and Zybura-Skrabalak [6] used a tool with a rectangular cross-section to mill slots and they compared the experimentally measured surface roughness values with those predicted by a computer model. Pattavanitch and Hinduja [7] also used a rectangular-shaped tool to mill deep and wide slots and they investigated the waviness of the base surface of the slots produced with different step-over distances. A numerical model using the boundary element (BE) method was also developed in order to predict the 3-D shape of slots. More recently, Vanderauwera et al. [8] also investigated the surface finish that can be obtained with electro-chemical milling. They found that the accuracy of the machined feature is improved with pulse milling.

Since several researchers have investigated electro-chemical milling of simple slots, this paper investigates the machining of more complex features at macro scale; the effect of different tool geometries and different type of tool paths are also studied.

Modelling of the ECM process has followed a similar path as the experimental research work. The initial models were confined to electro-chemical drilling and die sinking and these models used various techniques such as: the analytical methods deployed by Hewson-Browne [9] and Loutrel and Cook [10]; the finite difference method by Tipton [11] and Kozak [12]; the finite element method by Jain and Pandey [13] and Alkire, Bergh and Sani [14]; and the boundary element method by Narayanan, Hinduja and Noble [15] and Deconinck [16]. Again, BE models have been developed for electro-chemical milling [7] but only for simple slots. This paper discusses the difficulties encountered when the BE method as described in [7] is used to mill complex features.

Experimental setup

The experimental set-up consisted of a 3-axis Denford CNC milling machine, which was converted into an ECM machine. The workpiece was a rectangular bar made of SS-316 and was placed over a block of polymer that was wider than the workpiece bar (see Fig. 1(b)); both were submerged in a plastic work bath of electrolyte as shown in Fig. 1(a). The electrolyte was sodium nitrate ($NaNO_3$) (10% by weight in water). The tool was held in the spindle of the Denford CNC machine, the spindle being held stationary. A DC voltage was applied between the tool and the workpiece. A data acquisition system was used to record the voltage and current.

Two tools of different shapes were used in the investigations (see Fig. 2). These tools were made from copper; one had a square cross-section of size 1 × 1 mm and the other tool a circular cross-section of radius 0.5 mm.

BE model for electro-chemical milling

Although there were three components *i.e.* tool, workpiece and insulating block (see Fig. 1(b)), the BE method required only the outer surfaces of the tool and the workpiece to be modelled. For the tool, an open shell was formed by the end and side faces (oranges

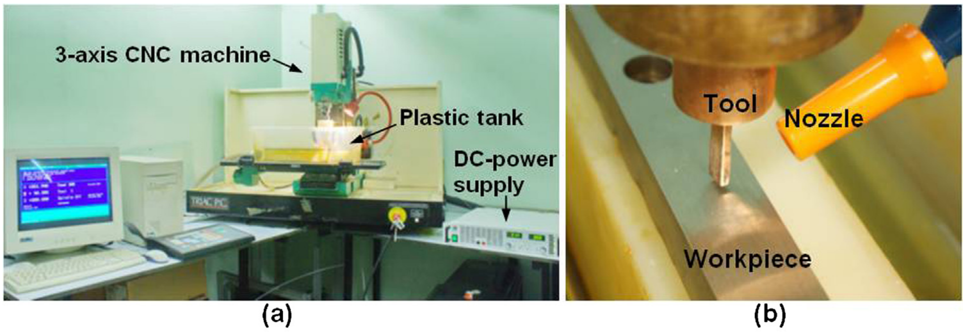

Fig. 1. (a) Three-axis ECM milling machine and DC power supply and (b) The tool, workpiece and nozzle.

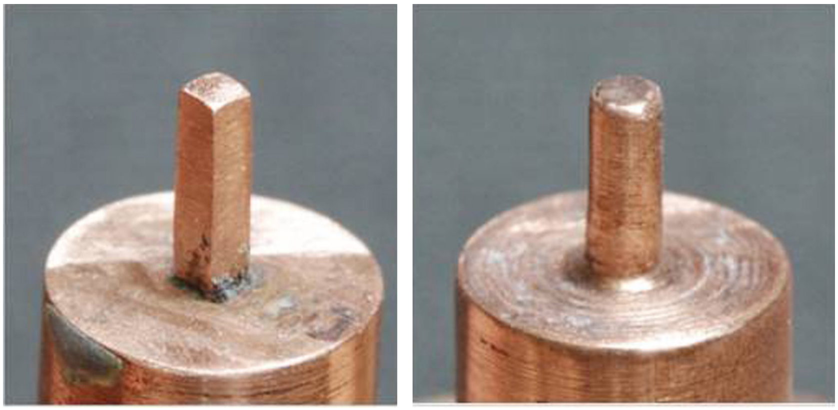

Fig. 2. Square and cylindrical tools.