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Real time electrode wear hybrid compensation strategies for micro electrical discharge milling of complex 3D features

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Abstract

The aim of this work is to develop robust, reliable and real-time hybrid compensation of tool electrode wear through integrated process/machine control and monitoring models in micro electrical discharge milling process. This approach would enable defect free, high precision and efficient machining of complex 3D micro geometries in electrically conductive materials. The focus is on generating and demonstrating an appropriate hardware and software framework for the integration of TWD (tool wear per discharge) and MRD (material removal per discharge) approaches into a hybrid wear compensation system. Furthermore, to effectively implement process control strategies and to facilitate future integration of additional process modules, a modular system will be developed, constructed and validated. Based on the newly constructed equipment and integrated tool wear compensation method, the enhanced capabilities of the micro EDM milling process will be demonstrated for several specific practical applications. Furthermore, hybrid tool wear compensation method is refined based on information using other parameters in micro-EDM such as light intensity of the sparks, acoustic emission signals, advance tool/ workpiece profile evaluation, application to variants such as dry micro-EDM etc. are also included.

Keywords: Precision machining, Tool electrode wear, TWD, MRD, Machine control and Process control.

1. Introduction

Micromachining technologies play an increasingly vital role in the manufacturing industry with applications ranging from biomedical to chemical micro-reactors and sensors. In most of such micro-components, the miniature dimensions and accurate geometry are essential to realize efficiently the intended function. Among micro-machining processes, micro-electrical discharge machining has become a well-known process for the production of 2½D and 3D micro components and for the generation of micro features on larger components [1]. Currently, micro-EDM milling is mostly used for the production of micro cavities with high aspect ratio and tools employed in mass or batch production of micro components, as for instance micro moulds for micro-injection moulding (see Fig. 1).

Micro-EDM is a thermal process for contactless material removal of electrically conductive materials where machining is performed by a sequence of electrical discharges occurring in an electrically insulated gap between a tool electrode and a workpiece. During the discharge pulses, a high temperature plasma channel is formed in the gap, causing local melting and evaporation of workpiece and electrode material. The machining forces are negligible compared to those in mechanical material removal processes thus making micro-EDM highly convenient for the generation of high aspect ratio cavities and slender protruding features.

1.1. Concept of tool wear in EDM

In the EDM process, each electrical discharge removes material also from the tool electrode. Therefore, during processing, the tool electrode also changes its geometry and affects the achievable accuracy of the feature machined.

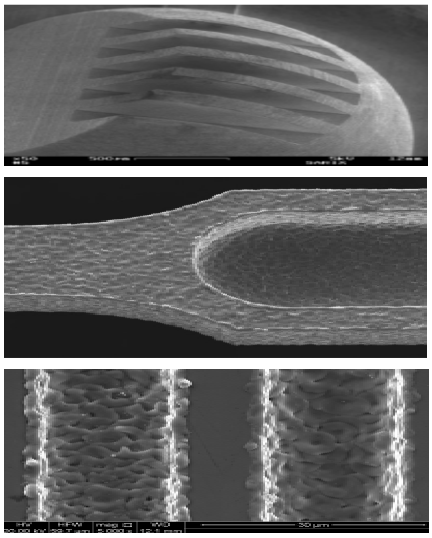

Fig. 1 micro features for components Top: detail of 3D micro mould insert, Centre: detail of stent for blood vessel with cavity for drug dispensing, Bottom: micro channels 15 µm wide in a microfluidic system in detail.

Material removal from the tool electrode is indicated with the term “tool wear” or “electrode wear”.

Tool wear is the single most important factor limiting the manufacturing accuracy in micro-EDM.

1.1.1. Tool wear in micro-EDM milling

Among micro-EDM configurations, micro-EDM milling provides the highest flexibility and shortest setup time. In micro-EDM milling, micro-electrodes essentially of cylindrical shape with diameters down to 10 µm, are driven along different paths while rotating, in a way similar to conventional 3 and 5-axis milling. In this configuration, the material is removed layer by layer, with layer thickness ranging from a few µm to 0.1 µm.

In micro-EDM, milling the material removal action is performed in very thin layers compared to the tool diameter. Thus, the tool profile stabilizes rapidly and compensation for tool electrode wear can be done by a one dimensional motion parallel to the electrode axis (see Fig. 2). Electrode wear must be effectively compensated for in order to achieve high accuracy of the machined features.

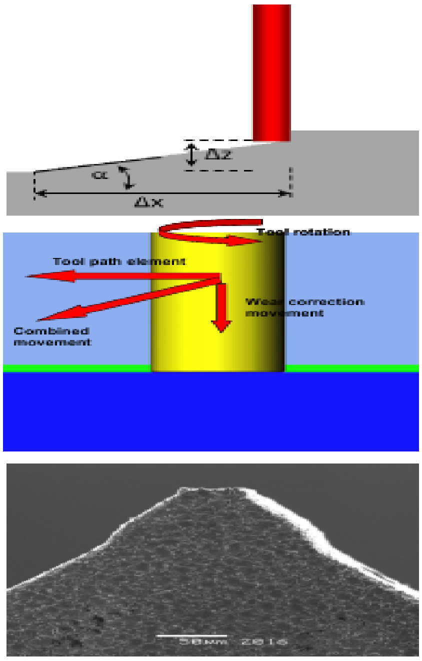

Fig. 2 Tool wear compensation in micro-EDM milling. Top: tool motion for undercompensated trajectory, Center: combined movements during the process, Bottom: Slope error in 3D machining due to wear compensation error.

2. Literature review

At the micro-scale, the structural, functional and tolerance requirements of the features demand appropriate selection of processes, materials and equipment for manufacturing. Typically, complex features such as high precision micro grooves are to be machined on ceramic substrate for applications in high precision micro bonding process [2]. During machining processes, the importance of correlation between discharge pulses, tool electrode wear and material removal has been realized earlier [3]. The tool wear has been identified as an important response variable affecting the performance of the micro EDM process, which needs to be systematically optimized [4]. Further, micro-EDM technologies were successfully introduced to the tool making industries, aiming at generation of complex 3D features at high machining accuracy and machine tool accuracy [5]. Further, micro-EDM has been successfully applied for machining of a complex feature, viz. bottom grooved micro mixer by employing the micro-EDM process [6]. Therefore, the generation of complex geometries on micro-components have become highly challenging and the study of tool electrode wear has gained increasing significance.

The literature review is focused on current research trends in tool electrode wear compensation. The articles were classified into four different sections: i) development of new methods, ii) modeling and simulation of tool wear compensation, iii) experimental characterization and measurement of tool wear and iv) micro-EDM system building. The development of new methods involved both techniques to directly evaluate and quantify tool wear or to correlate wear with other factors such as removal volume and discharge pulses. In literature on modeling and simulation, mathematical models or simulation models were developed and tool path was updated accordingly. The experimental characterization methods employs various methods to measure linear wear as well as volumetric wear and to apply the anticipated wear compensation strategies. A few parametric studies were also carried out to evaluate the effect of processing conditions on the wear compensation. In micro-EDM system building, in order to improve the accuracy and speed of machining, newer sensors/actuators are developed and modular systems are constructed [1].

Tool electrode wear compensation in micro-EDM milling can be based on off-line methods with limited accuracy such as the estimation of the volumetric wear ratio and continuous compensation proportional to the in-plane displacements (anticipated wear compensation) or real time wear sensing [1]. Real time wear compensation can in turn be based on full discharge pulse discrimination or on discharge counting and statistical treatment of the discharge population [8]. Real time tool wear compensation was investigated by several authors using real time full discharge discrimination [7]. However, due to the extremely short pulse durations in micro-EDM milling, down to 30 ns, real time discharge discrimination is not practical because of the limitations in signal processing speed and because of the larger relative measurement uncertainties. Therefore, under such conditions, pulse discrimination is certain to be inaccurate.

A new approach to tool wear compensation in micro-EDM milling has been recently developed at DTU based on discharge counting and statistical characterization of discharge population [8]. Such an approach was applied to electrode wear compensation based on tool wear per discharge (TWD) estimation. Later, work by the same research group at DTU focused on the development of an alternative and complementary approach where real time tool electrode wear compensation was based on statistical characterization of the discharge population and workpiece material removal per discharge (MRD) estimation [9]. The two methods are based on the recognition that machining normally takes place by means of a large number of discharges and even for rather small electrode diameters, more than one thousand discharges are necessary to produce a wear length of 1 µm. Therefore, it can be assumed that machining occurs by means of trains of discharges with identical distribution as that of the entire discharge population [8].

3. Proposed approach

On the basis of the literature review, it is evident that the EDM discharges should be characterized by the statistical distribution of the population in terms of discharge energy, tool wear per discharge (TWD) and material removal per discharge (MRD). Tool electrode wear can therefore be effectively compensated on the basis of discharge counting without the implementation of a pulse discrimination system. The TWD based approach allows the direct monitoring of the tool electrode frontal surface and has the advantage that TWD can be determined with high accuracy. The MRD based approach allows real time reconstruction of the actual machined surface (material removal mapping), having number of advantages such as the possibility to determine actual rest material for improved tool path generation for the following machining steps. The errors in estimation of TWD will produce a self-amplifying error on the tool electrode axial depth during machining [7]. At the same time, the errors in estimation of MRD will produce axial depth errors, which are not amplified during machining.

The two methods when considered individually still exhibit limited reliability when process instabilities occur and due to the errors associated with estimation of TWD as well as MRD. Thus, it is proposed that the implementation of a combined TWD and MRD based approach could be helpful in greatly improving the accuracy, reliability and thereby the robustness of tool electrode wear compensation. The limited interaction of the control unit of commercial micro EDM milling systems with the external sensors and control softwares is another issue.

In order to overcome the limitations outlined, this work aims at development of a combined wear compensation solution involving integration of the two approaches, viz. TWD method and MRD method by generating and demonstrating a hardware and software framework for the integration of the approaches. Therefore, the detailed objectives of the project are: i) to develop an integrated TWD and MRD approach for tool electrode wear compensation in micro-EDM milling, ii) to develop a hardware tool as well as software tool for real time tool wear estimation and to obtain an update of the tool trajectory, iii) to practically implement and validate the integrated tool wear compensation approach on the state of art micro-EDM milling machine, iv) to develop, construct and validate a modular system based on open architecture for the implementation of process control strategies and future integration of additional process modules, v) to widen the applications of the newly constructed equipment and integrated tool wear compensation solution, by focusing on application-oriented micro structured parts, such as mould inserts for hearing aid components, vi) to include the effects of other important parameters such as light intensity of sparks for TWD and MRD calculations, and for subsequent tool electrode wear compensation, vii) to perform detailed high-resolution experiments considering effects of advanced parameters and viii) to apply the tool wear compensation strategies for dry micro-EDM process.

4. Methodology

The methodology of the work is organized into the six stages as presented in Fig. 3.

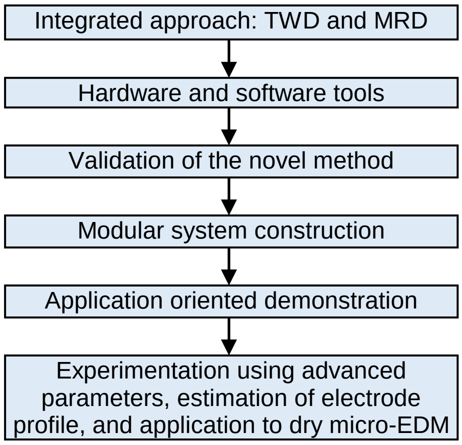

Fig. 3 Methodology for hybrid electrode wear compensation

In the first stage, the mathematical models for calculation of the downward elemental electrode displacements corresponding to elemental tool trajectory segments will be developed based on number of discharges, TWD and MRD information. The model development will be based on correlations between discharge population characteristics, tool-workpiece-dielectric fluid properties and other processing conditions. The validation of the models will be done by performing detailed experiments on the DTU MEK state-of-art micro EDM milling machine.

The developed mathematical models for estimation of the tool wear compensation are to be implemented practically. For this purpose, a software tool will be developed capable of calculating the TWD, MRD and the magnitude of tool electrode wear compensation. The tool would also handle the communication with the control unit of the machine.

The newly developed solution using integrated tool wear compensation method will be validated on the existing state-of-art micro-EDM milling machine available at DTU MEK. The accuracy and robustness of the developed solution will be validated at different process conditions and parametric levels. The efficacy of the newly developed solution against axial depth error amplification will be verified and analysed.

The commercial micro EDM milling systems allow limited interaction of the control unit with external sensors and control software. The speed of communication between control unit and the PC is extremely slow when using the external I/O ports on the control unit. Therefore, in order to realize efficient working, a modular table top micro-machining system will be developed. The system will be designed and developed in a such a way as to enable integration of additional process modules in the future.

Based on the integrated tool wear compensation solution and newly constructed set-up, application-oriented demonstration will be carried out. This is to make use of the enhanced capabilities of the micro-EDM milling process beyond the state of art by application to micro structured parts. The components involve: inserts for hearing aid components such as shells, RIC socket and plug, etc.

In the last stage, the integrated tool wear compensation solution will be further refined by performing detailed high-resolution experimentation by including a variety of process parameters and processing conditions. This is to widen the applicability of the method for different processing conditions. The factors additionally introduced would be light intensity of sparks; acoustic emission signals etc., by understanding and correlating the physics of the process with the tool electrode wear phenomena. The volumetric tool electrode wear as well as the tool wear length will be expressed as a function of these factors in real time. The analysis of the frequency spectrum using AE signals in real time would help in analysing different wear levels.

Considering the input parameters, accurate counting of number of discharges is of great relevance. Advanced tools such as wavelet analysis will be used for analysis and characterization of these discharges and exact evaluation of the number of discharges for calculation of the MRD and TWD in real time, and to further generate the combined wear compensation solution. The instantaneous tool electrode area is a necessary parameter used for evaluation of TWD, whereas the worn volume is essential for evaluation of MRD. Thus, real time and accurate evaluation of the electrode profile as well as the workpiece profile is essential. In this regard, camera based measurements based on optical sensors will be used for TWD (using CU2 tool, Conoptica) and for MRD (using CU2 track, Conoptica). This would further improve the accuracy in estimation of the tool electrode as well as the workpiece profile.

Dry electrical discharge machining is a novel variant of EDM [10], which uses gaseous dielectric, instead of the conventional liquid dielectric. The striking feature of this process is near-zero tool electrode wear. The dry micro-EDM also facilitates accurate and real time evaluation of the tool electrode profile as well as the workpiece profile, due to the absence of liquid dielectric. This will further helps in accurate estimation of the wear compensation length. Therefore, integrated real time tool electrode wear compensation solution can be effectively implemented in dry micro-EDM for generation of complex 3D features.

4. Conclusions

A new innovative tool wear compensation approach is proposed to enable defect free, high precision efficient manufacturing of complex 3D micro geometries. Integrated process/machine control and monitoring models will be developed to achieve robust and reliable tool wear compensation. In this regard, hardware-software tool will be developed and validated on state of art micro-EDM milling machine at DTU Mechanical Engineering. A new modular system will be constructed and process control strategies will be implemented on it. Furthermore, the new method developed will be demonstrated on application-oriented micro-parts. feasibility of the new method will be further enhanced by performing new high-resolution experiments considering new parameters, estimation of tool profile and application to dry micro-EDM.

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