Design of a μECM machine tool: a holistic approach and its implementation perspectives

Qingshun Bai[1, 2], Atanas Ivanov[1], Kai Cheng[1], Frank Wardle[3]
[1]*School of Engineering and Design, Brunel University, Uxbridge, UK*
[2]*Dept. of Mech. Manuf. & Autom., Harbin Institute of Technology, Harbin, China*
[3]*UPM Ltd, UK*

Qingshun.Bai@Brunel.ac.uk

Abstract

The electrochemical micromachining (μECM) machine using nanosecond pulses is the key facility for manufacturing miniature/micro parts or micro/nano scale structures in high precision and productivity. In this paper, a holistic design approach for μECM machine is presented particularly focusing the design exercise and innovative aspects of the machine. The key factors related to mechanical, electrical and chemical aspects of the machine have been holistically addressed in the machine system design and configuration. Dynamics driven finite element (FE) analysis for the spindle, mechanical structure and enclosure of the machine are conducted so as to obtain the machine optimal performance. The vibration modes in various inherent frequencies and their effects have been analyzed in detail particularly on the inter electrode gap (IEG) between tool anode and workpiece cathode. The electrolyte filtration system for the machine is designed by taking account of the compact design requirements. The holistic design approach is greatly helpful in reducing the machine development cycle, increasing the machine reliability and enabling the machine setup right at the first time. The paper concludes with further discussions on the potential and application of the approach for design of other high precision machines.

1 Introduction

Electrochemical micromachining (μECM) technology is an effective and powerful extension for the mechanical micro-machining. As an enable technology for ultra-precision machining, nanosecond pulse electrochemical machining (ECM) has gained wide awareness since it was developed [1]. The ultra-short pulse width between workpiece and tool electrode make it possible to achieve 3D features with extreme precision by working at micro inter electrode gap (IEG). The ironic reaction between tool anode and workpiece cathode can make the shaped electrode form mirror image into the workpiece surface by a controlled erosion process. Recently, some ECM machines for experiments were developed to test the capability and effectiveness of nanosecond pulse electrochemical machining [2, 3]. However, the experimental facilities mentioned above are limited to the laboratory level. The design of product level µECM machine has become an urgent issue to meet the requirement for the ever developing industry of micro manufacturing.

2 A holistic design approach for the µECM machine

µECM machine is a complex machining system, which involve with mechanical, electrical and chemical aspects. The objective of the design is to develop a machine that can be used to micro ECM features of less than 100 µm in spatial dimension to an accuracy of less than 1 µm. Fig. 1 shows the relationship of the factors that should be carefully considered in the whole design process. Each factor shown in the design consideration is holistically examined with respect to interaction.

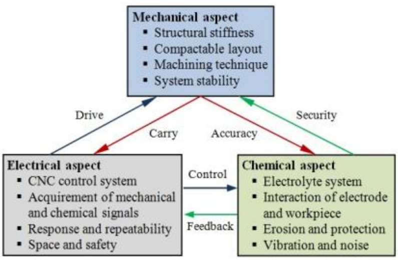
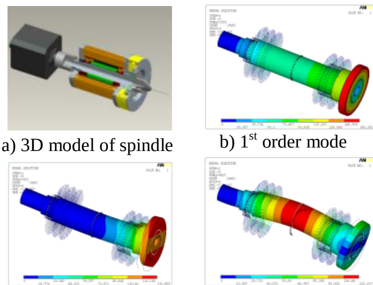


Fig. 1 Design consideration of the µECM machine tool



a) 3D model of spindle b) 1st order mode

c) 3rd order mode d) 5th order mode

Fig. 2 3D model and inherent vibration modes of spindle system

3 Design implementation perspectives

3.1 Dynamics-driven design of spindle, mechanical structure/ enclosure

Though there is no cutting force between tool and workpiece, the small vibration caused by dynamic performance of the system may threaten to the fine surface quality of electrochemical micro-machining. Furthermore, the dynamics of the machine mechanical structure can also affect the pulse current in the gap. The stiffness of spindle will definitely influence the stability of electrode and even the surface finish of workpiece. Fig. 2 shows the 3D spindle model and its vibration modes. It is shown that the first order inherent frequency is 2,991 Hz with the vibration mode of peripheral deform around its axis. For the reason of structural symmetry, the second and third order frequencies are same 3,921 Hz. The fourth and fifth order frequencies are same 6,827 Hz. It is shown that the stiffness is enough for the stability in the working conditions. The vibration mode in the first order can not affect the relative position between workpiece and tool electrode. Revolving errors of tool anode caused by self-vibration of the spindle may start from the second order frequency.

Fig. 3 shows the mechanical layout for the designed μECM machine. The *X* slide forms a gantry in order to minimize distortion. The *Z* slide is attached to the *X* slide whilst the *Y* slide is attached to the base. The slides are all fitted with DC linear motors, which provide 'cog free' motion of the carriage and generate negligible heat at the duty cycles required for the μECM process. The mechanical frame stands on a base cabinet, which houses the control system and electrolyte supply. Stiffness-related inherent properties have been analyzed for the mechanical frame and enclosure. FEA results show that the gantry frame of granite presents high stiffness especially in the sensitive direction for micro-machining. Fig. 4 shows the first order vibration mode in frequency of 248.12 Hz. Though the complete mechanical frame is isolated from its surroundings by rubber mounts, the disturbance from enclosure should be as small as possible. The overall enclosure of the machine was designed with metal sheets to get an optimized profile. The structural analysis result from enclosure layout is shown in Fig. 5, which presents a better dynamic performance.

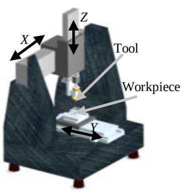


Fig. 3 Design layout

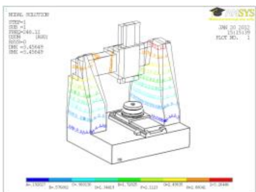


Fig. 4 Structure modal analysis

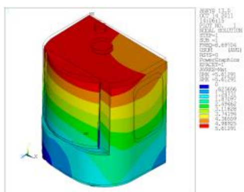


Fig. 5 Enclosure FEA

3.2 Electrolyte circling and numerical control system for the machine

Metal removal in the μECM process relies on passing a current between an electrode and a workpiece separated by a small gap that is filled with an electrolyte. The diagram for filtration system of μECM machine is presented in Fig. 6. Fig. 7 shows the control system for the machine. Power UMAC integration from Delta Tau is adopted as the system-level control system for the machine. Because of the utilization of the latest hardware and software technologies, it can provide the highest performance, most flexible and efficient implementation for the machining. Apart from the precision movement control in the axes, electrical chemical parameters will also be measured and controlled for the implementation of the machining process.

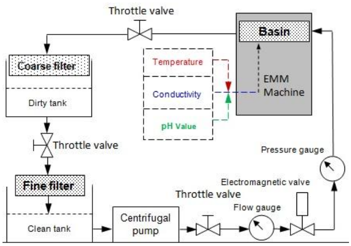


Fig. 6 Diagram for filtration of μECM machine

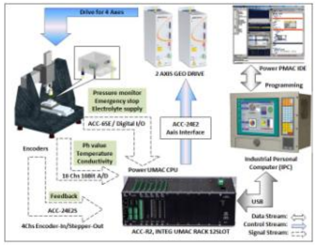


Fig.7 Control system of μECM machine

4 Concluding remarks

Three key aspects related to the design of the μECM machine are introduced with a holistic design approach. The mechanical dynamics, filtration system and control system are presented in details. It is shown that the designed μECM machine is a compact and integrated apparatus with higher precision and stability. The holistic design and analysis help better understanding of the μECM technique and its comprehensive integration with the machine development and building. The holistic design approach can also be applied to development of other high precision machines.

Acknowledgements

The work presented in this paper is partially supported by the European Union FP7 programs with contract Nos. 262072 and 228585.

References:

[1] R. Schuster, V. Kirchner, P. Allongue, G. Ertl. Electrochemical micromachining. Science, 2000, 289: 98-101.

[2] B. Bhattacharyya, M. Malapati, J. Munda, A. Sarkar. Influence of tool vibration on machining performance in electrochemical micro-machining of copper. Int. J. Mach. Tool Manu., 2007, 47: 335-342.

[3] D. Zhu, Y.B. Zeng, Z.Y. Xu, X.Y. Zhang. Precision machining of small holes by the hybrid process of electrochemical removal and grinding. CIRP Ann-Manuf. Techn., 2011, 60: 247-250.