International Journal of Machine Tools & Manufacture 92 (2015) 85–96

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

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

# Three-dimensional characteristics analysis of the wire-tool vibration considering spatial temperature field and electromagnetic field in WEDM

Zhi Chen [a], Yu Huang [a,b], Hao Huang [a], Zhen Zhang [a], Guojun Zhang [a,b,*]

[a] State Key Lab of Digital Manufacturing Equipment & Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, Hubei, China

[b] Guangdong Province Key Lab of Digital Manufacturing Equipment, Dong-guan, Guangdong, China

ARTICLE INFO

*Article history:*
Received 12 November 2014
Received in revised form
8 March 2015
Accepted 9 March 2015
Available online 22 March 2015

*Keywords:*
WEDM
Multi-physics coupling model
Vibration
Thermal model
Electromagnetic field
Multiple-spark

ABSTRACT

In this paper, a three-dimensional multi-physics coupling model (thermal model, electromagnetic field model and structural model) is proposed for analyzing and controlling the vibration of wire electrode in cutting thin plate process. Firstly, a three-dimensional thermal model is developed to evaluate temperature distribution of wire electrode considering heat convection and heat conduction, and the numerical solutions of wire temperature increment are performed under different process parameters. Secondly, the mechanism of electromagnetic force acting on wire tool is clarified in detail, and a spacial finite element method (FEM) program is designed to analyze the electromagnetic field considering electromagnetic induction. Then, combining thermal model with electromagnetic field model, and conventional structural model, a multi-physics coupling model is established to acquire the frequency and amplitude of wire vibration under random multiple-spark discharges. Furthermore, the simulational results of multi-physics coupling model on wire vibration show a good agreement with experimental data, and the influencing rules of processing parameters on wire vibration are also illustrated to seek the best parameter combination. Eventually, three practical methods are presented to restrain wire vibration performance, and the significant effects on suppressing the wire vibration and improving geometric accuracy have been obtained.



## 1. Introduction

In recent decades, wire electrical discharge machining (WEDM) is playing more and more important role in modern manufacturing industry, such as mould, instrument, aerospace and automotive industry and so on. This fact was attributed to its high-performance (precision, efficiency, stability and operability) and the capacity of machining varying hardness or complex shapes. However, as the request of manufacturing increasing, it is essential to further improve the precision performance of machine tools [1,2].

The accuracy-performance of WEDM mainly includes surface accuracy and geometric accuracy, and these two parts were always research hotspots to ameliorate processability of WEDM. As for surface accuracy, some researches designed a series of experiments to investigate the relationship between machining parameters and surface roughness, and some intelligence-optimized algorithms were used to select the most suitable parameter combination in order to obtain the desired surface quality [3–5], although the effectively improvement of surface accuracy had been achieved in a certain extent, these methods could not increase surface precision from mechanism. In regard to geometric accuracy, there are some previous studies about it which have been accomplished, and the geometric inaccuracy of workpiece is mainly generated by wire bending and vibration phenomena in the discharge gap, and their adverse impact mainly reflects in corner-cutting, taper-cutting and kerf width [6]. The wire lag phenomenon is the major cause of geometric inaccuracy when the workpiece is thicker than 10 mm, and this fact maybe attributes to the wire vibration phenomenon which is effectively restrained by the big damping coefficient in machining thick workpiece. On the other hand, the wire vibration phenomenon influences the geometric accuracy of the thin parts to a great extent, therein the bending amplitude of wire electrode is non-significant in machining less thickness part [7]. Some curve fitting methods (arc fitting, parabolic fitting, exponential curve fitting and fourth-order function fitting) were proposed to describe the wire trajectory, and

* Corresponding author at: State Key Lab of Digital Manufacturing Equipment & Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, Hubei, China.

*E-mail address:* zhanggj.hust@gmail.com (G. Zhang).

http://dx.doi.org/10.1016/j.ijmachtools.2015.03.003

several theory resolutions of wire bow error were derived to implement practical measures to reduce it, and these theory models can be applied to set a lead compensation into NC system in the future [8–11]. Sarkar and Mingqi developed novel calculation model and experimental method to evaluate wire deflection under any given cutting condition, respectively, and the discharge force intensity could be determined by the proposed analytical model, and wire lag compensation strategy was used to obtain enhanced precision of the cylinder workpiece [12,13]. Hsue, Han, Sanchez and Chen concentrated on fundamental geometry properties of WEDM in corner-cutting, some mathematical expressions of corner error were derived by analytical geometry, curve fitting method and simulation method, and a few ameliorative measures were applied to actual machining process [10,14–16]. Mohri carried out an investigation on the mechanism of wire vibration, and a mathematical model of wire vibration was established under single spark discharge condition, and a 3rd order system equation was designed to calculate the mathematical model considering machining removal and vibrational features [17]. Puri revealed a principle of the vibration characteristic of wire electrode and proposed an analytical method to solve the two-dimensional vibration equation of wire-tool considering multiple spark discharges, and the relationship between the amplitude of wire vibration and the machining conditions was reflected from the solution of the equation [18]. Di assumed the wire only vibrated in the lateral section, and presented a mathematical model of wire lateral vibration and derived its theoretical solution in micro-WEDM, and it was found that open voltage could be selected as the main parameter in controlling wire vibration [7]. Tomura expounded the mechanism of electromagnetic force acting on wire-tool and its impact on wire vibration, and two-dimensional distributions of current density and magnetic flux density were worked out [19]. Murphy focused on the influence of non-uniform temperature distribution on the vibration, a one-dimensional thermal model was established to acquire the axial temperature increment of wire electrode, after that a coupling structural–thermal model was developed to describe the vibration and stability characteristics [20]. However, in the actual discharge machining, the vibration performance of wire electrode is a three-dimensional motion state (including cutting directional and lateral vibration) in nature, and it is generated by the multiple-spark discharge force, electromagnetic force, nonuniform thermal stress and other causes, so the complicated behaviors by structural mechanics in WEDM cannot be explained.

This paper aims to develop a multi-physics coupling model which is closer to the practical vibration, and propose some effective measures to restrain the wire vibration and improve geometric accuracy in machining thin workpiece (thickness ≤2 mm). Firstly, a three-dimensional thermal model is proposed to gain the spatial temperature distribution of wire electrode considering heat input (from sparking), axial conduction, radial convection and temperature increment. Secondly, a model of three-dimensional electromagnetic field is presented to evaluate the distribution of magnetic field intensity in any given condition, then the electromagnetic force acting on wire electrode can be worked out. Furthermore, combining the thermal model with electromagnetic field and structural mechanics, a multi-physics coupling model is developed to calculate frequency and amplitude of wire vibration. After that, a series of experiments are carried out to investigate the reliability and feasibility of the proposed coupling model. Finally, three practical approaches are implemented to control wire vibration, and the significant effects on suppressing the wire vibration and improving geometric accuracy have been obtained. In addition, the sum of wire radius and lateral vibrational amplitude instead of wire radius should be set as offset in NC system in the future.

## 2. Modeling

### 2.1. Thermal model

#### 2.1.1. The configuration of thermal model

Wire electrical discharge machining (WEDM) is a specialized thermal physical processing method based on conventional electrical discharge machining (EDM), and the material is instantaneously removed by electrocorrosion, melting, evaporating and washing out at very high temperature due to high-frequency electrical discharges. Meanwhile, the temperature distribution of wire electrode is a spatial non-uniform field due to the complicated cutting condition, and it may be influenced by thickness of workpiece ($H$), physical properties of wire, transportation speed of wire, convection coefficient of inside and outside discharge gap, etc. Of course, non-uniform temperature distribution will generate axial thermal stress and expansion. Although, this thermal expansion is very small, it also clearly affects the wire movement characteristic [20–22].

In this subsection, a three-dimensional thermal model is developed based on classical thermodynamics equation. To simplify the thermal model, it can be assumed as follows:

1. The wire electrode is immersed in infinite dielectric fluid because the flushing velocity of dielectric is much faster than the wire speed.
2. Environment temperature ($T_{ref}$) remains constant at 20 °C, and the pressure of dielectric maintains at 0.8 MPa.
3. Workpiece is symmetrically set between upper and lower guides.
4. The convective heat transfer coefficient of the dielectric is only relevant to dielectric fluid pressure, and it is independent of wire speed.
5. Discharge energy uniformly acts on the volume of the wire electrode in discharge gap because the discharge position is with high-randomness. Hence, the terms of partial derivative $\partial T/\partial x = \partial T/\partial y = 0$, and the three-dimensional thermal model can be solved as a one-dimensional thermal model.

Through the former assumptions, the infinitesimal ($dz$) heat balance of wire should be carried out in discharge gap, and it is composed by energy input, heat convection, heat conduction and temperature:

(a) Energy input: total energy input comes from discharge energy per pulse ($Q_0$) in WEDM, expressed in Eq. (1) [23]. However, the temperature increment is resulted by a small part of discharge energy per pulse ($Q_1$) which is absorbed by wire electrode, and the rest energy is washed out by dielectric fluid, absorbed by workpiece, radiated out as photon. On the proportion of energy distribution in the discharge gap, many researches have done a lot of studies, the energy absorption coefficient ($f_w$) of wire is consistent with Ref. [20], and it is set as 0.012, so absorbed energy ($Q_1$) is calculated by Eq. (2):

$$Q_0 = \frac{dz}{H}\int_0^{tp} U_{(t)} I_{(t)}\, dt \tag{1}$$

$$Q_1 = f_w \frac{dz}{H}\int_0^{tp} U_{(t)} I_{(t)}\, dt \tag{2}$$

(b) Heat convection: wire electrode transports relatively to dielectric fluid between two guide wheels in WEDM, and the flushing speed is much faster than the velocity of wire, so the absorbed energy spreads into dielectric fluid through convection heat transfer, and the magnitude of the heat convection is $hC_w d_z(T - T_{ref})$.