Journal of Manufacturing Processes 31 (2018) 9–19

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

Technical Paper

Study on thermal deformation behavior and microstructural characteristics of wire electrical discharge machining thin-walled components

Yanming Zhang[a], Zhen Zhang[b,*], Hao Huang[a], Yu Huang[a], Guojun Zhang[a], Wenyuan Li[a], Chunhua Liu[a]

[a] State Key Lab of Digital Manufacturing Equipment & Technology, School of Mechanical Science and Engineering, Huazhong University of Science & Technology, Wuhan 430074, China
[b] School of Aerospace Engineering, Huazhong University of Science Technology, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 2 August 2017
Received in revised form 21 October 2017
Accepted 24 October 2017

Keywords:
WEDM
Thermal deformation
Residual stress
Micro-structure

ABSTRACT

Wire electrical discharge machine (WEDM) has been successfully applied to aerospace field, mold industry and medical apparatus and instruments due to its excellent abilities. However, thermal deformation behavior of thin-walled components is always ignored due to no macro-force in the WEDM process, and different materials processed by WEDM have different thermal deformation behaviors. This work mainly describes the complex thermal deformation behavior during the WEDM processing the thin-walled components of three typical engineering materials, namely AISI H13, SKD11, and Inconel 718. Firstly, a large number of experiments are conducted to investigate the effects of pulse-on time, water pressure, and wire speed on the thermal deformation of three different materials. Through analyzing the experimental results, it was not only confirmed the significance and universality of thermal deformation in WEDM processing different materials, but also revealed that the effects of physical properties of workpiece materials and process parameters of WEDM on the deformation scale. Furthermore, it was concluded that the yield strength and thermal conductivity of materials both paly the significant roles in the thermal deformation. What's more, we also presented micro-structure characteristics and residual stress of thin-walled components with the thermal deformation. Eventually, several more complex but interesting deformation phenomena during the WEDM process were introduced and discussed.

1. Introduction

The thin-walled components are widely used in aerospace engineering, marine engineering, auto manufacturing filed and other industrial fields due to its capacity of extraordinary heat dissipation and light weight [1,2]. In order to meet the growing demands in engineering field, a large number of researches about machining and manufacturing thin-walled components have been conducted aiming to improve the component performance by using all kinds of preparation methods, such as pulsed plasma arc additive manufacturing, electroplating, laser welding, et al. [3–5]. Additionally, Inconel 718 have been specially developed and selected for aircraft applications due to its high corrosion and oxidation resistance, high strength and long creep life at elevated temperatures, particularly in manufacturing of turbine disks, diffuser cases, and compressor disks [6]. AISI H13 and SKD11 are both typical die steel which can be applied to produce precise molds including thin-walled molds because of their excellent material characteristics [7,8]. So, it is worthwhile to study the performance and behavior of thin-walled components made by above typical engineering materials.

Wire electrical discharge machine (WEDM) has been successfully applied to aerospace field, mold industry and medical apparatus and instruments due to its ability of non-contact machining, non-macro cutting force, processing high hardness materials and shaped chambers with high precision [9]. The recent studies on WEDM process mainly focus on improving the surface quality and material removal rate *MRR* by optimizing the process parameter to reduce surface defects (such as surface cracks, recast layer thickness, etc.) as well as increase the machine efficiency [10]. However, few researches have focused on the thermal deformation phenomenon which usually appears when machining the thin-walled components in WEDM. The thermal deformation cannot be neglected due to its considerable influence on the mechanical per-

* Corresponding author at: School of Aerospace Engineering, Huazhong University of Science Technology, Wuhan 430074, China.
E-mail address: jameszhang198808@gmail.com (Z. Zhang).

https://doi.org/10.1016/j.jmapro.2017.10.024
1526-6125/

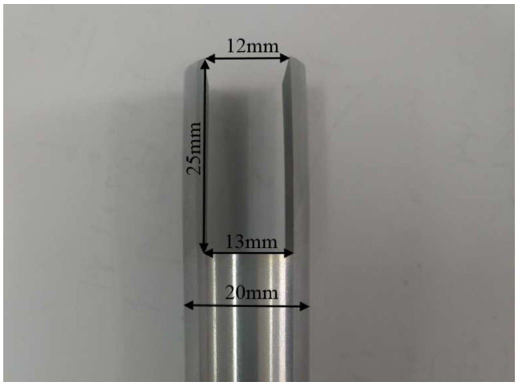

Fig. 1. The picture of explode workpiece.

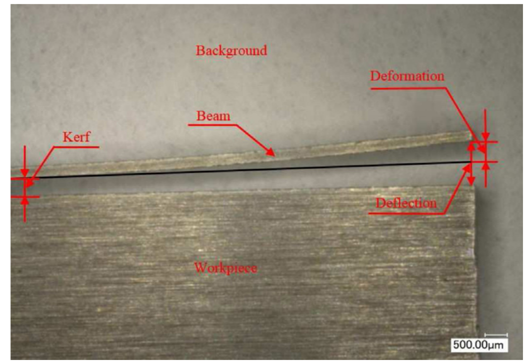

Fig. 2. The picture of workpiece and deformation.

formance and microstructure of the components during service life [11–13], especially machining the thin-walled components.

One reason for thermal deformation is always neglected is due to non-macro cutting force during the WEDM process. However, as a matter of fact, thermal effects play the dominant role in WEDM except for ultrashort discharges. The thermal deformation may be caused by two kinds of residual stress [14]. One is the residual stress exists in the workpiece before machining which can be released by annealing in the pre-processing, while the other one is the residual stress generated by the WEDM process which is not yet explained clearly. In WEDM process, sparks generated between the cathode and anode heat the surface of the workpiece arriving to over 10,000 °C within the radius of the plasma, and the thermal gradient during the thermal cycle can reach 10–12 K/m, resulting in complex thermal deformation phenomenon. After forming the molten area and removing the materials over the melting point, the recast layer starts to re-solidify in cooling process as well as the tensile residual is formed at the cooling area, resulting to the surface crater, surface cracks and thermal deformation. Das et al. [15] firstly established a finite element model for the EDM process to calculate the deformation, microstructure and residual stresses through predicting the transient temperature distribution, liquid- and solid-state material transformation. Based on a hypothesis that the thermal and electrostatic stress induced fracture, Miller et al. [16] studied the wire electrical discharge machining (WEDM) of cross-section with minimum thickness and compliant mechanisms. Recently, Zahiruddin and Kunieda [17,18] described the deformation of fin machined by micro-EDM and conducted thermal and structural analyses of fin deformation by calculating its residual stress. In the WEDM process, the similar thermal deformation leading to the high geometric error (maximum: 11.05%) is also found as shown in Fig. 2. It can be concluded from above researches that the geometric error is dependent on the thermal deformation which should be analyzed completely and reduced as much as possible.

In this paper, a set of experiments are designed on the thermal deformation of WEDM machining three different materials, namely SKD11, AISI H13, and Inconel 718 in Section 2. Section 3 presents the analyses and discussions of the effects of pulse-on time, water pressure, and wire feed on the thermal deformation of three different materials are presented, while Section 4 concludes the effects of the WEDM process parameters on the residual stress and the thermal deformation and provides some advice on reducing the thermal deformation.

2. Criterion of thermal deformation

A set of exploratory experiment was carried out to observe the thermal deformation in WEDM. Stainless steel rod with diameters of 20 mm was selected, and a 25 mm long and 13 mm wide workpiece was cut off with fixed parameters as shown in Fig. 1. It is obviously that the significant thermal deformation is generated by the cutting process, and the bottom distance between two walls is 13 mm while the top distance is 12 mm, which results in the high geometric error (7.69%). Therefore, according to the above real machining of thermal deformation in the process, it can be revealed that the phenomenon of deformation is universal and ineluctable. In order to study the complex phenomenon accurately, the beams with size of 10 mm × 0.65 mm × 10 mm were selected as experiment specimens. Moreover, the criterion of thermal deformation is performed. Generally, the bending degree, bending angle, and bending curvature could be used to express the deformation behavior. In our studies, the bending angle is too small to measure accurately and the bending curvature is hardly measured directly which would lead to the accumulated error. Though the magnitude of deformation during the WEDM process is micron scale, the bending degree can be measured directly by the KEYENCE VH-Z500R digital microscope. Therefore, the bending degree is selected as the criterion of the thermal deformation as shown in Fig. 2. Since the bending degree is determined by the size of deformation and the width of beam, it can be calculated by Eq. (1).

$$W = \frac{t}{T} \times (H - k) \quad (1)$$

where W means the bending degree, t is the thickness of beam, t/T is the width modification coefficient, H is the deflection of beam, and k is the kerf width.

3. Experimental procedure

3.1. Materials and experimental equipment

The experiments are conducted by an efficient and high-precision 5-axis CNC WEDM (model: HK-5040F) based on independent development. It also equipped with homenergic pulse generator and precision servo control system for generating stable normal discharge. The deionized water (electrical resistance 60 Ω) is used as dielectric and the copper wire with diameter of 0.25 mm acts as tool electrode. Inconel 718, SKD11 and AISI H13 are selected as test materials due to their excellent properties (high strength, high hardness and good corrosion resistance) and widely applications in industry. The chemical composition and physical properties are listed in Tables 1 and 2, respectively. Moreover, the plot of the relationship between yield strength, thermal conductivity and temperature has also been shown in Fig. 3.

3.2. Experimental design

According to our experience, literature survey, the characteristics of the experimental equipment [15,23,24], it can be found that