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Technical Paper

Mechanism analysation and parameter optimisation of electro discharge machining of titanium-zirconium-molybdenum alloy

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ABSTRACT

Titanium-zirconium-molybdenum (TZM) alloy is one of the most widely used molybdenum based high temperature alloys which is difficult-to-machine even for the non-traditional process. Throughout this research, a special phenomenon was disclosed and the material removal mechanism of TZM in EDM was studied based on single discharge experiments and FEM methods. When machining TZM with EDM, the crater diameter is much smaller than the plasma affected region, especially in the case of small discharge current. The single discharge experiment result showed that the crater size increases with the rising of the peak current but insensitive to the pulse duration when the discharge current is small. The reason that causes this phenomena is analyzed by analyzing the current density distribution along with plasma radius and considering the influence of TZM's special thermal physical properties, such as high melting point and good thermal conductivity. Additionally, a single discharge thermal erosion simulation based on time integration effect (TIE) method was conducted to support the explanation above as well as to investigate the temperature distribution on the workpiece. According to the results of the mechanism analyzation, difference machining characteristics and effects were presented for ED-machining of TZM material. In order to improve the machining performance, the Box–Behnken method was implemented to optimize the parameters. Last, a TZM hot-gas valve with complex internal flow channels was machined as a means to verify the findings of this research.

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1. Introduction

TZM alloy is an important high temperature engineering material due to its advanced properties, such as its high melting point ($T_m > 2800$ K), high thermal conductivity, high corrosion resistance, high elastic modulus and creep resistance and low thermal expansion coefficient [1]. Moreover, the excellent high temperature mechanical properties enables it suitable for many design requirements like good dimensional stability, high precision, good strength and stiffness at high temperature [2]. Recently, the ever-increasing demand for high temperature material has attracted significant interest in producing and machining TZM alloys. More and more components, such as rocket injectors, hot-gas valves, heat engines, heat exchangers, and nuclear reactor radiation shields are made of TZM alloy [3,4].

However, the alloyed Ti and Zr elements (contains 0.5–0.8 wt.% titanium, 0.08–0.1 wt.% zirconium, 0.016–0.02 wt.% carbon and molybdenum balance) not only bring excellent high temperature mechanical properties to TZM, but also make it as a typical difficult-to-machine material. Although high-speed milling is able to machine TZM alloy with cemented carbide cutting tools, the surface quality of the machined workpiece still needs to be improved. Furthermore, for some parts such as shrouded blisk, hot-gas valve and pump impeller that possess some special features (especially the complex flow channels and shaped holes), it is very difficult or even impossible to machine with conventional cutting methods. Due to the non-contact thermal material removal mechanism [5,6], electrical discharge machining (EDM) was introduced as an alternative process to machine those complex features. Since the machining capacity of EDM is not sensitive to hardness, strength and even the toughness of the workpiece, it is currently the most widely used method to machine difficult-to-cut materials and parts [7,8]. Kumar et al. [9] studied the machining parameter and surface integrity in conventional EDM and cryogenic EDM of Al-SiCp MMC. Mohammadreza et al. [10] investigated the surface characteristics and machining performance of Ti-6Al-4V alloy by adding carbon nanotube into dielectric in EDM process. Torres et al. [11] researched the surface finish, electrode wear and material removal rate (MRR) in EDM of hard-to-machine alloys. Moreover, the influence of those materials thermal physical properties (such

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as melting point, thermal conductivity and specific heat capacity) on their EDM performance are not mentioned in above researches.

In order to investigate the effect of material thermal physical properties on EDM capability, Mohri et al. [12] studied the mutual relationship between the material removal rate and the product of λ and θ (where θ is the material's melting point and λ is its thermal conductivity). Their research reflects that material removal rate decreases when the $\lambda \cdot \theta$ value increases. Based on this, Mahardika et al. [13] further proposed the $\lambda \cdot \theta \cdot \sigma$ theory by additionally considering the material's electrical resistivity σ. It indicates that the material is more difficult to machine when its $\lambda \cdot \theta \cdot \sigma$ value is higher. In addition, the corrosion resistant coefficient ($C_m = \lambda \cdot c \cdot \theta^2$) is also widely used to indicate the difficulty of processing the material with EDM [14]. According to this, when the C_m value of the material is larger, it is more difficult to be eroded. All researches mentioned above indicate that thermal physical properties have significant effect on the EDM performance. Therefore, the influence of TZMs thermal physical properties on EDM mechanism need to be further studied since this alloy has some special thermal physical characters.

In this research, the EDM mechanism was analyzed firstly under the condition of single discharge. To do that, the influence of the thermal physical properties of TZM alloy on the material removal effect was investigated. A single discharge thermal erosion simulation was conducted to investigate the temperature distribution on the workpiece surface. Furthermore, based on preliminary experimental results, in order to optimize the machining performance of TZM in EDM, a set of parameter optimization experiments in conjunction with the Box–Behnken design was carried out to establish the mathematical relationship between the input parameters and the responses. Additionally, the surface characteristics under two different optimized parameters were analyzed to study the influence of discharge energy on machined surface quality. Lastly, a TZM alloy hot-gas valve part sample which has flow channels was machined based on the experimental findings.

2. EDM mechanism analysation of TZM alloy

2.1. Thermal physical properties of TZM alloy

In EDM process, the formed plasma channel transfers thermal energy to the workpiece and then erode the workpiece material, meanwhile leaving craters on its surface. Therefore, the thermal properties of the workpiece material, such as melting point, thermal conductivity along with its specific heat will greatly influence the machining performance. The thermal properties of TZM were compared with a typical material, namely Cr12 die steel, as shown in Table 1.

As shown, TZM alloy has a much higher melting point, better thermal and electrical conductivity than that of Cr12 die steel. Higher melting point indicates that higher temperature is necessary to melt material during the EDM process. Higher thermal conductivity results in a much rapid heat disperse from the molten area and results in a slower temperature incensement of the workpiece.

From the literatures mentioned above, the $\lambda \cdot \theta \cdot \sigma$ theory and corrosion resistant coefficient C_m of the material can be used as the criteria of judging the difficulty of machining with EDM. Moreover,

Table 1
Thermal physical properties of TZM and Cr12.

Material	Melting point θ [K]	Thermal conductivity λ [W/(m K)]	Specific heat c [J/(kg K)]	Electrical resistivity σ [Ω cm]
TZM	2890	126	250	5.7E−6
Cr12	1600	40	420	9.7E−6

Table 2
The $\lambda \cdot \theta \cdot \sigma$ and C_m values of TZM and Cr12 die steel.

Material	$\lambda \cdot \theta \cdot \sigma$	C_m
TZM	0.0208	2.63×10^{11}
Cr12	0.0062	0.43×10^{11}

Table 3
Single discharge experimental parameters.

Parameters	Values
Electrode	Graphite
Workpiece	TZM alloy, positive
Peak current, A	4, 8, 20
Pulse duration, μs	10, 20, 30, 40,50

both of them indicate that the workpiece material is more difficult to be eroded by the discharge spark when the criteria values are greater. The values of $\lambda \cdot \theta \cdot \sigma$ and C_m of TZM alloy and Cr12 steel are listed in Table 2. it is obvious that the product of the TZM criteria are much higher than that of Cr12, which indicating TZM is much more difficult to be processed by EDM process.

2.2. Single discharge experiment of TZM material

2.2.1. Experimental procedure

Although the existing theories ($\lambda \cdot \theta \cdot \sigma$ theory and C_m theory) indicate that that the TZM alloy is difficult to be eroded by EDM, its characteristics such as the influential factors on efficiency and quality are also need to be further studied. The single discharge experiment is an effective method to study EDM characteristics [15,16]. Therefore, in order to better understand the EDM mechanism of the TZM alloy, a series of single discharge experiments were conducted on an EDM machine (type: BIEM-Sodick C40) as shown in Fig. 1.

In the single discharge experiment, input discharge parameters mainly including the peak current and pulse duration which determine the input discharge energy. Therefore, the chosen variables of this experiment are those two factors, and other discharge parameters are set constant. The experimental conditions are listed in Table 3, and the open voltage was set as 90 V, the dielectric is hydrocarbon-based liquid (the pulse interval is not considered in single discharge experiment). The experimental results focus on the variation of the crater geometry and size of the workpiece which influence the ultimate material remove rate as well as the surface quality. The experimental results focus on the geometry and size of the crater which influence the material remove rate as well as the surface quality. The crater geometry was observed and measured by a Zeiss Stemi 2000-C stereomicroscope.

2.2.2. Experimental results and analysis

Fig. 2 shows the generated crater under different discharge parameters and a typical discharge crater is marked in Fig. 2, the characteristic of a typical discharge crater is described and marked in Fig. 3. As shown, most trials in the experiment generate a crater (black region in the center) which is surrounded by a dark gray circular region. Generally, the crater is regarded as the result of the discharging plasma but the causation of the dark circular has not been reported and analyzed before. The discharge crater is small and deep, while the dark gray annular region is much shallower and is only about a few microns. According to Ref. [17], their experimental results indicate that the plasma diameter is several times greater than that of discharge craters. It can be deduced that the dark grey region is also the effect of the plasma channel but the workpiece material was not removed effectively during discharging. Thus, the dark grey region was considered as the plasma region in this research.

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