Precision Engineering 45 (2016) 285–291

Contents lists available at ScienceDirect

Precision Engineering

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

An investigation into wire electrochemical micro machining of pure tungsten

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ARTICLE INFO

Article history:
Received 3 December 2015
Received in revised form 15 February 2016
Accepted 7 March 2016
Available online 16 March 2016

Keywords:
Micromachining
Electrochemical
Wire
Tungsten
ECM
WECM
Multi
Microstructure

ABSTRACT

Tungsten-based microstructures have attracted great interest in many industrial advanced applications. Nevertheless, with a disadvantageous combination of high hardness, toughness and brittleness, the micro machining of pure tungsten poses significant difficulty. In this paper, an investigation into the wire electrochemical micro machining (WEMM) of pure tungsten at low alkaline electrolyte concentration and small pulse duration is presented. Under the optimal machining conditions, tungsten-based microstructures with a side gap of 4 μm, slit width of 18 μm and aspect ratio of 5.6, as well as with a side gap of 5 μm, slit width of 20 μm and aspect ratio of 15, were obtained. In order to improve productivity in the machining of multi-slit microstructures, multi-wire electrochemical micro machining of tungsten was introduced. Using a 3-wire electrode, a 9-slit microstructure with a slit width of approximately 24 μm was produced and the machining efficiency was improved by a factor of three. The results revealed that it was a promising method for the fabrication of tungsten-based periodic or quasi-periodic microstructures, such as the gratings used in the X-ray absorption contrast system of imaging.

1. Introduction

Tungsten exhibits the highest operating temperature of all metals, at around 2900 °C (3173 K), with a high melting point of 3420 °C (3695 K), good heat stability and high temperature resistance, as well as excellent X-ray absorption ability [1,2]. Tungsten-based micro devices have attracted great interest in electronics, semiconductor manufacturing processes and medical treatments [3]. For example, tungsten has been applied in micro electrodes, emitter tips, rocket engine nozzles and the plasma-facing parts in a fusion reactor, due to its advanced high-temperature properties [4,5]. With a rating of 9 on the Mohs Hardness Scale, tungsten serves as a perfect mold material to produce plastic bio-MEMS chips [6]. In addition, the collimator and detector, two key parts in a medical computed tomography (CT) machine, are generally shaped from tungsten plates with a thickness of several hundred microns, owing to the material's excellent X-ray absorption ability. Moreover, tungsten is a promising candidate for making the metal grating in the X-ray phase contrast imaging system, which has a prospective application when combined with CT technology to produce new X-ray phase contrast CT equipment [7]. X-ray phase contrast technology can effectively reduce the irradiation dose of X-rays during CT diagnosis, enabling the detection of tiny cancerous tumors with high sensitivity so as to achieve early detection of cancer.

In high-precision devices, the feature size of some tungsten-based parts has shrunk to the micro scale. High machining accuracy and good surface quality are also required. For instance, the collimator and detector in medical CT machines have complex shapes, and the width of the micro slits in them is generally only a dozen or a few dozens of micrometers. Moreover, the period of metal gratings in the X-ray phase contrast system has reached the micron scale, and they need to be of high aspect ratio. With a disadvantageous combination of high hardness, toughness and brittleness; however, the micro machining of tungsten poses significant difficulty. Generally, very high tool wear is to be expected for traditional machining methods [3]. Thus, several non-traditional methods have been introduced for the machining of tungsten. Micro wire electro discharge machining (μ-wire EDM) is currently used to produce planar tungsten-based micro devices such as the collimator and detector in medical CT machines [3], but it generates significant surface damage and micro-cracks in the shaped parts, which can lead to failures [9,10]. It also suffers from tool wear [11], and so the wire used in μ-wire EDM cannot be too small. In addition, Song et al. [6] obtained tungsten-based microstructures with a feature size of less than 3 μm and an aspect ratio above 13 using inductively

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http://dx.doi.org/10.1016/j.precisioneng.2016.03.005
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coupled plasma etching at an etch rate of 37 nm/s. However, the process involved in this method was complex and thus the practical application of it was limited.

Wire electrochemical micro machining (WEMM) has been increasingly recognized as an effective method for the production of complex-shaped microstructures that require a high aspect ratio. It not only has the basic characteristics of electrochemical machining (ECM), but does not require the fabrication of a complex-shape cathode. Superior to μ-wire EDM, WEMM neither suffers from surface defects nor wears out a tool electrode [12]. In consequence, a thinner wire can be used, allowing a narrower machined slit to be obtained. Zhu et al. [13] fabricated microstructures with a slit width of less than 20 μm on nickel plate measuring 80 μm in thickness using a 5 μm-diameter tungsten wire. Through optimizing the pulse conditions of the WEMM process, Shin et al. [14] obtained micro grooves with a wall width of about 9 μm and a gear with an external diameter of 580 μm on stainless steel plates. Wang et al. [15] found that low-frequency, small-amplitude vibration could significantly improve the processing stability, overcut, machining accuracy and repeatability accuracy of the WEMM process. Zeng et al. [16,17] presented three approaches to enhance mass transport, namely, wire traveling in one direction, electrolyte flushing along the wire, and wire reciprocated traveling in the axial direction to remove electrolysis products and renew electrolyte in the machining area. Moreover, they produced micro cams with $R_a = 0.058$ μm and $R_{\max} = 0.670$ μm in cobalt-based alloy substrates measuring 80 μm in thickness through optimizing the cathode traveling, anode vibration and pulse conditions [17].

Although widely implemented in process investigations of the WEMM of various materials, acidic or neutral solution generally acted as the electrolyte, however, rather than alkaline solution. During ECM of pure tungsten, WO_3 anodic film forms on the machined surface, which is totally insoluble in acidic and neutral solutions and will prevent the subsequent electrochemical dissolution. But this film can be highly soluble in alkaline solutions [18]. Thus, an alkaline solution needs to be employed as the electrolyte for the WEMM of tungsten. On the basis of previous work, there is a lack of literature on investigations into the process of WEMM using an alkaline electrolyte, as well as on the shaping of pure tungsten through WEMM, apart from the paper presented by Liu et al. [19]. They demonstrated that WEMM was capable of producing tungsten micro-tools with complex shapes effectively. But in their research, a large pulse duration (150–190 ns) and a high electrolyte concentration (0.9–1.0 mol/L) needed to be applied for a stable process, which resulted in a large machined slit width (>60 μm) and side gap (>20 μm).

In this paper, the process for the WEMM of pure tungsten with a low electrolyte concentration and a small pulse duration was investigated. The minimum values of pulse duration and electrolyte concentration necessary for a stable process were reduced to 60 ns and 0.1 mol/L, respectively. Under the optimal parameters, tungsten-based microstructures with a side gap of 4 μm, slit width of 18 μm and aspect ratio of 5.6, as well as a side gap of 5 μm, slit width of 20 μm and aspect ratio of 15, were obtained. In order to improve the productivity during the machining of multi-slit microstructures, multi-wire electrochemical micro machining of pure tungsten was introduced. The results revealed that it was a promising method for the fabrication of tungsten-based periodic or quasi-periodic microstructures such as the gratings used in the X-ray absorption contrast imaging system.

2. Experimental details

Fig. 1 illustrates the principle of WEMM [15]. In the machining process, ultra-short voltage pulses between the electrodes were supplied by a pulse generator, and an oscilloscope was used to monitor the machining current. A commercial 10 μm-diameter tungsten wire (Goodfellow Ltd., UK) was employed as the cathode

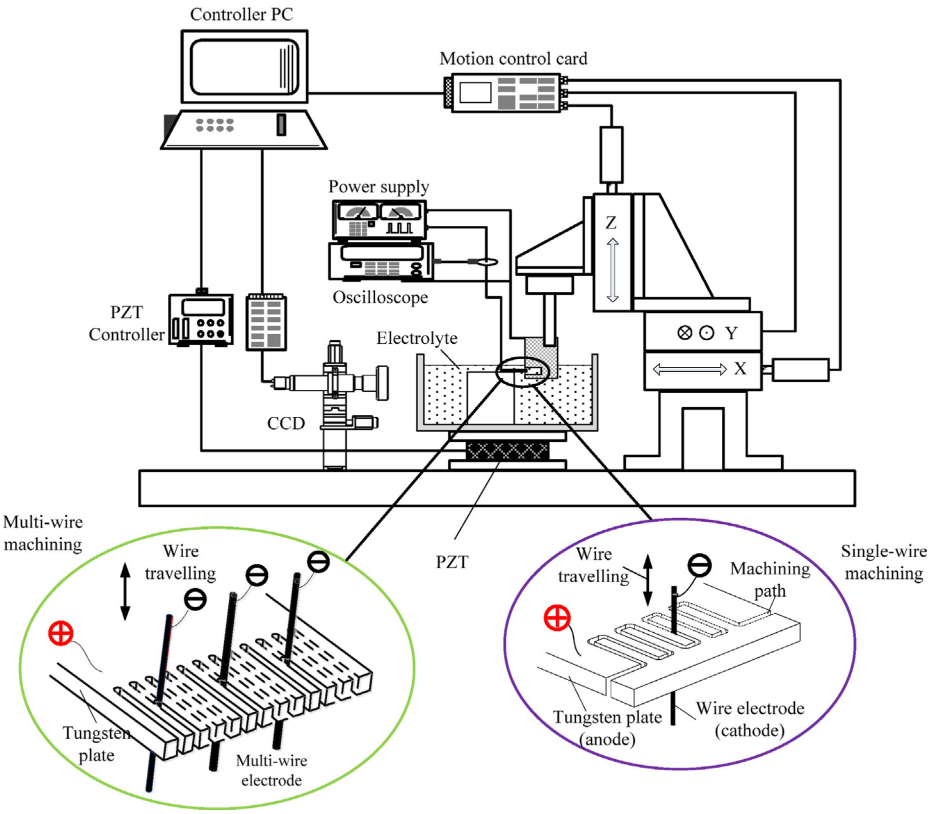

Fig. 1. Schematic diagram of experimental system [17].