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# Micropatterning of Ni-based metallic glass by pulsed wire electrochemical micro machining

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The technique of wire electrochemical micro machining (WECMM) is proposed firstly for the micropatterning of Ni-based metallic glass in this paper. Metallic glass (MG) exhibits many outstanding properties such as high hardness and strength, which enable it to be used as functional and structural materials in micro electromechanical systems (MEMS). A significant limitation to the application of MGs is the challenge of shaping them on micro scale. WECMM is a non-traditional machining technique to fabricate microstructures that has some unique advantages over other methods, which will be a promising technique for micro shaping of metallic glass structures. Taking the example of a Ni-based glassy alloy, $Ni_{72}Cr_{19}Si_{7}B_{2}$, the polarization and fabrication characteristic in dilute hydrochloric acid electrolyte were investigated. Changes in the machined slit width in terms of several experimental parameters were investigated to find the optimal ones. Finally, the optimal machining parameters: HCl electrolyte concentration of 0.1 M, applied voltage of 4.5 V, pulse duration of 80 ns, pulse period of 3 μs and feed rate of 0.3 $\mu m\ s^{-1}$ were employed for the fabrication of microstructures. Such as a micro square helix with a slit width of 14.0 μm, standard deviation of 0.2 μm and total length up to 2000 μm, along with a micro pentagram structure with side length of 90 μm and sharp corner of 36°, were machined with a high level of stability and accuracy.



## 1. Introduction

The development of new materials and micro shaping techniques for micrometer or nanometer scale components used in micro electromechanical systems (MEMS) has attracted considerable scientific and technological interest from material and mechanical science communities [1–3]. Metallic glasses (MGs) have been recognized as promising materials for realizing high-performance micro devices due to their excellent characteristics as functional or structural materials [4–6]. A new trend in metallic glass research is the development of manufacturing processes for micro- or nano-patterned structures with functional properties for use in MEMS [7,8].

Microstructures in metallic glass are now generally fabricated by superplastic forming, which is carried out in the undercooled liquid region, in other words, between the glass transition temperature $T_g$ and crystallization temperature $T_x$, where metallic glass behaves as a highly viscous liquid [4,8,9]. However, it is difficult to control the deformation temperature and rate during the superplastic forming process because of the narrower undercooled liquid region, and crystallization may occur in the super liquid region during micro forming. On the other hand, the microstructures produced by superplastic forming have only low aspect ratio features, so the applications of such materials are limited by the fabrication methods. The new task of high aspect ratio features can only be fulfilled with new processing routes for metallic glass. For example, a process for the replication of surface microstructures with high aspect ratio features in metallic glass has been developed based on a casting process with separation of mold filling and quenching in time [10]. Additionally, a specific microstructure in Zr-based glassy alloy fabricated by micro electrical discharge machining (MEDM) has been researched by Chen et al. [11]. However, a number of processing-induced defects such as recast layer, heat-affected zone and micro-cracking are typically encountered, because MEDM is a high temperature process to melt and evaporate the surface

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material [12]. These micro forming techniques are only successful for selected glassy alloys that are of limited technological importance. Therefore, a low-cost technique which is applicable to the micro manufacturing of a wide range of glassy alloy systems is desirable.

Wire electrochemical micro machining (WECMM) is a particular kind of electrochemical micro machining (ECMM) method that has been increasingly recognized as a flexible and effective method for the fabrication of complex-shaped components [13–15]. In this process, the workpiece acts as an anode and the micro wire acts as a cathode. A sub-micrometer level of precision can be achieved when an ultra-short pulse is used. Tool wear and induction of heat or stress into the workpiece are eliminated and material removal is independent of the hardness and strength of workpiece, making WECMM a promising fabrication technique for MEMS. According to the electrochemical double layer (DL) theory, for only a small distance between the workpiece and tool electrode, the resistance through the electrolyte is small enough and the electrochemical double layer is locally charged sufficiently for significant anodic workpiece dissolution [16–18]. Therefore, the highly localized material removal is possible when an ultra-short voltage pulse is applied during WECMM. The ECMM technique has been successfully established for the machining of crystalline material such as Cu, Ni and stainless steel [15,19,20]. However, the ECMM processing of MGs is quite complicated due to the multi-component alloy nature and unusual reactivity of the metastable phase. The applicability of pulsed ECMM to glassy alloys was first proven by Koza et al. [21] with a Zr-based MG. The principal feasibility of ECMM was also demonstrated by Sueptitz et al. [22] with a Fe-based glassy alloy in a non-aqueous electrolyte. So far, the WECMM processing of complex structures with high aspect ratio features from metallic glasses has hardly been investigated at all.

In this paper, the first introduction of WECMM processing for a Ni-based MG ($Ni_{72}Cr_{19}Si_7B_2$) in dilute hydrochloric acid electrolyte is researched. Changes in the machined slit width in terms of pulse duration, feed rate, applied voltage, pulse period and electrolyte concentration are investigated experimentally to find the optimal machining parameters. Many complex microstructures are fabricated from the $Ni_{72}Cr_{19}Si_7B_2$ glassy alloy with a high level of stability and accuracy under the optimal machining conditions.

## 2. Principle of WECMM

Fig. 1(a) illustrates the principle of WECMM. In the machining process, an ultra-short pulse generator is applied between the electrodes in an electrolytic cell. The electrical potential on the workpiece will be charged in a pulse duration time and material removal starts at a certain potential level. A narrow slit is produced as the cathode wire electrode is fed towards the anode workpiece along the programmed tool trajectory. Meanwhile, the cathode wire travels with a reciprocating motion and the anode workpiece vibrates in the Z direction during the machining process.

As shown in Fig. 1(b), the bubbles and solid electrolytic products (such as hydroxide precipitation, Si and B solid particles) are produced in the machining gap. These can seriously affect the conductivity of the electrolyte. The electrolyte conductivity $\kappa$ is significantly affected by the electrolysis products fraction $\beta$ and the initial electrolyte conductivity $\kappa_0$ in the manner described in Eq. (1) [23].

$$\kappa = \kappa_0 \frac{2(1-\beta)}{2+\beta} \quad (1)$$

As the machining gap is deep and narrow, the diffusion of bubbles and solid electrolytic products, along with the renewal of electrolyte are difficult. It will reduce the electrolyte conductivity and cause electrical short circuits, which results in poor machining results. In this study, the cathode wire travelling and anode workpiece vibration during the machining process have been developed as an effective method for enhancing mass transport.

The machining accuracy of the proposed method mainly depends on the side gap $\Delta_s$, which is defined as follows [23].

$$\Delta_s = \frac{S-D}{2} \cong \Delta_b \sqrt{\frac{2D}{\Delta_b}+1} \quad (2)$$

where $S$ is the machined slit width, $D$ is the diameter of the wire electrode, and $\Delta_b$ is the machining equilibrium gap, which can be calculated by:

$$\Delta_b = \frac{\eta \omega \kappa U}{v} \quad (3)$$

where $\eta$ is the current efficiency of anodic metal dissolution, $\omega$ is the volumetric electrochemical equivalent, $\kappa$ is the electrolyte conductivity, $U$ is the machining voltage and $v$ is the feed rate.

From Eqs. (1)–(3), it can be concluded that the wire feed rate, applied voltage, electrolyte concentration and electrolysis products fraction will influence the slit width. Therefore, a series of experiments need to be carried out to explore the influence of process parameters on the machining accuracy. Based on a pre-trial of stable machining, the machining parameters are chosen in specific ranges that will be studied in the following sections.

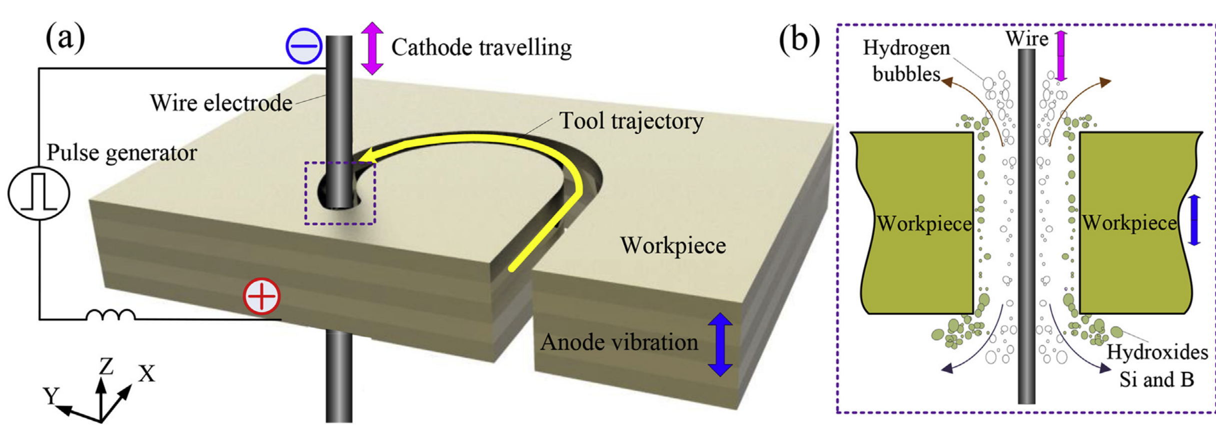


**Fig. 1.** (a) Schematic diagram of WECMM; (b) Schematic of electrolysis products in the machining gap.