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Reducing the residual stress in micro electroforming layer by megasonic agitation

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ABSTRACT

In order to reduce the large residual stress in micro elelctroforming layer, megasonic assisted electroforming is proposed here. Micro electroforming experiments were performed with and without megasonic agitation, respectively. Four different megasonic power densities were applied to investigate the influence of megasonic agitation on reducing the residual stress. The residual stress was measured by X-ray diffraction (XRD) method. Experiment results show that the residual stresses fabricated with megasonic agitation are less than that fabricated without megasonic. When the megasonic power density is 2 W/cm^2, the residual stress can be the minimum value of −125.7 MPa, reduced by 60% in comparison with the value of −315.1 MPa electroformed without megasonic agitation. For exploring the mechanism of megasonic agitation on reducing the residual stress, the dislocation density and crystal orientation were calculated by the single-line Voigt profile analysis and Relative Texture Coefficient (RTC) method, respectively. The diameters and distributions of pits on the surface of electroforming layer were observed by the STM-6 tool microscope and counted by the Image-Pro Plus software. It reveals that one hand of the mechanism is the acoustic streaming produced by megasonic can strengthen the motion of dislocation in crystal lattice and makes the crystal lattices grow towards the equilibrium shape, which is benefit to crystallization with low residual stress. When the megasonic power density is 2 W/cm^2, the dislocation density increases to be the maximum value of 8.09×10^{15} m^{-2} and the difference between RTC$_{(1\,1\,1)}$ and RTC$_{(2\,0\,0)}$ decreases to be zero, which is consistent with the residual stress results. The other hand is that the stable cavitation produced by megasonic can provide residual stress release points during the electroforming process.

1. Introduction

Micro electroforming technology has become the first choice to fabricate metal microdevices in MEMS due to its high machining precision, low cost and mass production [1]. Metal microdevices including micro inertia switch, micro fuse security device and micro actuator have a wide application in aerospace fields and military transport systems. However, during the electroforming process, the metal microdevices usually suffer from the large residual stress, which may lead to the warpage or delamination of electroforming layer and finally result in the fabrication failure. Meanwhile, the large residual stress has an adverse influence on the dimensional precision, mechanical properties and service lifetime of the microdevice. This problem will be serious with increasing the height of electroforming layer and the high aspect ratio of microstructures.

Many contributions have been made for reducing the large residual stress, including process parameters optimization, high-temperature annealing, ultrasonic vibration aging and ultrasonic assisted electroforming. In terms of parameters optimization, Zhang et al. [2] investigated the influences of nickel sulfamate concentration, current density, pH value and electrolyte temperature on the residual stress in Ni electroformed layer. The optimum process parameters of 300–350 g/L nickel sulfamate concentration, 2–3A/dm^2 current density, 4.0–4.5 pH value and 50–55 °C electrolyte temperature were obtained by amount of experiments. Chan et al. [3] proposed that electroforming with reverse pulse current is beneficial to obtain the Ni electroforming layer with a low residual stress. Experiment results showed that the residual stress can be the lowest at a frequency of 1000 Hz, a current density of 8 A/dm^2, a negative peak current of 80 A and a duty cycle of 0.2. It is obvious that process parameters optimization greatly depends on the environmental conditions and time-consuming. In addition, Xue et al. [4] proved that high-temperature annealing is effective for

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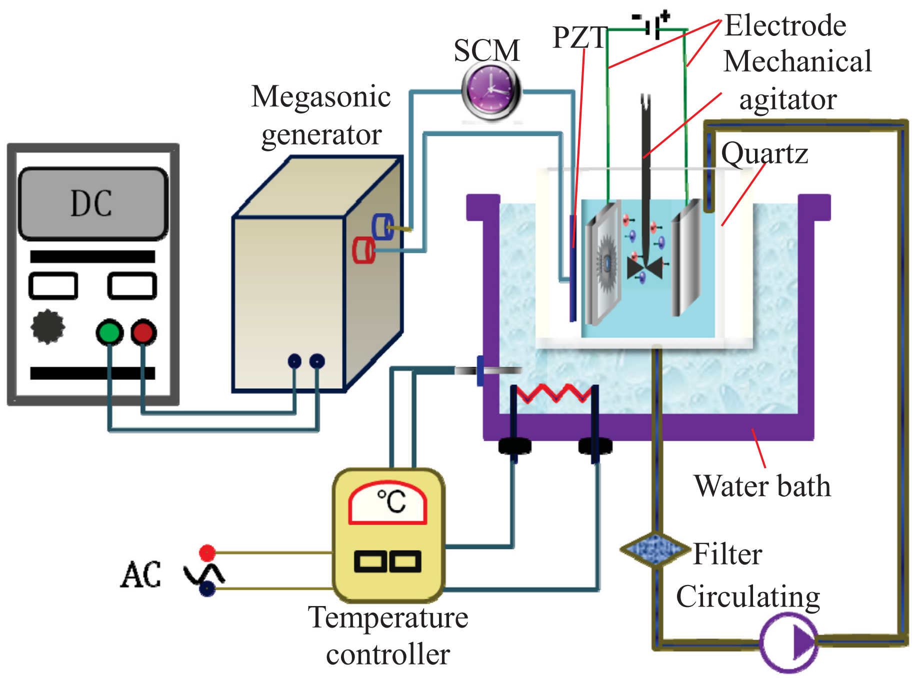

Fig. 1. The schematic of ME1000 type megasonic micro electroforming equipment [23]

removal of the large residual stress in Ni electroplating layer. Cheng et al. [5] proposed that ultrasonic impact treatment can alleviate the tensile stress concentration and enhance the fatigue strength. Du et al. [6] introduced the ultrasonic vibration aging to reduce the residual stress in Ni electroforming layer and obtained the best removal from −209.0 MPa to −109.0 MPa with the relief rate of 47.9% under proper parameters. However, heat treatment and ultrasonic vibration aging are post-processing methods, the reduction of these two methods are limited. At present, the assisted of ultrasound in electrochemical process [7] and electroplating in particular [8] has also been reported to improve the electrodeposition process itself and the characteristics of deposits. In ultrasonic assisted electrodeposition, Walker et al. [9] found that ultrasound can reduce the concentration polarization, increase the cathodic current efficiency during electrodeposition, which contributes to produce the deposited layer with finer grain size and low residual stress. Nevers and Hihn et al. [10] revealed that ultrasound can change the microstructure to be the [1 1 1] preferential orientation, decrease the cathodic overpotential, increase the current density ranges and finally obtains less structured silver electrodeposits. Expect for the improvement of electrodeposition process, Vausdevan et al. [11] used ultrasound electroplating to solve the problems of coating cracking and embrittlement, and pointed out that ultrasound can reduce tensile stress during the electroplating process. Prasad [12–15] and Wang [16] both found that ultrasound electroplating can reduce the tensile stress, improve the hardness and fatigue strength of Ni coating. In the previous work [17], we also investigated the influence of ultrasonic power on reducing the residual stress in Ni electroforming layer under nickel sulphamate solution. The residual stress could be the smallest at the ultrasonic parameters of 40 kHz and 200 W, decreased from −259 MPa to −144.4 MPa with the stress relief ratio of 44%. Currently, ultrasonic assisted electroforming has been proved to be the most effective method to reduce the residual stress. But the ultrasonic assisted electroforming is restricted by the photoresist mold deformation or damage, because of the high cavitation energy resulting from the transient collapse of bubbles produced by ultrasonic acoustic wave [18]. Thus, these existing methods are imperfect for obtaining the electroforming layer with low residual stress. In order to avoid the disadvantage of high transient cavitation energy, a higher frequency acoustic agitation is taken into account for the electroforming process in this paper.

Megasonic, known as the ultrasonic frequency nearly 1 MHz, has significant advantages of low cavitation effect, high sound intensity and acoustic streaming. Since 1970, megasonic has been employed for cleaning in micro technology [19] and it presents superiorities on the gentle cleaning. Moreover, the megasonic supported development of LIGA microstructure has been widely proposed and investigated in MEMS [20–22]. It reveals that megasonic agitation can increase the development rate and cause little damage, which especially benefits to the development of microstructure with a high aspect ratio. Currently, megasonic assisted electroforming has been used to improve the uniformity of micro electroforming layer [23]. It reveals that the megasonic wave can reduce the thickness of Nernst diffusion layer and improve the dispersion ability of the electrolyte solution so as to eliminate the uneven phenomena in the electroforming process. Thus, megasonic can provide superior advantages in electroforming process and may provide a new physical mechanism compared with low frequency ultrasonic wave. To our knowledge, there are few studies on reducing the residual stress in micro electroforming layer by megasonic agitation.

In this paper, the megasonic agitation is proposed to reduce the residual stress in Ni electroforming layer. In order to investigate the influences of megasonic agitation on residual stress, micro electroforming experiments are carried out with four different megasonic power densities. The surface morphologies of electroforming layers are observed and the pits in electroforming layers are counted by Image-Pro plus software to analyze the megasonic cavitation effect. The dislocation density and crystal orientation are calculated. The relationship between dislocation density, crystal orientation and the residual stress are analyzed to reveal the mechanism of megasonic agitation on reducing the residual stress in micro electroforming layer.

2. Experiment procedure

Micro electroforming experiments were carried out on the self-developed ME1000 type megasonic micro electroforming equipment. The experiments were divided into two parts, electroformed without megasonic agitation and electroformed with megasonic agitation under different megasonic power densities. Fig. 1 shows the schematic of the experiment equipment, which mainly consists of megasonic generator, megasonic agitator, quartz electroforming device, electroforming