A DEVICE OF TRANSDUCING MECHANICAL FORCE USING METAL DIFFRACTION GRATING SENSOR

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A device of transducing mechanical force using a metal based diffractive grating sensor is presented The diffraction gratings are successfully fabricated on a metal at sub-micron order using the holographic interferometry and molding processes . First, holographic interference using a He-Cd (325nm) laser was used to create the master of the periodic line structure on an i-line sub-micron positive photoresist film. A 200nm nickel thin film was then sputtered onto the positive photoresist. Pattern was then transferred to a metal using Nickel-Cobalt electroforming. The micro MTS tensile test incorporated with the surface diffraction grating experiment showed that a relationship between the load and the observed diffraction pattern shift could be obtained with an excellent correlation .

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1. Introduction

Investigation in strain sensing has been an active research area for the past 60 years, and the results have the potential to impact a large number of industries and disciplines [1-4]. The technologies applied to date in the tactile sensing field include metal strain gages, conductive elastomers, ferroelectric polymers (i.e. PVF2), semiconductor strain gages, and optoelectronics [1]. The characteristics of all strain sensors depend, to some degree, on the properties of the deformable contact materials. Each material has its advantages and disadvantages, depending on physical properties and manufacturing concerns. For example, the advantage of metal strain gages is that they are inexpensive, commonly used in industry, and have a wide range of sensitivity. The disadvantages of metal strain gages are that they are not suitable for large deformation applications and that the gage factors are small, which yields a low sensitivity. The advantage of using PVF2 film is that it is flexible and can withstand rather large strains without severe deterioration. However, the material is structurally weak and prone to damage. In addition, the material suffers from poor fatigue life and from shrinkage due to aging and temperature.

Another means of transducing mechanical strain is the use of optical technique. Most of the free space optical approach employs interferometric technique. Examples of these methods include infrared photoelasticity, advance Moiré, Moiré interferometry, white-light speckle photography, etc. [5]. Here we present a novel means of transducing strain along the axial direction using a diffractive Bragg grating sensor.

Reflection gratings are an important component of modern high resolution spectrometers and related x-ray optics [6-9]. The conventional way of fabricating grating includes the steps of patterning and etching. These traditional methods result in gratings which suffer from a number of deficiencies, including high surface roughness and poor control of groove profile. These deficiencies lead to poor diffraction efficiency and high levels of scattered light.

One of the main processes of fabricating grating is to pattern gratings on photoresister. These typical techniques include holographic surface relief grating [10,11], electro-beam (e-beam) lithography [12], laser-beam direct writing [13], X-ray mask technology[14], and phase mask lithography [15,16]. Although these tools provide high precision in manufacturing, they are often limited by the size of the device that can actually be manufactured. These tools are also hard to get and relatively expensive. On the other hand, the holographic interferometry offers important advantages compared to other techniques because it can easily control the period and depth of gratings, and it is more suitable for to the production of high-resolution gratings than other techniques, yielding good uniformity of the grating period with greater ease. In addition, the theoretical limit of the frequency of the interference pattern produced by two intersecting beams is half of the wavelength of the incident beam. Thus, the grating period is limited only by the wavelength of the light source. Therefore, in this paper we will describe a technique combining the holographic interferometric and electroforming processes to create a high aspect ratio grating structure on a metal surface.

2. Experimental results and discussion

The technique of forming grating patterns on the metal involved three processing steps: First, a grating pattern is holographically exposed using two-beam interference pattern on a positive photoresist film. A 280nm nickel thin film is then sputtered onto the positive photoresist mold. This mold can be subsequently used to transfer the final gratings pattern onto a metal by electroforming process. The following sections describe the process involved for the grating fabrication [17].

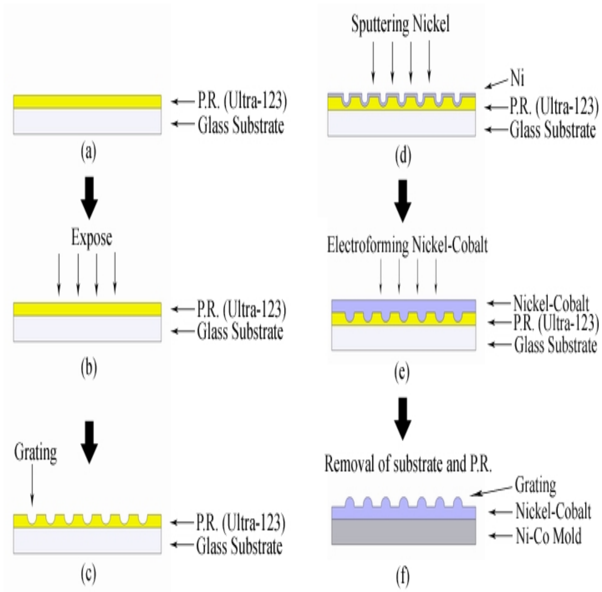


Fig.1 Schematic illustration of the metal grating fabrication

The master grating patterns on a positive photoresister (Ultra123, Microchem. Corp. MA) were holographically exposed using a two-beam interferometer technique (Fig.1 (a)-(c)). The details of the process were described in the previous reports [18].

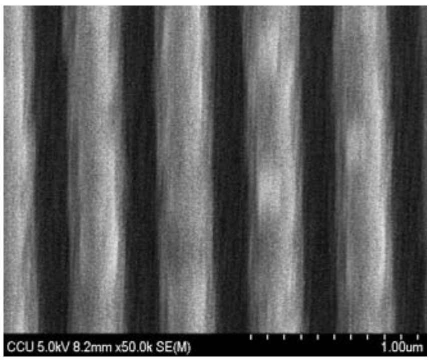
For increasing the adhesion, a 200nm nickel thin film first sputtered onto the positive photoresist mold to serve as a seed layer for the subsequent electroplating of Ni-Co alloy, i.e., a nickel thin film was sputtered onto the positive photoresist mold by a RF sputter for 5 minutes (Fig.1 (d)). The power source is 50W, and the pressure is controlled under 5 x10^{-3} Torr. The thickness of nickel is about 200nm. Electroplating process using nickel-cobalt alloy was applied to create the metal grating. The sample is then immersed into a tank filled with solution of nickel and cobalt salt diluted in boric acid. Bars of nickel and cobalt hang in the tank served as anodes to keep the solution in balance. An electrical current passed through the solution, causing atoms from each element to form a metal on the surface being plated.

Table 1 Ni-Co alloy electrolyte composition

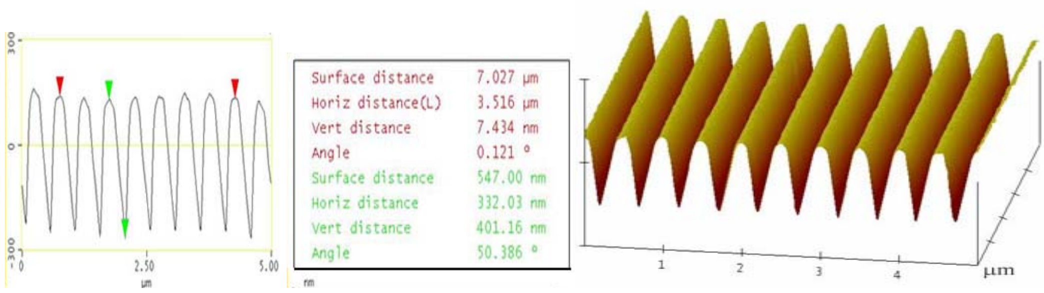
Ni concentration	70 g/L
Co concentration	1~20% (w/o) in sol.
Boric acid	30~40 g/L
Current density	1~10 ASD (Adm^{-2})
PH	4.0±0.5
Temperature	55±1ºC
Agitation	Magnetic stirrer

In our setting, Boric acid: 30 - 40g/l and Co concentration between 1 to 20g/l and 70g/l were used. The pH level was kept around 4.0 and temperature was maintained near 55^{o}C, and the solution was agitated by a magnetic stirrer (Table 1).

For improving the thickness uniformity of electroplating mold, which is usually in concave shape, a secondary cathode was applied. The secondary cathode was placed at a specific distance (less than 2.5mm) from the primary cathode during the electroplating process. Two power supplies are used; one is for the primary cathode, and the other one is for the secondary electrode. Both cathodes share with the same anodes, and the applied current density is the same for both cathodes. The purpose of the second cathode was to reduce the local ion concentration of the double layer surface plating area. This process hindered the grow rate on the edges of the deposited mold. When high deposition rate occurs on the edges of the plating field, the secondary cathode becomes a frame shaped like the plating area, which adapts to locally reduce the deposition rate on the primary cathode.



(a)



(b)

Fig.2 The SEM and AFM micrographs of gratings on PCpolymer (a) SEM (b) AFM (475 nm grating period and 401 nm grating depth).

After 15 hours of continuous deposition at a deposition rate of 15.6μm/hour, a 234μm thick layer of Ni-Co metal is deposited above the surface of the positive resist mold (Fig.1 (e)). The positive photoresist was then stripped away using acetone (Fig.1 (f)).

The AFM and SEM micrographs of the gratings on metal show that a high aspect ratio periodical structure can be obtained by the above fabricated process (Fig.2). The average surface roughness is about 48 nm.

In order to investigate the performance of the diffraction gratings, the first order diffraction efficiencies,η, of the gratings with period of 480 nm and depth of 403 nm on the Ni-Co metal were measured by a blue laser at a wavelength of 473 nm, which with TEM00 mode was incident in the normal direction to the metal grating surface. A polarizer with vertical polarization direction was set in front of the grating to make the transverse electric wave illuminate the grating. Then, a first order diffraction beam was observed at the reflection plane with 71° respect to the normal direction. The diffraction efficiency of 79% was attained for +/- first order modes.

The metal gratings with period of 473 nm and depth of 404 nm (the dimension is 1cm x 1cm) was then glued on the center of an Al alloy sample by the JB-782 epoxy for the tensile test (Fig.3). The micro Materials Test System machine (MTS) was used to apply the tensile load on the Al alloy sample with metal grating sensor. The change of the gratings period on the sample due to a tensile load was observed based on the strain-induced grating period shift using the Raman scattering setup (Figure 4). The diffracting angle measurement was used to calculate the displacing grating period using the Raman principle. A He-Ne laser (wavelength=632.8nm) was used to provide the incident light intensity that was focused on the center of the diffracting gratings. The distance between the sample and observed diffraction intensity is 5.6 cm. The positions of the diffracted light were measured at some predetermined location using a straight ruler with a 1mm resolution.

The diffracted angle of the metal gratings based on normal incident is defined as

$$\sin\theta_d = m\frac{\lambda_0}{\Lambda} \tag{1}$$

where, θ_d is the diffracted angle from the grating, λ_0 is the free space wavelength of the laser light, Λ is the grating period, and m is equal to $\pm$ 1. The diffracted angle can be obtained from the displacement *y* (distance between the central maximum to the first order maximum) and *D* (separation between gratings to the observed screen),

$$\tan\theta_d = \frac{y}{D} \tag{2}$$

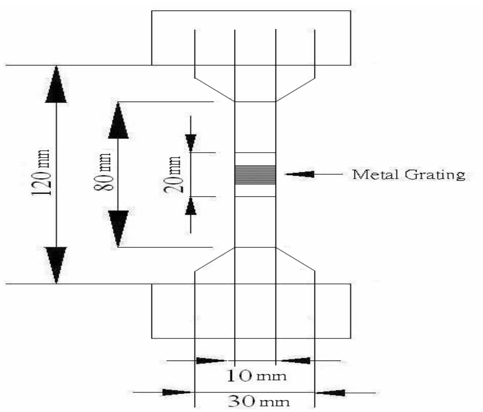


Fig. 3. The top view of the tensile test sample (the dimension unit is mm).

Fig. 5 shows that the gratings period increased with an increase of axial load .The period appears to change nonlinearly with the axial load. Based on the initial study, we found the sensitivity of the diffracting grating sensor is good. Since the sensitivity of the load cell was limited at 0.1N, our sensor's sensitivity is currently set at 0.1 N for the tensile force sensing. We believe this number should be one orders or better if a better loading and optical setups were used for the measurement.

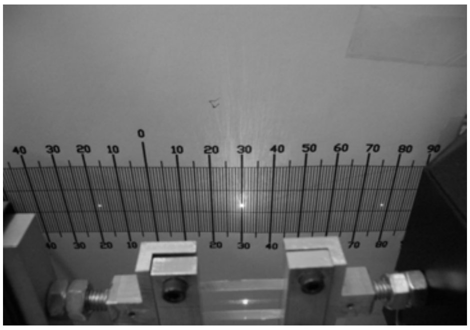


Fig. 4. The micro MTS test accompanied with the Raman experiment.

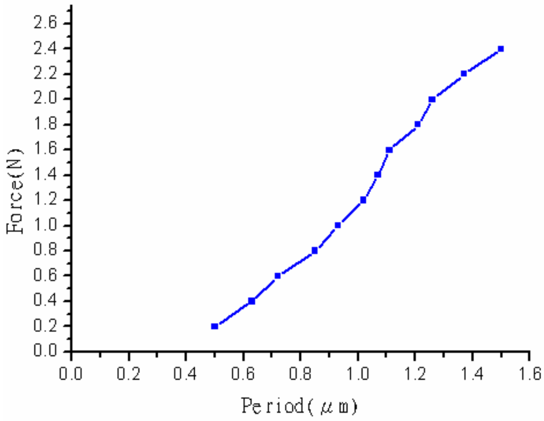


Fig. 5. the gratings change as a function of the load

3. Conclusion

In conclusion, the metal diffraction gratings were successfully fabricated using electroforming and holographic interference techniques . A large aspect ratio on the grating pattern could be obtained. The micro MTS tests incorporated with the Raman experiment showed that the grating period on metal was sensitive to the tensile stress. The results from our preliminary study show the metal sensor capable of measuring very small axial load . It is our intention that a tensile/shear sensor will be derived for mechanical or biomedical applications.

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