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THE INFLUENCE OF COATING FABRICATION PROCESSES ON THE OPTICAL EFFICIENCY OF REPLICATED MOIRÉ DIFFRACTION GRATINGS

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Abstract

One of the most important parameters in the study of diffraction gratings is their optical efficiency. This paper analyzes the different manufacturing processes to cover gratings of Moiré interferometry and their influence on the quality and absolute efficiency of replicated gratings on the surfaces of specimens. The Moiré interferometry is a field measurement technique that has been used in many different fields such as applied mechanics, microelectronics, biomechanics or micromechanics, hence the importance of this study. The applied reflected coating was done by sputtering and aluminium vaporization processes. In this work different materials and thickness layers were analyzed. The obtained coatings have a high degree of reflectivity on the replicated gratings.

Keywords: diffraction gratings, Moiré interferometry, gratings replication, optical efficiency.

1. Introduction

Moiré interferometry is a well-known optical technique to measure in-plane displacements on the surface of solid bodies. This technique is used to measure small deformations of objects, caused by mechanical forces, temperature changes, or other environmental variations. To implement this method the replication of the Moiré diffraction grating (MDG) on the object surface is required and the use of coherent light (lasers) to form an interferometer. The interferometer directs a pair of collimated wavefronts to the specimen diffraction grating at specific angles. When a deformation occurs in the object, the grating suffers a deformation and the diffracted wavefronts interfere to create patterns which represent the in-plane displacements on the specimen surface [1].

In the last decades, the optical experimental technique, Moiré Interferometry, has been implemented in many fields, of which the most important are the material characterization [2–4], microelectronics devices [5, 6], micromechanics [7, 8], fracture mechanics [9–11], the residual stress [12–14], composite materials [15, 16] and biomechanics [17, 18]. For all these cases the main goal is the global measurement of displacement fields without contact with high resolution and accuracy that the Moiré Interferometry method can offer.

In referred applications the measurement results depends on the quality and efficiency of gratings, these could be directly created on the object surface or replicated from a grating mold to the surface. The first technique is applied on small-dimension objects and the replicated method has no limitation of the object dimension that must be measured. However, the gratings replication process is a manual and laborious work which needs years of practice and natural skills to be successful in obtaining good replicated gratings on the surface to measure. The procedure to apply diffraction gratings on the surface specimen is a challenging step to obtain a good optical sensor [19]. There are numerous methods [20, 21] to perform this

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task depending on the specimen size and stiffness as well as the temperature at which the specimen is to be tested.

Another important parameter to achieve good quality gratings is the efficiency of the reflective layer that depends on the fabrication process, the metallic material used, the thickness of the layer and the environmental cleanness. In this context, the main contribution of this paper is to analyze the influence of coating fabrication processes on the optical efficiency of MDGs obtained by replication.

2. Moiré diffraction gratings

Moiré interferometry is an optical technique that uses diffraction gratings for measuring the surface deformation of an object. The approach proposed in this paper considers the grating onto surface as regularly spaced bars or furrows. The Moiré diffraction gratings present a high spatial frequency (*e.g.*, 300 to 2400 lines/mm) and are called phase gratings [22]. A coherent light beam (laser) must be produced in order to provide the incident light for doing the measurements. There are two different kinds of diffraction gratings: transmission and reflection. In the case of transmission gratings, the incident light passes through the grating; then, both the incident and the diffracted light beams appear on opposite sides of the grating. With the reflection gratings, the incident and diffracted beams are on the same side and the substrate is usually opaque. A grating divides the incident wave train into several wave trains of smaller intensities. These wave trains emerge in a given preferred direction (called diffraction orders). The Moiré interferometry principle is schematically represented in Fig. 1.

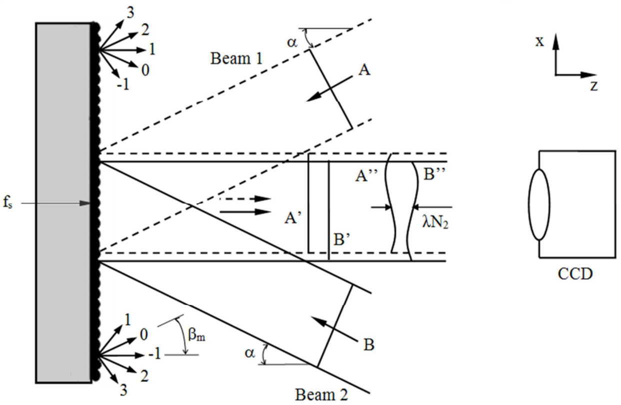

Fig. 1. Moiré interferometry principle [23].

The incident beams (A and B) illuminated the diffraction grating with a frequency of f_s and the beams are diffracted (A' and B' or A'' and B'' before or after deformation, respectively) from the Moiré grating creating fringe patterns.

The angles of diffraction are determined by the grating equation [23]:

$$\sin(\beta_m) = \sin(\alpha) + m\lambda f_s, \tag{1}$$

where m is the diffraction order, f_s [lines/mm] is the grating frequency, α [rad] is the angle of incidence and β_m [rad] is the angle mth diffraction order and λ [mm] is the wavelength of the laser light.

The application of diffraction grating on the object surface (where it is intended to measure the displacements) can be done in two ways [24]. The first one is doing its pattering directly on the surface to be measured. Alternatively, it is possible to replicate the gratings that were previously applied in a mold (master grating). The first case is applicable only for small objects with easy handling. However, the most common is the technique of replicating the grating from a mold. The grating mold can be obtained by two different processes: mechanically ruled, made by burnishing grooves individually with a diamond tool against a coating of evaporated metal applied to a plane or concave surface, or gratings based on a holographic process [25]. The ruled gratings have a triangular shape and the holographic gratings a sinusoidal one. This paper uses the holographic gratings because they are the most common in Moiré Interferometry.

The holographic method involves the recording of an interference fringe field obtained by two wave fronts on photosensitive polymers, designated by photoresist. In this process a glass plate with a very low roughness ($<\lambda/5$) is covered with a very thin layer of photoresist and is exposed to a virtual grating of frequency $f/2$, formed by two intersecting collimated beams of coherent light (usually ultraviolet and blue light). The interference pattern captured by the plate has a simple harmonic intensity distribution assuring that the furrows have a symmetrical profile. The resist is developed in a solvent that preferentially dissolves the resist. The solubility of the resist polymer increases with exposure to light, and therefore the resist dissolves most rapidly in the zones of constructive interference. Fig. 2 presents a scheme which represents the technique to obtain the holographic gratings using photoresist:

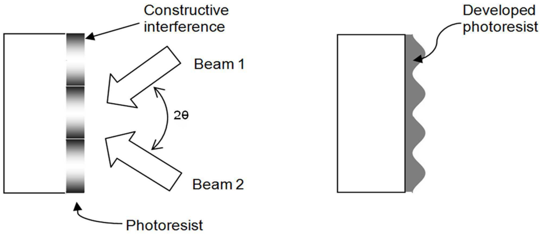

Fig. 2. Holographic grating obtained with photoresist [23].

The grating frequency could be controlled by the incident beams angle. Considering the angle θ [rad] that is the angle between the two incident beams, the specimen grating frequency, f_s is:

$$f_s = \frac{2}{\lambda}\sin(\theta), \tag{2}$$

where λ is the wavelength of the laser light.

In this paper was used this photoresist process, where the depth of furrows can be optimized by controlling the light exposure. Parallel line gratings of 1200 line/mm have been produced with good diffraction efficiencies in each of two first-order diffractions. After creating the holographic gratings with photoresist (RZJ-390 positive photoresist), it was necessary to cover them using a thin layer of reflective metal, usually aluminium or gold. The most common techniques to cover the gratings are aluminium evaporation and sputtering. The grating mold created by a holographic process is replicated on the surface of a specimen. Before the replication, the mold is prepared by applying a reflexive metal film on its grating surface. A double coating of aluminium is used, where the first layer is oxidized by allowing air into a vacuum chamber and then a second coating is applied, usually is used as the wetting agent between the first and the second layer. The second coating is the one that is fixed on the replicated grating. The replication of grating is done through an adhesive between the grating mold and the specimen surface. After the polymerization of the adhesive, the mold is pried off, leaving a reflective diffraction grating bonded to the surface of the specimen.

The weakest interface occurs between the mold and the metal film, which accounts for the transfer of the reflective film to the specimen [23].

3. Experimental procedure

One of the most important contribution to the optical efficiency in replicated gratings is the reflexive quality of metal coatings and this factor depends on the coating technique, material and thickness of the layer. In this experimental work we present the most common processes to coat the gratings, aluminium evaporation and sputtering, for both techniques we compared the efficiency of gratings for different kinds of coating materials, aluminium (evaporation and sputtering) and gold (sputtering), as well as different thickness of layers. Six different samples were prepared and coated with different techniques, thickness and coating materials. The process to obtain the grating mold is the same as the holographic technique already described in this paper. Therefore the importance of the quality gratings before the metallic coating, the goal of this work is not focused on the holographic technique. The grating molds developed and produced in this work were parallel line gratings of 1200 lines/mm. After coating the grating mold they were replicated on the specimen surface, which is a steel plate with a R_a roughness of 2.1 μm. The replication of gratings must be done carefully to maintain the reflection quality of the grating and replicate all the grating area of the mold. The measurements to obtain the diffraction efficiencies of gratings were done before and after the replication of coating gratings.

3.1. Coating the diffraction grating mold

The work presented in this paper intends to achieve good procedures in order to obtain better diffraction efficiencies in each of two first-order diffractions. In the first place, the most common method was used and the material for coating gratings, aluminium, applied with the aluminium evaporation technique. This procedure was followed for the first two samples, but the results were not very good and an alternative technique was tried, the sputtering. Two mold grating sample 3 were coated with aluminium, using the sputtering, but, unfortunately, the results were worse than with the former ones. Meanwhile, it was verified that few parameters in the evaporation aluminium technique could be changed; allowing better results compared with the first two samples, so three more samples were prepared (4, 5 and 6) and the obtained results were satisfactory. On the samples 1 and 2, the gratings were coated with two layers of aluminium using the aluminium evaporation process. Between the two layers a wetting agent was applied (Kodak PhotoFlo®). In Table 1 it is possible to observe the thickness of each layer.

Table 1. The aluminium layer thickness on the gratings of sample 1 and 2.

Sample	First Layer [nm]	Second Layer [nm]
1	20	60
2	40	40

The quality of these coatings did not seem to be very good. However, comparing the two samples, sample 1 appeared to have a more uniform coating, on the other hand, it presented a dark color and low reflectivity. Sample 2 was less uniform, showing areas with a very bad appearance, while others had a good quality and strong reflection.

The gratings of sample 3 were coated with one layer of aluminium using the sputtering process. The wetting agent was applied to the first layer. The first aluminium layer had a thickness of 10 nm and the second layers had 20 nm of thickness.

The samples 4, 5 and 6 were coated with aluminium produced by the aluminium evaporation process. In this case also two coatings were used. The thicknesses of each layer is presented in Table 2.

Table 2. The aluminium layer thickness on the gratings of sample 4, 5 and 6.

Sample	First Layer [nm]	Second Layer [nm]
4	30	30
5	30	50
6	30	70

The coating of sample 4 had a low coefficient of reflection, so this sample was not replicated in any specimen. Samples 5 and 6 had a much higher reflection, although the sample 6 had a region whose reflection was lower than the rest of the sample surface.

3.2. Replication of gratings

The grating replication is a process developed to apply the diffraction gratings on specimen which we want to measure.

This process of replication was done for most of the samples and we analyzed the reflection quality of the gratings. To compare the obtained results, the replication was executed on specimen of steel with the same geometry, dimensions and surface finishing (Ra = 2.1 µm). These steel specimen have a length of 20 mm, width of 25 mm and thickness of 5 mm.

Comparing the replication of the sample 1 and 2, it was possible to observe for the first sample that the coating of replicated grating had a low quality (ripples and fractures), low reflectivity of the replicated grating and difficulty in the diffraction of light on the replicated grating. On the other hand, the coating of sample 2 had a strong variation among regions, some had low and others acceptable quality, the reflection of light on the replicated grating was interspersed between areas of good reflection and others with low- reflection.

Analyzing the replication of samples 3 it was possible to verify that the sputtering process leads to a very high adherence of aluminium layers. The process of prying off was difficult, the diffraction grating transfer of sample 3 was not uniform, causing regions with good transfer and others where no transfer of aluminium layer occurred.

In sample 5 can be noted that the substrate reacted with the aluminium coating layer giving rise to a very dark and opaque one; this reaction has occurred possibly due to excessive dust that existed in the area of the epoxy grating. Sample 6 is very similar to sample 4, having a more uniform coating. However, the sample 6 had a better quality of coatings than the other samples studied in this work, which was verified by the good diffraction efficiency.

In the Fig. 3 it is possible to see some images of replicated gratings, observed in an optical microscope at a magnification of 500 times.

Fig. 3. Some replicated gratings observed in an optical microscope: a) sample 2; b) sample 3; c) sample 6. Magnification of 500x.

These observations lead us to conclude that the sputtering process is not adaptable to these applications.

3.3. Light power measurement

To obtain the optical efficiency of a diffracted beams it is need to measure its power and the power of the direct laser beam. To measure the power of beams a Laser Power Meter model PM121D was used and the light source was a 2 W laser from Coherent (Verdi). The power of the laser source applied in the measurements was 100 mW with a wave length of 532 nm. The laser beam used in the measurements had a linear polarization state. The power measurements of the first order diffracted beam light in each grating (before and after replication) are indicated in Table 3. The given values were measured on the highest diffraction regions of the gratings.

The measured power of the directed beam light from the laser source was 100.02 mW.

Table 3. The measurement of the first order diffracted beam power, before and after the replication of grating.

Sample	Before Grating Replication [mW]	After Grating Replication [mW]
1	17.26	14.38
2	18.57	17.28
3	15.41	14.75
4	16.97	15.77
5	21.43	20.02
6	22.51	21.39

4. Determination of efficiency

For a reflection grating, efficiency is defined as the energy flow (power) of monochromatic light diffracted into the order being measured, relative either to the energy flow of the incident light (absolute efficiency) or to the energy flow of specular reflection from a polished mirror substrate coated with the same material (relative efficiency) [26]. In this work the absolute efficiency was determined:

$$\text{Efficiency} = \frac{\text{Diffracted beam power}}{\text{Direct beam laser power}} \tag{3}$$

The gratings developed in this work are very low modulation gratings and operate in the scalar domain, where the theoretical efficiency peak for sinusoidal grooves is 33.8% [24].

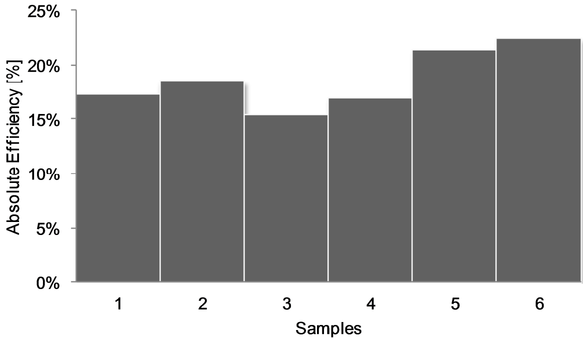

Fig. 4. The absolute efficiency of the coated gratings before the replication.

The first order diffraction beam (+1 or –1) is the one which must be used for measurement purposes, because in the zero order, the grating acts either as a window or a mirror, so, the absolute efficiency of the first order diffraction beam was determined. The absolute efficiency is computed for a diffraction angle of 77.4° and a wave length of 532 nm. Fig. 4 and 5 represent the absolute efficiency for the coated gratings before and after their replication, respectively.

The best absolute efficiency was obtained with the gold coating. The efficiency of samples 5 and 6 are also acceptable for measurement applications.

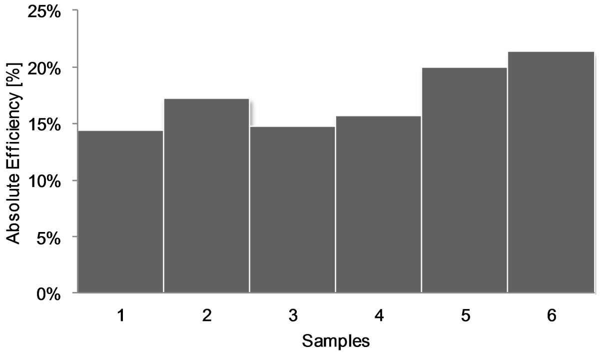

Fig. 5. The absolute efficiency of the coated gratings after the replication.

It is possible to verify that the efficiency decreases after the replication. Some of mold gratings could not be replicated.

5. Conclusions

The metallic coatings obtained with the sputtering process are acceptable, but they are very difficult to replicate because they stay strongly fixed to subtract (mould gratings). On the other hand, with the aluminium vaporization process it is possible to obtain metallic coatings with a high reflection index if the second layer is thicker, this process is better for replication of the gratings. It is very important to control the cleanness of the environment, any dust causes opaque surfaces which lower the light reflection.

The efficiency before the replication has a range between 16% and 27% and after between 13% and 22%. It is possible to conclude that the efficiency decreases after the replication, but the efficiency is suitable for optical measurement and control applications.

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