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Letter

Fabrication of micro-scale gratings for moiré method with a femtosecond laser

Gaosheng Yan [a], Jianguo Zhu [a,*], Yanlong Huang [a], Wenfen Hao [a], Yanjie Li [b]

[a] Faculty of Civil Engineering and Mechanics, Jiangsu University, Zhenjiang 212013, China
[b] School of Civil Engineering and Architecture, University of Jinan, Jinan 250022, China

HIGHLIGHTS

- We fabricate 500 lines/mm parallel gratings using a femtosecond laser.
- We theoretically optimize the grating profile to form high quality moiré patterns.
- Clear scanning electron microscope (SEM) moiré fringes are observed which is suitable for deformation measurement.

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ABSTRACT

Fabrication of micro gratings using a femtosecond laser exposure system is experimentally investigated for the electron moiré method. Micro holes and lines are firstly etched for parameter study. Grating profile is theoretically optimized to form high quality moiré patterns. For a demonstration, a parallel grating is fabricated on a specimen of quartz glass. The minimum line width and the distance between two adjacent lines are both set to be 1 μm, and the frequency of grating is 500 lines/mm. The experimental results indicate that the quality of gratings is good and the relative error of the gratings pitch is about 1.5%. Based on moiré method, scanning electron microscope (SEM) moiré patterns are observed clearly, which manifests that gratings fabricated with the femtosecond laser exposure is suitable for micro scale deformation measurement.

Deformation measurement and analysis under load is a key issue when the mechanical properties of materials and structures are considered. With the development of science and technology, measurement methods for multiscale deformation from macroscale to micro-/nanoscale have drawn great attention. As a basic optical component, gratings can be used in various optical technologies, such as moiré interferometry [1], geometric phase analysis (GPA) [2], and various microscopic moiré methods [3], to measure the surface deformation on an object. As a conventional grating fabrication method developed in the early 1960s [4], holography lithography technique (HLT) is based on the interference of two coherent beams of light and the exposure of a photoresist. The process of HLT is relatively complex and includes coating the photoresist, exposure, development, and metal film deposition. In recent years, researchers have investigated a number of microscale fabrication technologies to fabricate gratings, such as X-ray lithography [5], electron beam lithography (EBL) [6], and focused ion beam milling [7]. Although high-resolution alignment can be realized with these technologies, they are time consuming and of low throughput. In the mid-1990s, nanoimprint lithography (NIL) was initially proposed and developed by Chou's group. It can create micro- and nanoscale patterns with submicron alignment over a large area.

As a major achievement of science and technology in 20th century, lasers have been widely used for microscale processing owing to a very high instantaneous power and small heat-affected zone. Recently they have been used to fabricate microstructures directly on the surface of materials such as metals, semiconductors, and ceramics [8]. Moreover, femtosecond laser can fabricate micro-gratings on the surface of the specimen without a mask, which provides an alternative method for grating fabrication, and its related research is of significant importance. Recently, femtosecond lasers were reported to fabricate microscale periodic structures. For example, Cheng fabricated micro-scale lines using femtosecond laser in indium tin oxide [9]. Tan fabricated gratings by femtosecond laser interferometry method [10]. Kishimoto proposed the fabrication of micromodel grids on the surface

* Corresponding author.
E-mail address: zhujg@ujs.edu.cn (J. Zhu).

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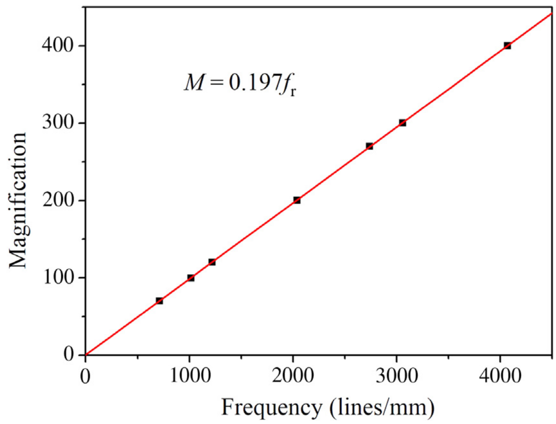

Fig. 1. Calibration of frequency of reference grating with magnification ($N = 480$).

of polished steel specimens for various moiré methods by femtosecond laser exposure [11,12]. With recent development of science and technology, the performance of femtosecond lasers has been improved, including spatial resolution and high peak intensity. Therefore, there remains a further study on high-frequency gratings fabricated using a femtosecond laser for deformation measurement with moiré method.

In order to measure deformation in micro scale, moiré method are usually combined with a scanning electron microscope (SEM). The scanning lines in the SEM system can be regarded as a periodical grid and play the role of a reference grating. The SEM scanning moiré is generated by the superposition of the specimen grating and the scanning lines. The frequency of the reference grating, f_r, is expressed as [13]

$$f_r = \frac{MN}{L_0}, \tag{1}$$

where M represents magnification, N is the number of scanning lines, and L_0 represents the gauge length of the SEM monitor perpendicular to the scanning lines. It can be seen that the frequency of the scanning lines is proportional to the magnification and the number of scanning lines while inversely proportional to the view field.

When the specimen grating is identical to the reference grating, moiré fringes will turn out, and the specimen grating will deform with the specimen if a load is applied. Generally, displacements and strains can be measured more accurately with gratings of higher frequency. Therefore, fabrication of high-frequency gratings is of great importance [14]. The frequency of the specimen grating is constant after fabrication while the frequency of the reference grating varies with the magnification. For the convenience of experiment with a JSM-7001F SEM, the frequency of reference grating has been calibrated as shown in Fig. 1. The available number of scanning lines is 480. The size of each view field under different magnifications was measured and the corresponding frequencies were calculated. By fitting the relationship of the frequency of the reference grating with the magnification, the matched magnification M_0 to form null field moiré can be derived according to the frequency of the specimen grating.

The substrate was a quartz glass. The specimen was machined and polished, and then the micro holes and lines were fabricated by laser exposure of the femtosecond laser system (Pharos FemtoLAB) with high magnification lens and highly accurate X–Y stage. During the exposure of the femtosecond laser on the surface, the X–Y stage moved with positioning accuracy of 1 μm. The exposure condition is shown in Table 1.

Micro holes with diameters from 1 μm to 8 μm were firstly fabricated as shown in Fig. 2. The micro holes are very fine circles.

Table 1
Exposure condition of femtosecond laser.

Parameter	Value
Wavelength	343 nm
Pulse width	200–10 fs
Repetition rate	1 kHz
Maximum energy of pulse	1.5 mJ
Average of power	15 W

Table 2
Processing parameters and measured depth of micro holes with the multi-pulse femtosecond laser.

Prescribed diameter (μm)	Energy of pulse (μJ)	Pulse number	Measured depth (μm)
1	0.18	2	0.5
2	0.24	5	1.2
3	0.73	7	3
4	2	9	4
6	11	7	5.6
8	14.4	7	7.8

Table 3
Processing parameters and measured depth of micro lines with the multi-pulse femtosecond laser.

Prescribed width (μm)	Energy of pulse (μJ)	Scanning speed ($mm \cdot s^{-1}$)	Measured depth (μm)
1	0.29	30	0.5–1
2	0.51	30	1–1.5
3	1.05	50	2–3
4	1.05	40	3–4
5	4.9	40	4–5
6	6.4	40	5–6
7	7.2	40	6–7
8	9.6	40	7–8

These fine holes were considered to be fabricated by femtosecond laser ablation. When the diameter is less than 4 μm, the affected zone around the hole can hardly be observed, since the energy of laser pulse is less than 1 μJ, as shown in Table 2. When the diameter is larger than 4 μm, the affected zone around the hole is obvious and it increases with the raised energy of pulse. Also the measured depth of the hole increases when the energy of pulse goes up.

Micro lines were fabricated by scanning the laser pulse with speed of 30–50 mm/s, as shown in Fig. 3. The micro lines are very fine straight lines with almost equal width along the line. When the diameter is less than 4 μm and the maximum energy of laser pulse is 1.05 μJ, the affected zone along the line can hardly be observed, which is the same as fabrication of micro holes, as shown in Table 3. When the diameter is larger than 4 μm, the affected zone along the line is obvious and it also increases with the raised energy of pulse. The measured depth of the line increases when the energy of pulse goes up.

Parallel gratings were fabricated based on studying the above parameters. When parallel gratings are fabricated using a femtosecond laser, the frequency f and pitch p of the gratings can be expressed as

$$f = \frac{1}{p}, \tag{2}$$

$$p = D + d, \tag{3}$$

where d is the distance between two adjacent lines, and D represents the line width. Theoretically, the grating frequency is higher when D and d are smaller.

The fabrication of gratings with a femtosecond laser can be explained as shown in Fig. 4. Assume that the horizontal dashed line is the threshold fluence for quartz glass ablation. The peak fluence of the laser beam is higher than the ablation threshold

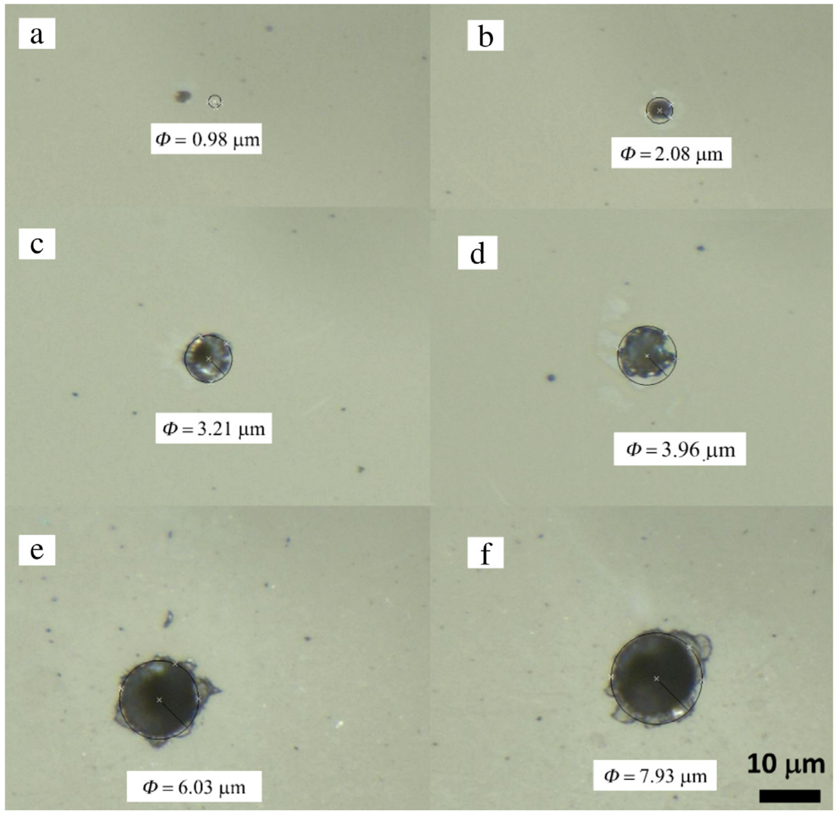

Fig. 2. Optical images of micro holes fabricated with the femtosecond laser, and the measured diameter of the holes is (a) 0.98 μm, (b) 2.08 μm, (c) 3.21 μm, (d) 3.96 μm, (e) 6.03 μm, and (f) 7.93 μm.

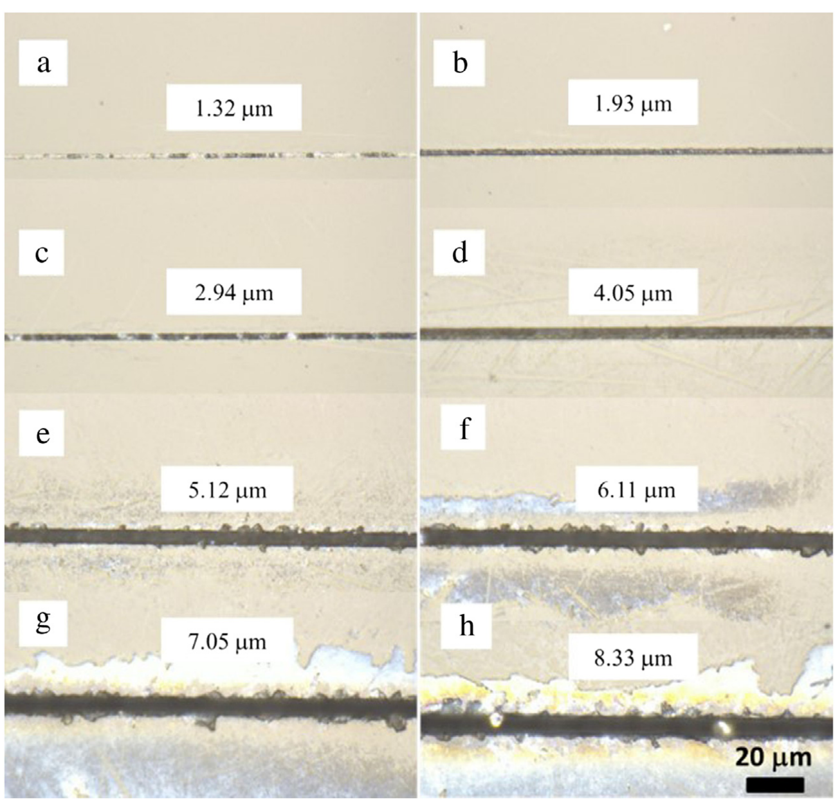

Fig. 3. Optical images of micro lines fabricated with the femtosecond laser, and the prescribed width of the lines is 1–8 μm from (a)–(h).

of quartz glass, and thus, the center area is ablated. The oblique line area of the laser pulse equals the ablated line width *D*, which changes with the energy of the laser pulse. However, the outer edges are subjected to lower irradiation intensity, and thus, a strip of quartz glass remained. According to the femtosecond laser system, the minimum line width and moving displacement of the

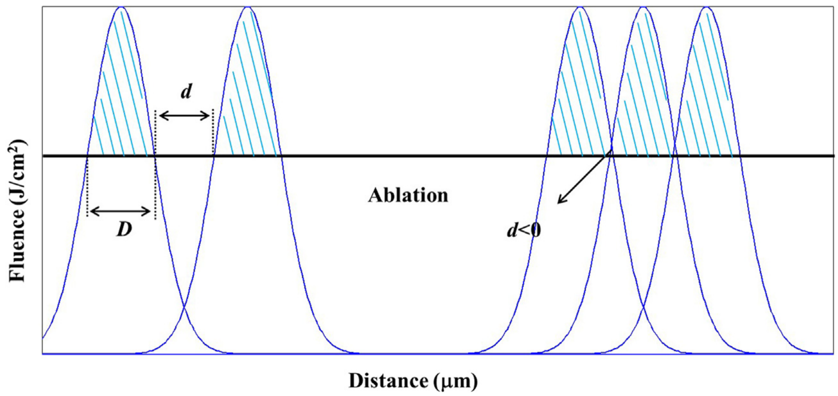

Fig. 4. Schematic diagram of fabricating parallel gratings with a femtosecond laser.

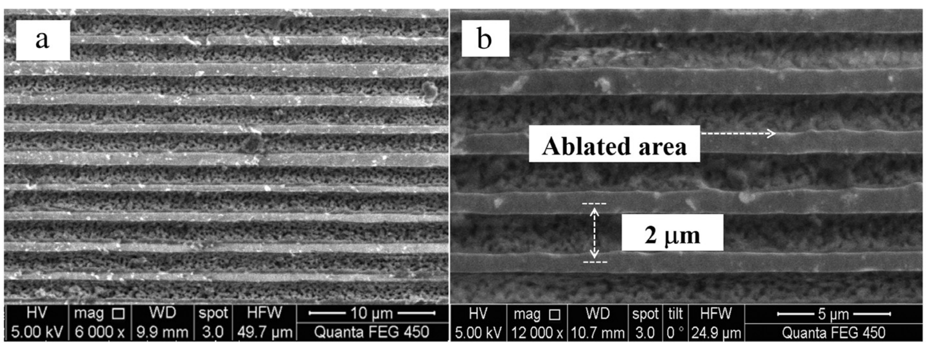

Fig. 5. Parallel gratings fabricated by femtosecond laser exposure, (a) 6000x and (b)12000x.

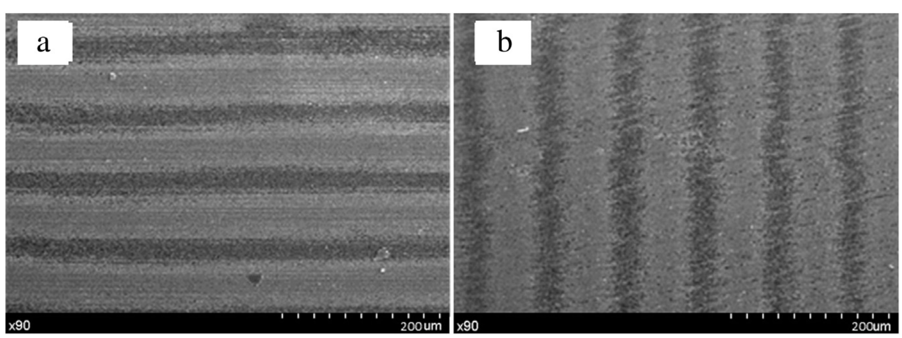

Fig. 6. SEM moiré patterns: (a) parallel moiré and (b) rotational moiré.

X–Y stage are both 1 μm. In order to fabricate high-frequency gratings, D was also set to be 1 μm and d can be set less than 1 μm with ablated areas overlapped, as shown on the right in Fig. 4. However, moiré patterns have the best quality when the line width D equals to the distance between two adjacent lines d, or the duty ratio (D/d) equals to 1 [15]. Therefore, the magnitude of d was also set to be 1 μm for the purpose of forming high quality moiré patterns.

Parallel gratings within area 3 mm × 3 mm were fabricated with the femtosecond laser, as shown in Fig. 5. As can be seen, the boundary of each line is clear, and the contrast between the ablated lines and original material is obvious. The average pitch is about 2 μm and average frequency of the gratings is 500 lines/mm, and the relative error is about 1.5%. However, the measured duty ratio (D/d) is about 1.5, which is larger than the prescribed value. This is caused by the processing error of the femtosecond laser system, which can be reduced by carefully refining the experimental parameter of the specimen.

SEM moiré patterns were observed using the above parallel gratings (Fig. 5). According to Fig. 1, $M_0 = 98.5$ to form a null field moiré with the frequency of specimen (f_s) equals to 500 lines/mm. In practice, M was set to be 70–130, SEM moiré patterns were observed, as shown in Fig. 6. Figure 6(a) and (b) show parallel moiré pattern and rotational moiré pattern, respectively. It can be seen that the moiré fringes are clear with dark and bright lines and the lines are equispaced and parallel with each other. The magnification is 90 and the frequency of scanning line (f_r) is about 457 lines/mm, which is similar to the frequency of specimen. The strain of parallel moiré can be calculated as

$$\varepsilon = \frac{p_s - p_r}{p_r}, \tag{4}$$

where p_s and p_r are pitch of specimen gratings and scanning lines, respectively. Rotational moiré pattern can be formed by the superimposition of two similar patterns rotated by an angle ϕ. The relation of p_s, p_r, and the pitch of moiré (p_m) is defined as [16,17]

$$p_m = \frac{p_s p_r}{\sqrt{p_s^2 + p_r^2 - 2p_s p_r \cos\phi}}, \tag{5}$$

where ϕ is the angle between the reference grating and the specimen grating.

In summary, the femtosecond laser exposure system was used to fabricate the micro gratings for the electron moiré method. Micro holes and lines were firstly experimentally investigated for parameter study. Grating profile was theoretically optimized to form high quality moiré patterns. For a demonstration, a parallel grating was fabricated on a specimen of quartz glass. The minimum line width and the distance between two adjacent lines were both set to be 1 μm, and the frequency of grating was 500 lines/mm. The experimental results indicate that the quality of gratings is good and the relative error of the average gratings pitch is about 1.5%. Based on moiré method, SEM moiré patterns were observed clearly, which manifests that gratings fabricated with the femtosecond laser exposure is suitable for micro scale deformation measurement. Furthermore, the gratings are suitable to be applied for the measurement of high temperature deformation since they are fabricated directly on the surface of specimen.

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