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Relationship Between the Depth of Drilling and Residual Strain Relief in Fiber Reinforced Composite Materials

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The mechanical properties of fiber are quite different from matrix in composite laminates, and parameters, such as the angle of ply, and the temperature and pressure during composite forming, would play an important role in residual stress in the composite. The residual strains between layers depend on the forming parameters and their mechanical properties. In this article, grating rosette, Moiré interferometry, and step drilling-hole method are used to measure the relief strains when drilling each single laminate step by step, and find some relationship between the depth of drilling and residual strain relief in fiber reinforced composite material.

Keywords grating rosette, step drilling-hole method, residual strain relief, Moiré interferometry

1. Introduction

The mechanical properties and expansion coefficient of fiber are different from that of matrix in composite laminates. There usually are residual stresses in matrix, fiber, and the interface between them after cooling the composite to room temperature at the conclusion of forming process. In addition there are residual stresses between layers, which influence the properties of composite material. For example, the residual tensile stresses in matrix influence its ductility, fatigue strength, and compression strength; and the residual compression stresses in fiber may result in fiber bending. Residual stresses in the interface between fiber and matrix are complicated; the interface may be in tension, compression, or shearing which influence the cohesive strength. The residual stresses between layers can result in matrix damage and deformed structure.

There has been a considerable amount of research on measuring residual stresses (Ref 1). Many methods have been developed to measure the residual stresses, such as strain gage embedding (Ref 2), fiber optic sensor (Ref 3), hole-drilling method (Ref 4), etc.

In this article, a grating rosette made by the authors, by means of the Moiré interference technique and step hole-drilling is used to measure the residual stains between layers.

2. Measurement Principle

The residual stresses on a specimen are relaxed when a hole is drilled. They can be determined by detecting the deformation on specimen surface. For measuring the deformation, the grating rosette and Moiré interfering method are applied. The directions of the grating rosette are distributed along 0°, 45°, and 90°, the corresponding Moiré patterns in each direction before and after drilling-hole can be obtained. Comparing the corresponding Moiré patterns before and after drilling, three strain components ε_0, ε_{45}, and ε_{90} can be computed (Ref 5):

$$\varepsilon_x = \frac{\partial U}{\partial x} = \frac{1}{2f}\frac{N_{x2} - N_{x1}}{\Delta x} \qquad \text{(Eq 1)}$$

where ε_x as normal strain along x, x denotes 0°, 90°, and 45° direction, respectively, f as frequency of grating ($f = 500$ lines/mm), and Δx as a small increment in distance, N_{x1}, N_{x2} are numbers of Moiré fringes in Δx before and after drilling-hole, respectively.

2.1 Grating Rosette

In crossed grating and Moiré interference method, two perpendicular fringe patterns (u,v field) can be obtained in each test, furthermore two strain components ε_x, ε_y, and shear strain γ_{xy} are determined (Ref 5) by comparing fringe patterns before and after loading. It should be noted that in grating rosette system, three fringe patterns could be obtained to determine three strain components (ε_0, ε_{90}, and ε_{45}). By comparing fringe patterns in each direction before and after loading, the specimen can be re-positioned accurately to avoid specimen movement. In addition, the fringe change was measured always along their normal direction (Fig. 1).

2.2 Hole-Drilling Method for Anisotropic Material

A small area of the surface is investigated as shown in Fig. 2, which is under plane stress conditions. Components σ_1 and σ_2 denote the principal stress. A hole with diameter $2a$ is drilled at the interested point of the surface. The center O of the hole is a conventional point, where the residual stresses must be determined. r is the distance from the center of the hole to point A, or point B, or C. Due to drilling of hole, the releasing strain at point A, B, C are ε'_{rA}, ε'_{rB}, and ε'_{rC}, respectively.

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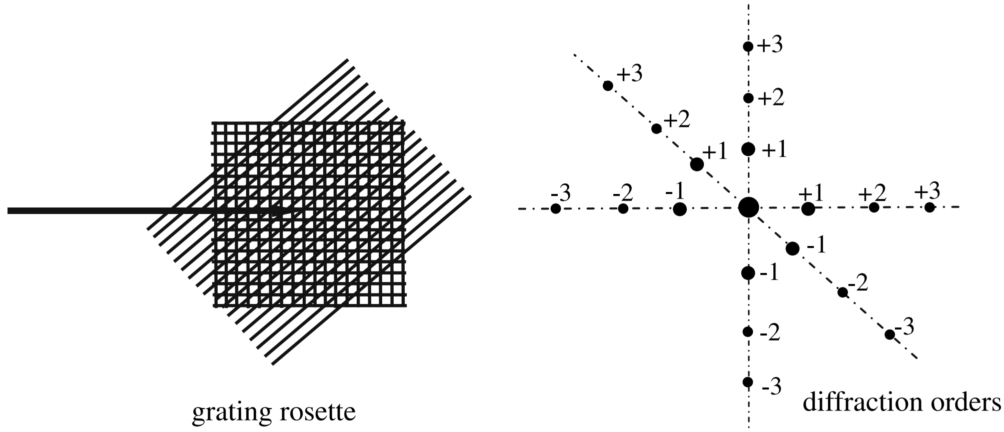

Fig. 1 Grating rosette and its diffraction orders

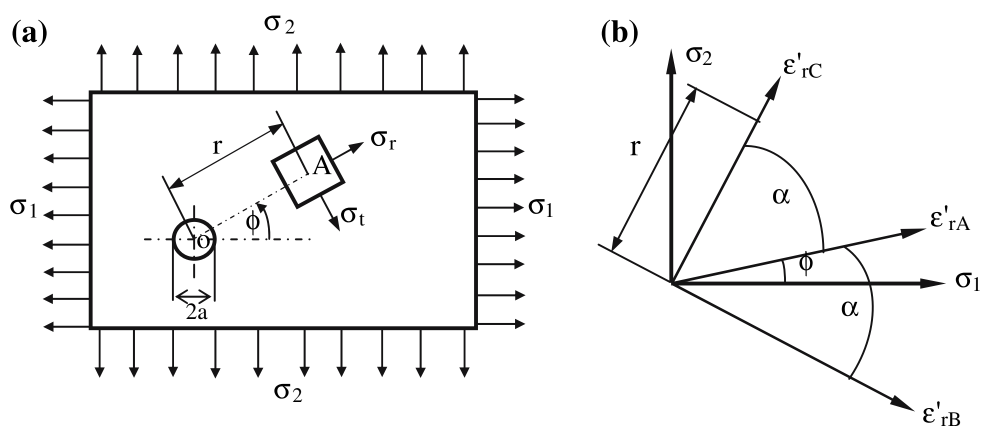

Fig. 2 The principle of drilling-hole

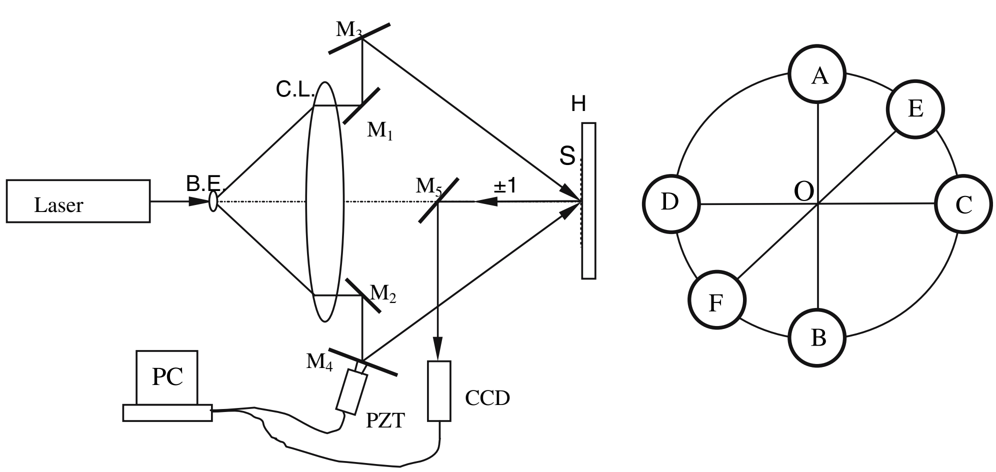

Fig. 3 The basic set-up of grating rosette Moiré interferometry

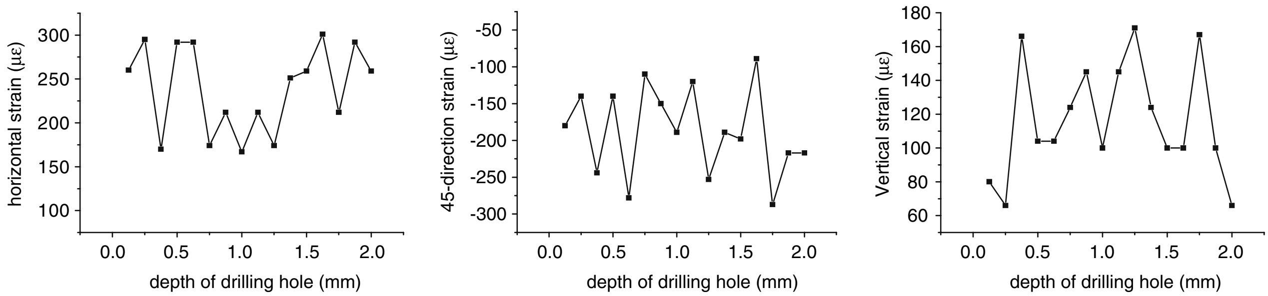

Fig. 4 The curves of relaxed strain and depth of drilling-hole (20 MPa 135 °C $[0/90]_{16}$)

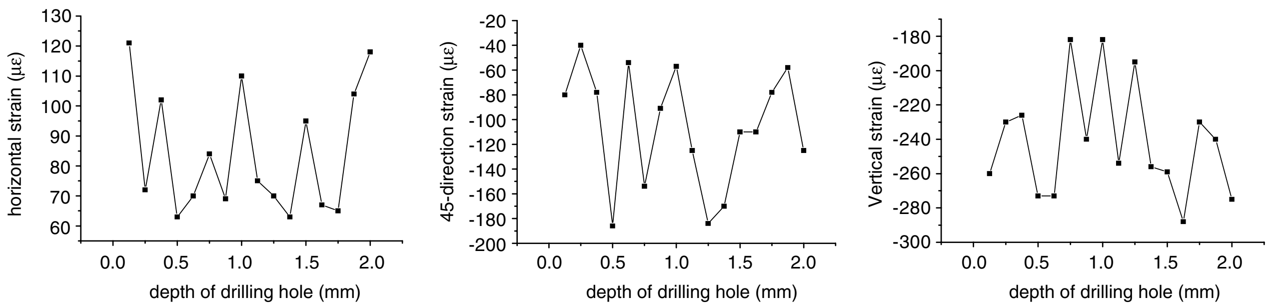

Fig. 5 The curves of relaxed strain and depth of drilling-hole (20 MPa 125 °C $[0/0]_{16}$)

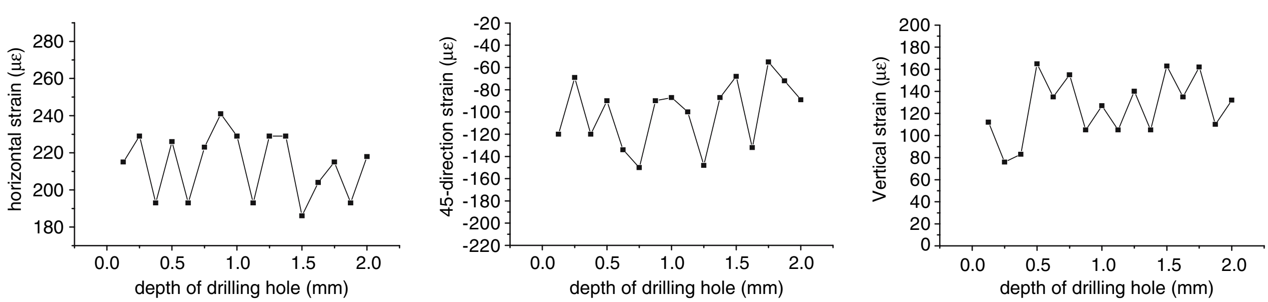

Fig. 6 The curves of relaxed strain and depth of drilling-hole (27 MPa 135 °C $[\pm 30°]_{16}$)

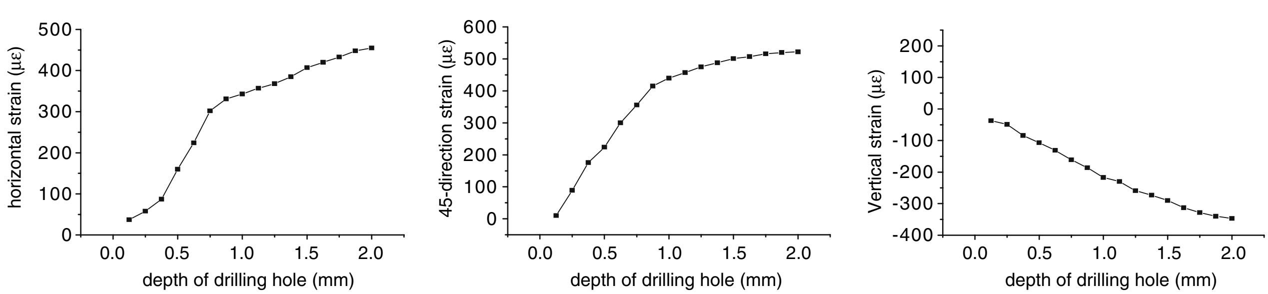

Fig. 7 The curves of relaxed strain and depth of drilling-hole (aluminum alloy)

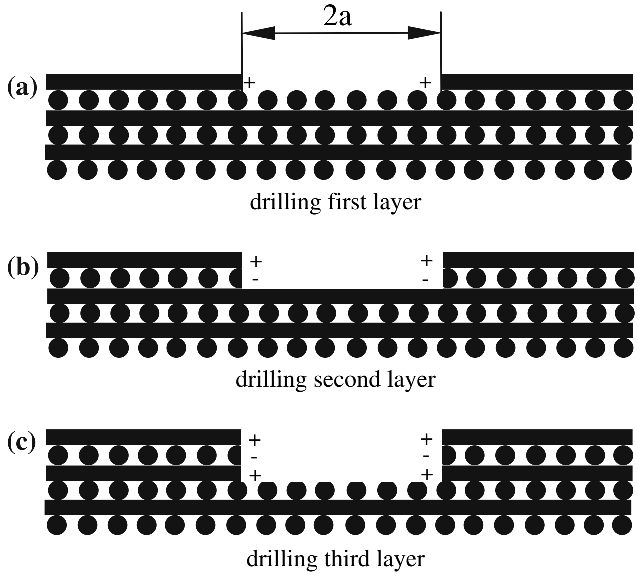

Fig. 8 The residual strains between neighboring layers during drilling

3. Experimental Set-Up and Procedure

The basic set-up was designed for grating rosette and is shown in Fig. 3.

Where L: laser, B.E.: beam expander, M_1, M_2, M_3, M_4, M_5: mirrors, C.L.: collimate lens, S: specimen, H: holder, PZT: piezoelectric transition, CCD: video camera, PC: computer.

In Fig. 3, the coherent light beam provided by laser is expanded into spherical wave when it passes through the beam expander, and then collimated by the C.L., after six incident collimated beams (A, B, C, D, E, and F) illuminate the desired area of specimen surface with same angle α (here $\alpha = \arcsin \lambda f$, λ is wavelength of incident beam, f is frequency of grating rosette). The first diffraction order of all the six beams will intersect at the same point and propagate along the specimen normal. Each pair of symmetrical diffraction beams—A and B, C and D, and E and F—will interfere and form a virtual grating rosette in the area along 0°, 90°, and 45° direction, respectively. Therefore, three displacement fields (u, v, and s) result from superposition of virtual grating rosette and specimen grating rosette. By means of CCD camera and computer, the Moire patterns can be gathered and stored for analyzing the deformation information.

3.1 Material

The composite laminate specimen is composed of carbon fiber and epoxy and combination with 16 layers. The specimen size is $150 \times 100 \times 2$ mm^3. The forming pressure, temperature, and angle of ply are different. For example 20 MPa 135 °C$[0/90]_{16}$, indicates 20 MPa: pressure, 135 °C: temperature during forming, [0/90]: fiber angle of ply, and the subscript 16 is number of layers.

3.2 Testing

The specimen with grating rosette replicated before should be installed properly in the holder so that first diffraction order of all the six beams will intersect of the same point and propagate along the specimen normal. Each pair of symmetrical diffraction beams will interfere and form a virtual three-directional grating, which will superimpose on the specimen grating. The three directional Moiré patterns before drilling-hole were gathered by CCD camera. Second, a 1 mm diameter hole is drilled in first layer and the specimen is re-positioned by comparing this Moiré pattern with the pattern before drilling the hole. This procedure is repeated to obtain drilling second layer, third layer..., up to final layer. Finally, all three directional relaxed strains are calculated by comparing Moiré patterns before and after drilling in each step.

4. Results and Discussion

Three kind of composite laminate specimen and aluminum alloy specimen were tested. The test results are shown in Fig. 4–7.

From the curves of relaxed strain and depth of drilling-hole, it is noted that, for aluminum alloy, relaxed residual strains monotonically increase or decrease with the depth of drilling-hole. But for composite laminate the behavior is alternated. It means the residual strains between layers in composite laminate are complicated.

Second, the residual strains between neighboring layers vary not only in their magnitude but also in their character.

Third, the relaxed residual strain is approximately symmetrical about the middle layer.

For aluminum alloy, when drilling depth is within approximate drilling diameter, the relaxed strain gradient is much more than that when the depth of drilling exceeds drilling diameter. But the total relaxed strain is sizable when the depth exceeds the drilling diameter.

As shown in Fig. 8, when drilling the first layer of composite material $[0/90]_{16}$, the relaxed strain is contributed by stress along one certain direction, so it should lead to specific direction strain. When drilling second layer or more, the relaxed strain is contributed by two or more layers, and the relaxed strain depends on the combination of different layers, so it is more complicated than drilling single layer and isotropic materials (aluminum alloy).

5. Conclusions

Moiré interferometry and step-depth drilling techniques were used to determine the residual strain relief in fiber reinforced composites as a function of depth of drilling. The results show that whereas the residual strain relief exhibited a systematic variation with depth in unreinforced aluminum, the behavior was complicated in composites, and depended on the residual stresses in neighboring layers.

Acknowledgment

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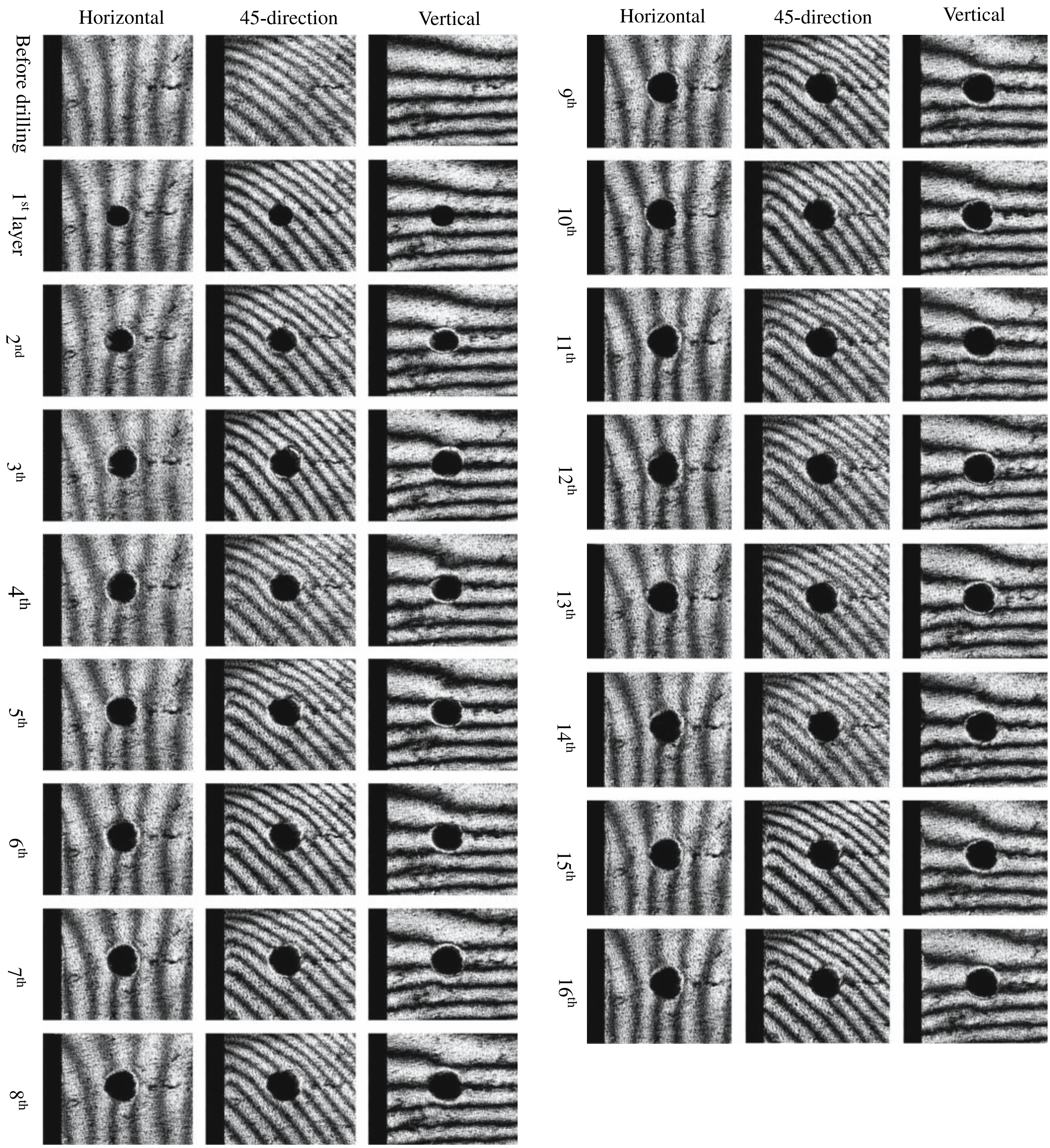
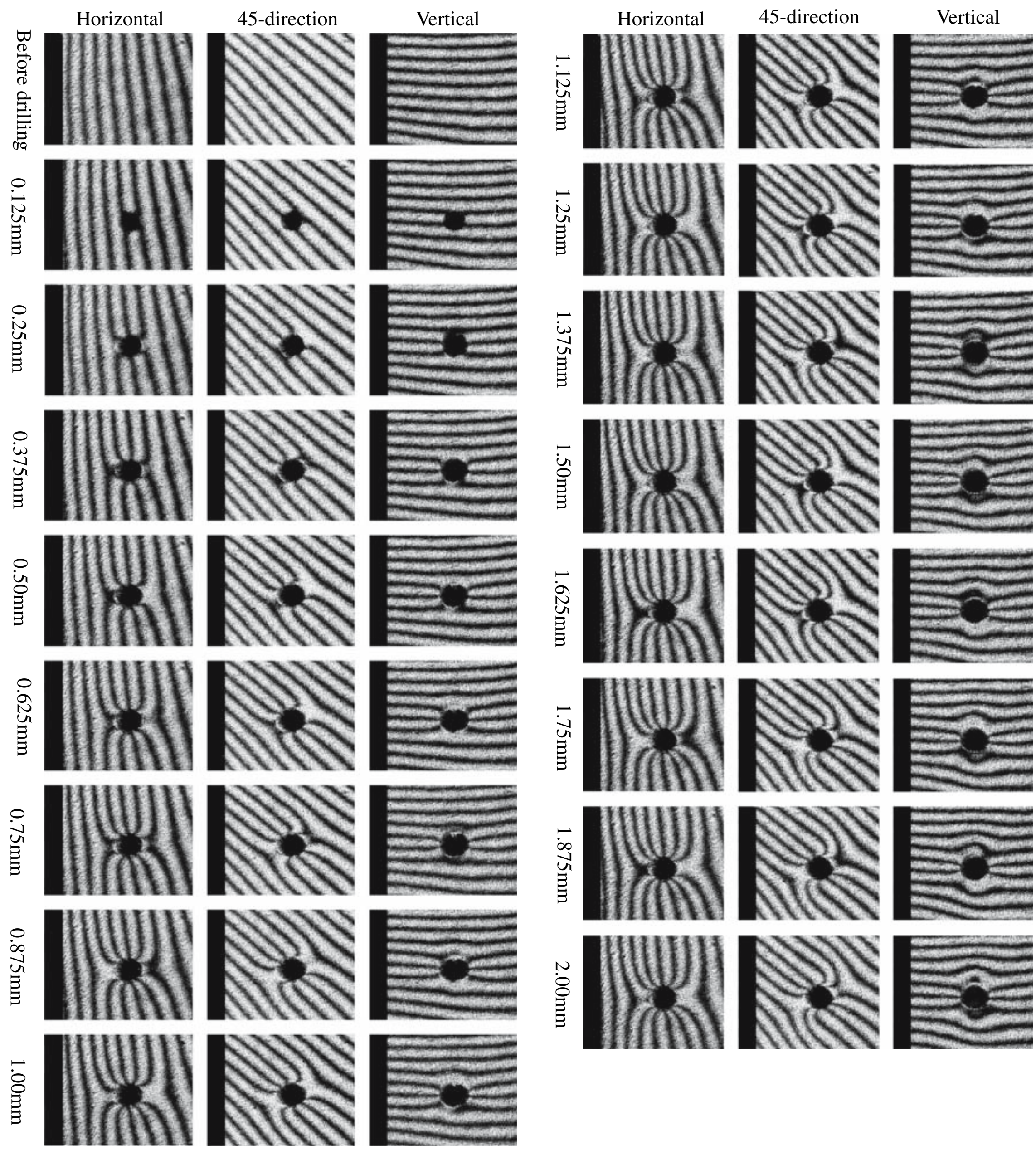
APPENDIX

1. Step drilling-hole Moiré patterns (27 MPa 135°C[±30°])$_{16}$



2. Step drilling-hole Moiré patterns (aluminum alloy)



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