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Deformation Analysis of Impact Damaged Composite Tube Using Thermal Shearography

Koung-Suk Kim*, Ho-Seob Chang**, Su-Ok Jang***, Seung-seok Lee****, Wan-Sik Jang*****
and Hyun-Chul Jung*†

Abstract Composite materials are widely used as structural materials for aerospace engineering because of its excellent mechanical properties such as light weight, high stiffness, and low thermal expansion. In driving, impact damage is one of the common but dangerous damages, caused by internal failure of the laminas interface which is not detected by in the surface. Many techniques to detect defects or delaminate between laminates have been reported. Shearography is a kind of laser speckle pattern interferometry with the advantages of non-destructive, non-contact, high resolution and displacement slope measurement. In this paper, the shearography is used to evaluate non-destructively impact damaged surface of the composite material and a measuring method using shearography for the thermal deformation of a impact damaged composite material is discussed. The basic principles of the technique are also described briefly.

Keywords: Composite Materials, Impact Damage, Shearography, Thermal Deformation

1. Introduction

Composite materials are increasingly used in the modern industry, suitable on demand of the modern industry, especially in the aerospace industry where they subjected to dynamic loads. The fiber-reinforced composite material is one of the composite materials having excellent mechanical properties such as high modulus, high specific strength and high specific modulus more than other metal materials. It is used in aerospace engineering and automobiles industry because it has a good fatigue quality and low coefficient of thermal expansion(Heo et al., 1997). When the composite materials is subjected to the loads which exceeds elastic strain energy, destruction or damages should be occurred and the mechanical properties is decreased sharply. Composite structure has a weak compressive strength quality. When the damage or delamination occurred the material specific strength decreases. After the occurrence of a small defect or a delamination the life of the composite materials structure decreases and that causes an unexpected accident or any problems. Also, when the collision due to tools falling or the FOD (foreign object debris) of the aircraft causes an impact damage, a delamination, or a crack, the damage will be increase by impact energy then the role as the structure can not be

Received: May 8, 2008, Revised: June 18, 2008, Accepted: June 20, 2008. * Department of Mechanical Design Engineering, Chosun University, Gwangju, 501-759, Korea, ** Laser Center, Chosun University, Gwangju, 501-759, Korea *** Department of Advanced Parts and Materials Engineering, Graduate school, Chosun University, Gwangju, 501-759, Korea *** Korea Research Institute of Standard and Science, Daejeon 305-353. Korea, **** Department of Mechanical Engineering, Chosun University, Gwangju, 501-759, Korea, ***** Department of Mechanical Design Engineering, Chosun University, Gwangju, 501-759, Korea † Corresponding Author: yonggary@soback.kornet.net

able to accomplish (Kong et al., 2007; Choi, 2003). Consequently, it is important to detect damages or delamination and cracks by any means and to evaluate a external impact inside the composite materials in advance.

Speckle interferometry is a deformation measurement method using coherent characteristic of laser. Among others, the electronic speckle pattern interferometry (ESPI) and the shearography have been used frequency. ESPI may measure the deformation precisely; however, it is very sensitive to the external noise and the vibration so that it has very low applicability in the industrial site. However, the shearography, measures the slope of the deformation by appropriately organizing the optical-interferometer so that it does not require the optical table, and is very excellent in measuring the defect of the subject matter; and on the basis of its robustness in noise and vibration, it is widely used for detecting technique of inner defect in the industrial site (Steincheon and Yang, 2003). In this paper, shearography uses to measure thermal deformation of impact damaged composite materials and to analyze behavior of composite materials containing impact load on the surface of the materials is used.

2. Background

2.1 Principle of Shearography

As shown in Fig. 1, When an object is irradiated by a divergence light, beam reflected on the surface of an object is divided by a beam splitter into two beams. One beam is imaged to the image plane after the reflection on the Mirror 1 and the other beam is imaged to image plane after the reflection on the Mirror 2 which can be tilted. At this time, if Mirror 2 is tilted, the wave-front reflected on the Mirror 2 is formed and it makes a sheared image to an image formed by beam reflected on the Mirror 1. The interference fringe pattern resulted

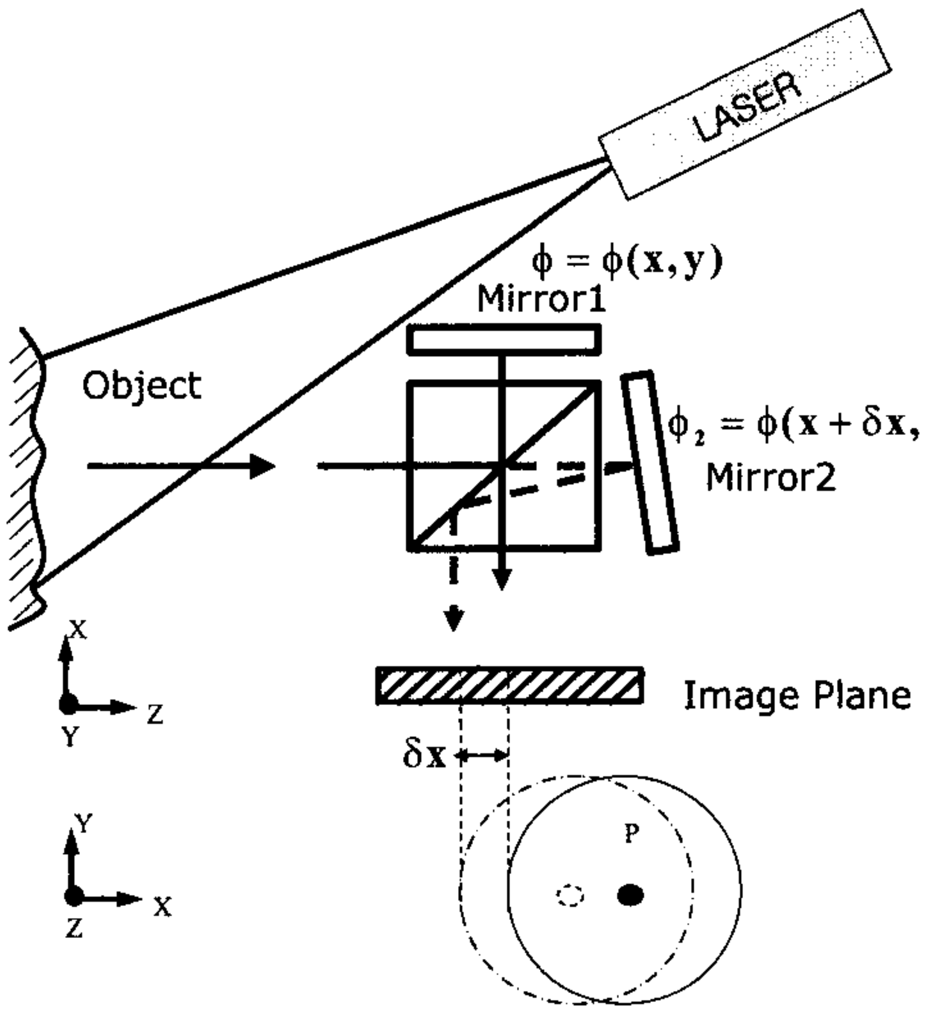


Fig. 1 Speckle pattern shearing interferometry

from two-beam interference presents the slop of the out-of-plane deformation of an object occurred after the deformation.

δx expresses the tilted angle and it is called shearing or shearing amount. Formation of interference fringe pattern can be controlled by shearing and shearing direction. Eqn. (1) expressed difference between d and d' (Lee et al., 2006). no is the unit vector of irradiation direction and ns is the unit vector of observation direction.

$$\Delta\phi = \frac{2\pi}{\lambda}(\mathbf{n}_o - \mathbf{n}_s)\cdot(\mathbf{d} - \mathbf{d}') \quad (1)$$

If the incident direction of the laser beam irradiated to the object is the same as the vertical observation direction, eqn. (1) can be re-rewritten as eqn. (2).

$$\Delta\phi = \frac{4\pi}{\lambda}\Delta\mathbf{d} \quad (2)$$

Δd is expressed to eqn. (3) by using Taylor series. The deformation of x direction is depended on the shearing amount Δx. The high order terms of right side in eqn. (4) is very small so more than second term can be ignored. Therefore eqn. (2) is expressed as eqn. (4) by eqn. (3).

$$\Delta \mathbf{d} = \frac{\partial \mathbf{d}}{\partial \mathbf{x}}\frac{\Delta \mathbf{x}}{\mathbf{1!}} + \frac{\partial^2 \mathbf{d}}{\partial \mathbf{x}^2}\frac{(\Delta \mathbf{x})^2}{\mathbf{2!}} + \cdots \qquad (3)$$

$$\Delta \phi = \frac{4\pi}{\lambda}\left(\frac{\partial d}{\partial x}\right)\Delta x \qquad (4)$$

3. Deformation Measurement of Shearography

The deformation of a point on the deformed object is the same as the difference between two point apart as much as the shearing amount and this result can't integration. Because the image processing is used in ESPI and shearography, if the eqn (4) is replaced with deformation f, correspondence pixel x_i, shearing pixel h, eqn. (4) can be rewritten as eqn. (5). Also, when it rearrange with f', eqn. (5) can be rewritten as eqn. (6)

$$f'(x_i)\,h \approx f(x_i + h) - f(x_i) \qquad (5)$$

$$f'(x_i) \approx \frac{f(x_i + h) - f(x_i)}{h} \qquad (6)$$

Eqn. (6) is identical result with calculus of finite differences using Taylor theorem, shearography uses the front calculus and backward calculus in calculus of finite difference according to shearing direction, so it can numerically integrate. Therefore, $\Delta\phi$ is rewritten as

$$\Delta\phi \approx \frac{4\pi}{\lambda} f'h \qquad (7)$$

The deformation of an square plate is measured as the cosine function. When shearing mirror is tilted by any angle, an image is formed on the array of the CCD camera.

If the real out-of-plane deformation shape of an object is like this deformation line, then some shearing amount can be applied to the real deformation and we can get sheared deformation with parallel movement as much as the number of sheared pixel. This is the same as the cosine function translated by the number of pixel as shown in Fig. 2(a). Subtraction between the real deformation and the sheared deformation result in shearing result as shown in Fig. 2(b) and it is similar to the result of shearography. Also, Fig. 2(b) is presented average slope in arbitrary two point. If this result is divided by the number of pixel and integrated, finally the reconstructed deformation can be acquired as shown in Fig. 2(c). Therefore, the out-of-plane deformation occurred on an object can be measured by Shearography (Chang et al., 2007).

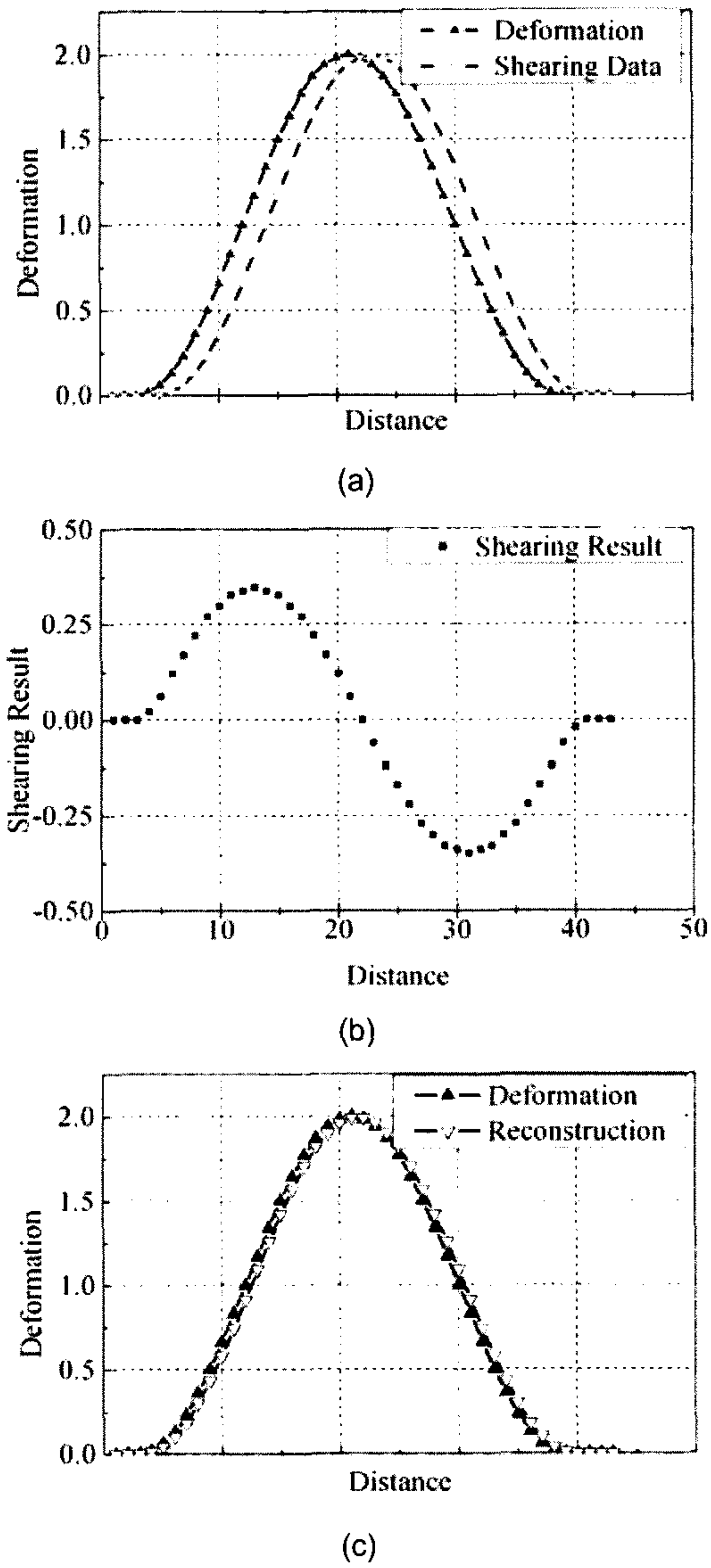


Fig. 2 Algorithm of deformation reconstruction (a) deformation and shearing data, (b) shearing result, (c) deformation and reconstruction

4. Experiment

In this experiment as shown in Fig. 3, the specimen was made of composite materials (CFRP) tube shaped with thickness 9 mm. The external defect was made by impact with different impact energy 15J, 30J and 45J. Fig. 3 shows the shape of the specimen and the location of the line profile. In order to measure the thermal deformation the specimen was heated up to 40 °C in a vacuum chamber. The deformation was measured when the temperature changes from 29 °C to 28 °C. For each measurement temperature difference was 1 °C. If temperature difference is more than 1 °C, the result can't be analyzed because of too dense fringe. The temperature difference was measured by non-contact thermometer and thermocouple for each measurement. Shearograms obtained by thermal shearography are shown in Fig. 4. The shearing amount was 10 mm. Phase map and line profile of identical location for each specimen was acquired and compared.

5. Results

As described in previous section, the impact damaged composite materials was heated up to 40 °C, then its thermal deformation measured by using thermal shearography when the temperature changes from 29 °C to 28 °C.. Fig. 4 shows the phase map of each impact damaged composite tube.

As shown in Fig. 4, the deformation area tends to increase according to the impact energy. It is difficult to acquire data from the middle part of 45J, because of large deformation. Deformation data of the each specimen obtained from top, middle, and bottom line are shown in Figs. 5, 6, and 7, respectively.

From Fig. 5(a), it shows generally identical destruction form in impact damaged part. And part of impact because to be higher density than no impact damaged part. The 15J-2 result shows generally similar trend with the 15J-1 result. Delamination did not occur and density was increased in the case of the 15J. Although the

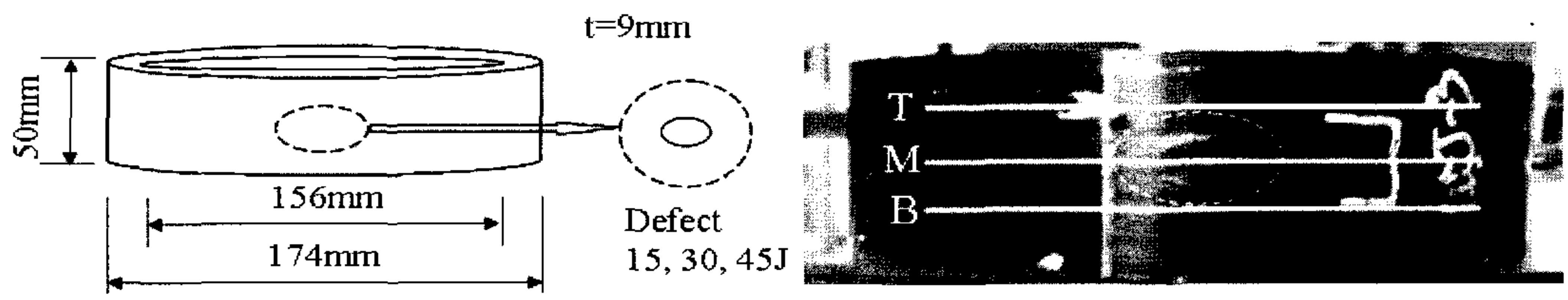


Fig. 3 Specimen with defect created by impact damage

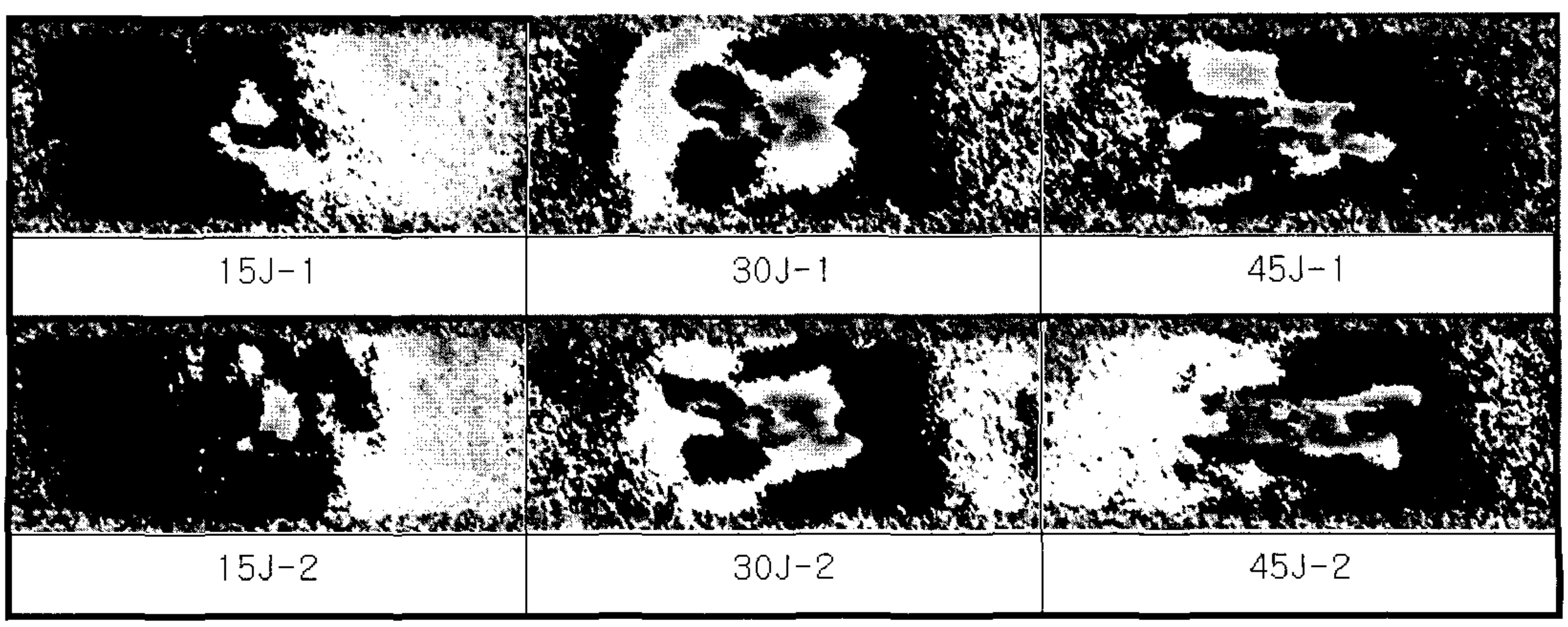
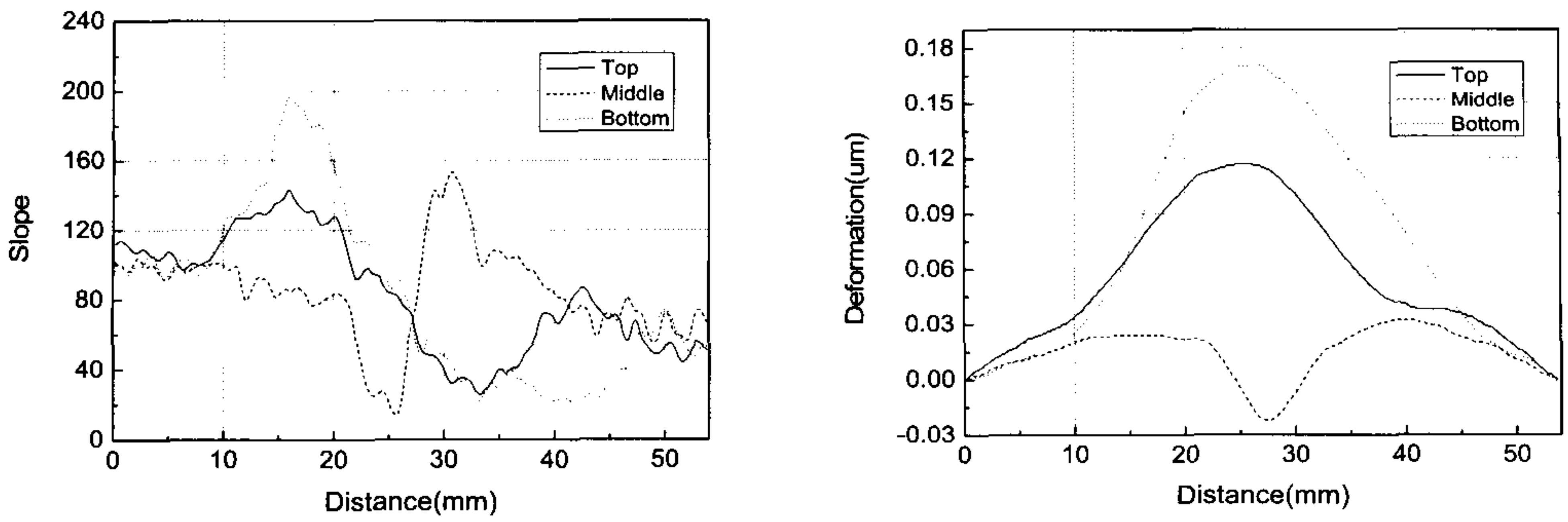
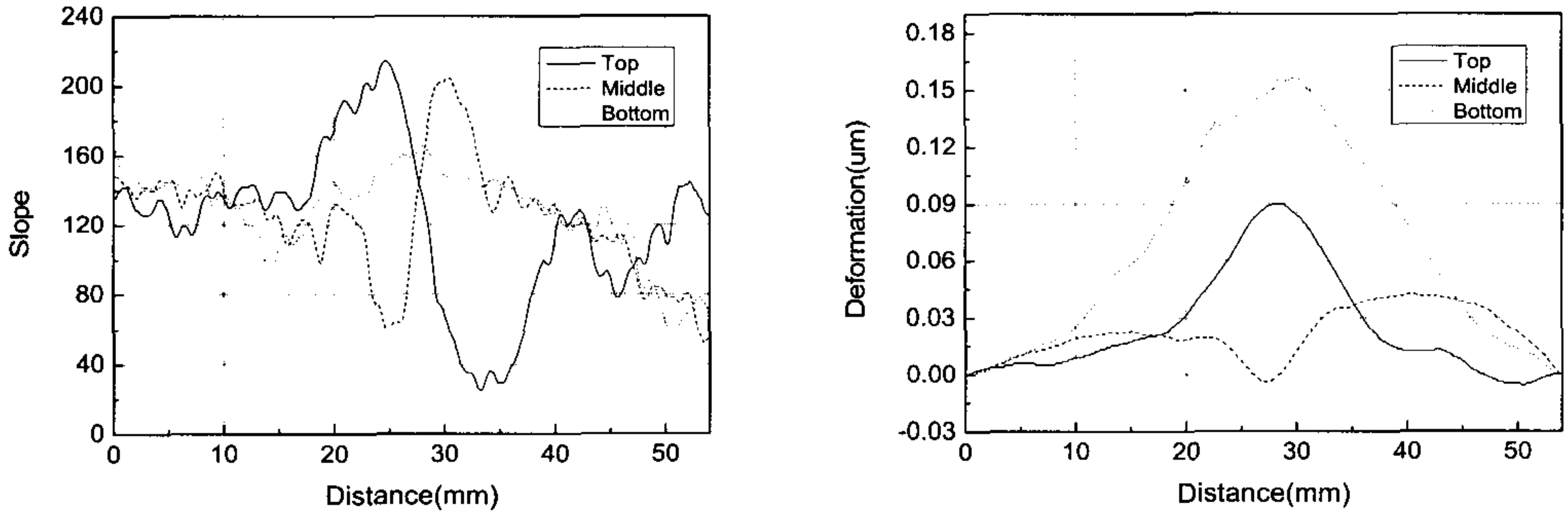


Fig. 4 Phase map of specimen

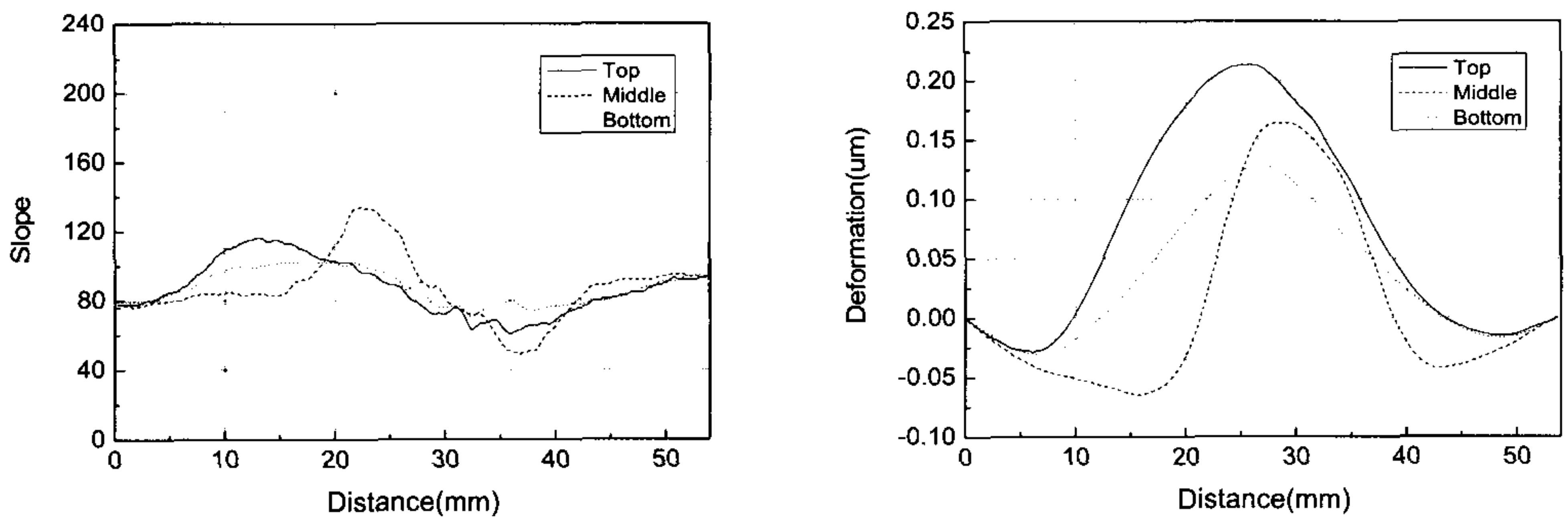


(a) 15J-1

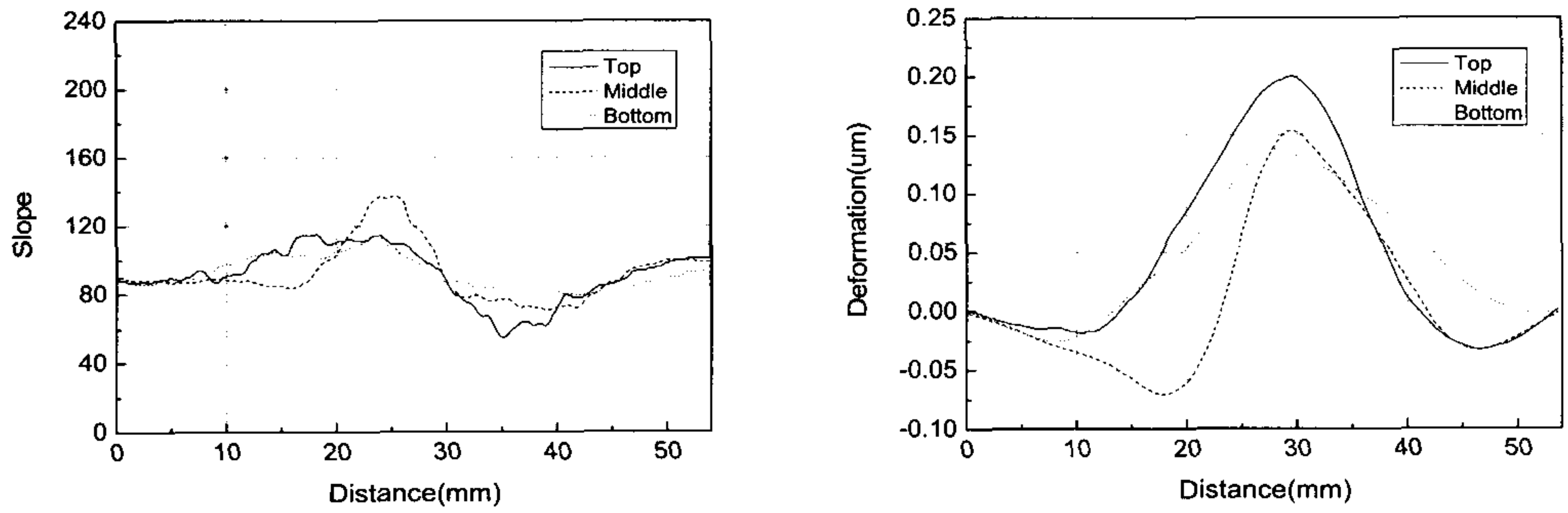


(b) 15J-2

Fig. 5 Profile and deformation of 15J



(a) 30J-1

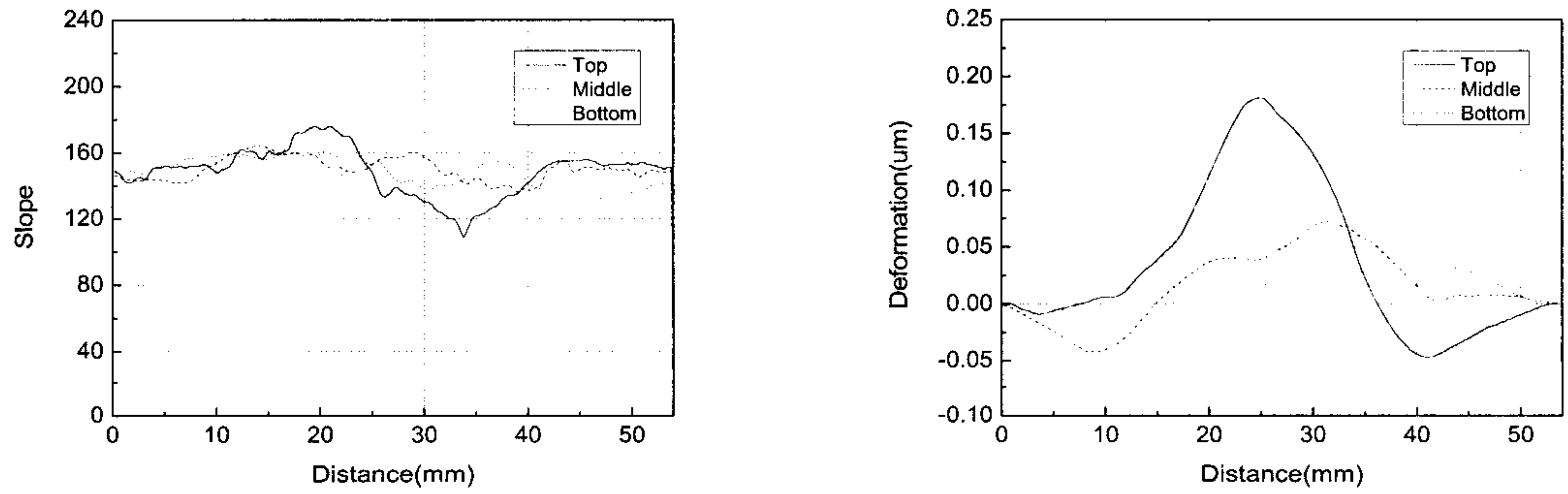


(b) 30J-2

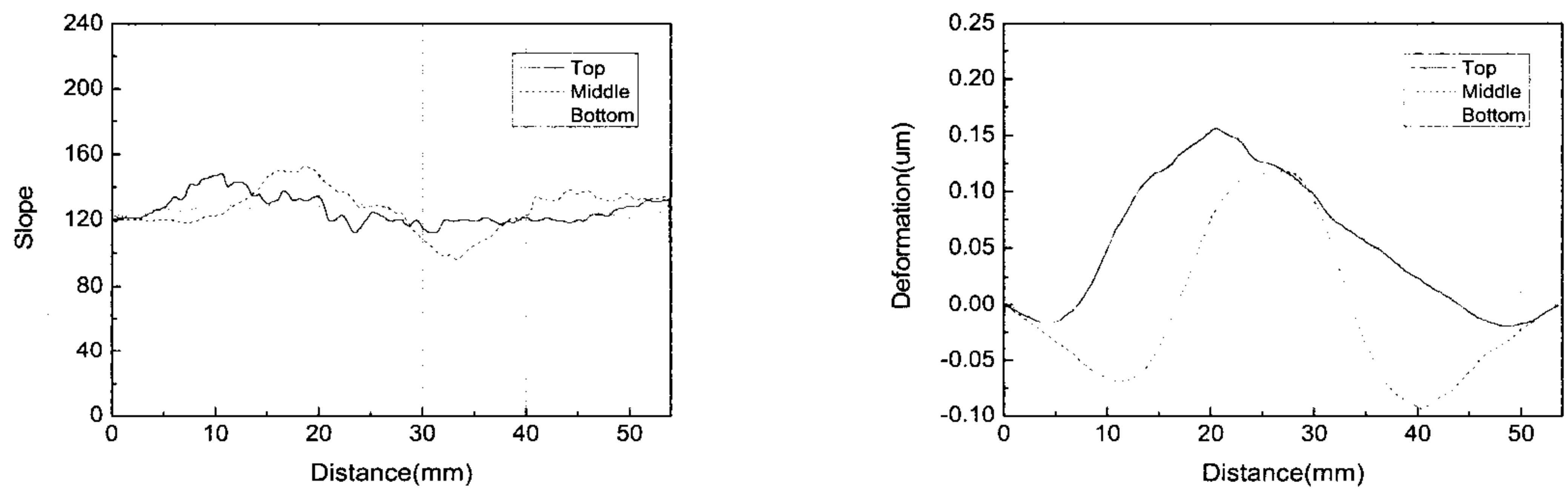
Fig. 6 Profile and deformation of 30J

30J-1result shows similar trend with the 15J-1 as shown Fig. 5(b), middle line showed opposite deformation when compared with the 15J-1. The reason was caused by delamination by impact in the 30J. Also deformation area is equal at the top and bottom but middle part is relatively narrow. The 30J-2 result shows generally similar trend with the case of the 30J-1 and it will know to be higher than impact value of the 30J-1.

As shown in Fig. 7, the case of 45J-1 and the 45J-2 showed that outside of composite tube was destroyed by impact and the deformation forms of both cases are similar. The defect at middle part of 45J is difficult to analyze because of destruction of composite tube. From the top, middle, bottom line which compares the variation of the whole, comparison of deformation at each line are shown in Fig. 8, 9 and 10. From Fig. 8, the deformation at top line is double in the compared 15J with 30J impacted energy and small deformation occur in the 45J impacted



(a) 45J-1



(b) 45J-2

Fig. 7 Profile and deformation of 45J

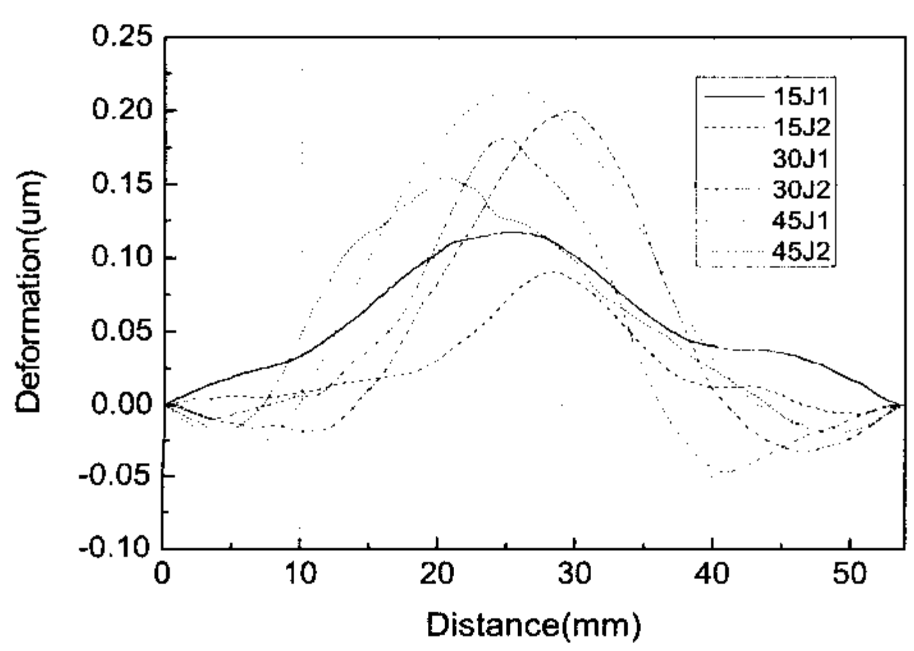


Fig. 8 Deformation of top line

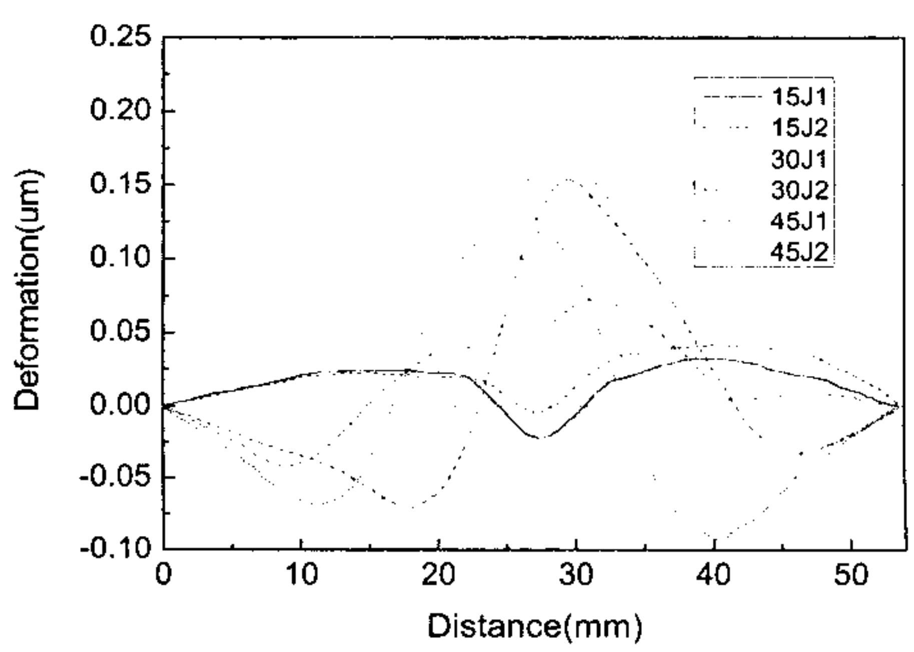


Fig. 9 Deformation of middle line

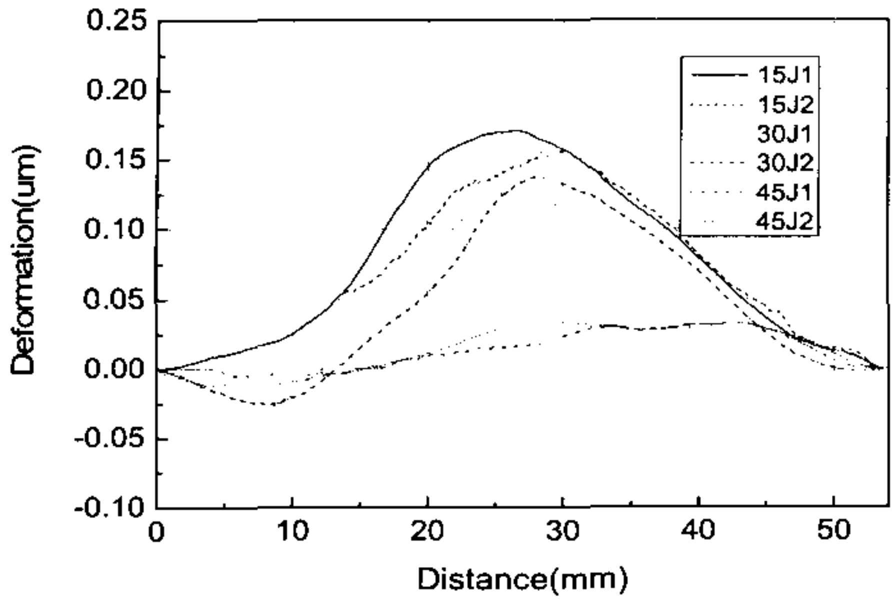


Fig. 10 Deformation of bottom line

energy because of the complete breaking.

As shown in Fig. 9, the size of deformation area in the case of 15J impact energy at middle line is 11 mm. According to this result, it was found that the damaged area was impacted by a rigid body whose size is smaller than 11 mm. Also, the damaged area was not delaminated and it was found that the density of this area was higher than that of the area with no impact damage. In case of the 30J, the delamination was appeared and the deformation of composite materials is very large. Also, the deformation data of 45J was showed complete breaking. From the comparison results of the Bottom line, the size difference of the thermal deformation area tend to 15J<30J<45J.

6. Conclusions

In this paper, the thermal deformations of composite material produced by impact energy were measured by thermal shearography and our conclusions are as follows:

1) From phase map of specimen, the deformation of area tends to increase according to the impact energy. And large deformation presented large deformation in middle part of 45J.
2) It was found that deformation area is 15J<30J<45J, but deformation amount is 15J<45J<30J because of the complete breaking in 45J impact energy. And it was found that the 30J was appeared to delamination and the 15J was disappeared to delamination
3) It could be found whether delamination and fracture is exist or not

With further study, it is expected that thermal shearography can be applied to detect the inside defect of composite materials caused by impact damage.

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