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Non-Destructive Evaluation of Separation and Void Defect of a Pneumatic Tire by Speckle Shearing Interferometry

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This paper describes the speckle shearing interferometry, a non-destructive optical method, for quantitative estimation of void defect and monitoring separation defect inside of a pneumatic tire. Previous shearing interferometry has not supplied quantitative result of inside defect, due to effective factors. In the study, factors related to the details of an inside defect are classified and optimized with pipeline simulator. The size and the shape of defect can be estimated accurately to find a critical point and also is closely related with shearing direction. The technique is applied for quantitative estimation of defects inside of a pneumatic tire. The actual traveling tire is monitored to reveal the cause of separation and the starting points. And also unknown void defects on tread are inspected and the size and shape of defects are estimated which has good agreement with the result of visual inspection.

Key Words : Speckle Shearing Interferometry, Pneumatic Tire, Quantitative Estimation, Separation Defect, Void Defect, Effective Factor, Amount of Shearing

1. Introduction

Since the invention of laser, optical technology has been recognized as a powerful inspection technique for detecting inside or surface defects and process variations in the tire manufacture. Holography has been successful in providing solutions for ply separations, poor adhesion, bread area blisters and many types of defects related to bonding. While X-ray is the method of choice for the examination of belt placement in the manufacture of new tires, it is very poor at detecting bonding defects in tires (Berger, 1981). Holography provides a film showing fringes lines outlining separations and bonding defects, areas in the tire that deform under small vacuum load (Borza, 1998). Even though holography provides the powerful solution, there must be built into a very stable frame that prevents environmental vibration disturbance when the information is recorded on hologram. In an effort to reduce the detrimental effects of the disturbance, a new laser interferometry technique based on speckle shearing interferometry was developed by Hung in 1974, called Shearography (Hung, 1974). Shearography at that time used film as well but while possessed the sensitivity of holography to defects, speckle shearing interferometry is remarkably insensitive to environmental vibration.

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While the novel technique is improved to digital method with CCD camera and image processing technique, there is problem in the quantitative evaluation of defects (Newman, 1993). This drawback makes the decision of acceptance or rejection very difficult. Many of the images still require considerable training to interpret. Even though Shang (1991) and Ettemeyer (1996) presented the possibility of quantitative evaluation, the effective factors related to evaluate defect quantitatively was neglected and the estimation depends on high-skilled operator. Therefore, real time inspection technique and easy quantitative evaluation technique are required for industrial application. To solve the problem, the paper describes the application technique for quantitative evaluation of inside defects, as examined correlation between the defect size and effective factors related optical interferometer or induced load. Separations and actual voids induced by road driving test or abnormal manufacturing processing are inspected and estimated quantitatively. In this paper, effective factors to evaluate defect, such as amount of shearing, the direction of shearing and induced load are classified, which has depended on inspector's skill positively but also affect in-situ workability until now. The correlation between effective factors and a defect is optimized with pipeline simulator system. From the data, the inside defects of automobile tire are evaluated quantitatively.

2. Speckle Shearing Interferometry

A schematic diagram of a digital speckle shearing interferometer is shown in Fig. 1. The coherent laser is expanded by an objective lens and illuminates an object to be inspected. Scattered lights from the surface pass through beam splitter and are reflected on the tilt mirror and the mirror with Piezo-electronic transducer (PZT). The PZT mirror for phase shifting technique lies parallel to the CCD camera and one can shift the images with respect to parallel image by tilt mirror. The direction and the tilt angle (the shearing on CCD image plane) between two images can be manually adjusted by tilt mirror. The intensity at a point on CCD image plane corresponds to the superposition of the light scattered from two adjacent points on the original object (Rastogi, 2001).

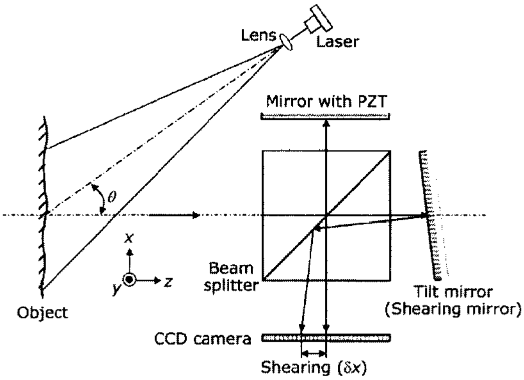
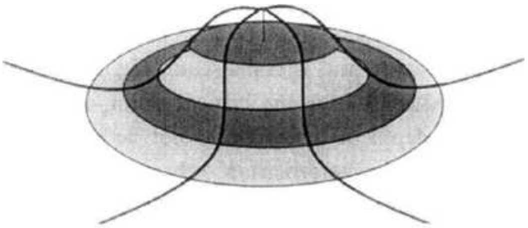


Fig. 1 Schematic of speckle shearing interferometer

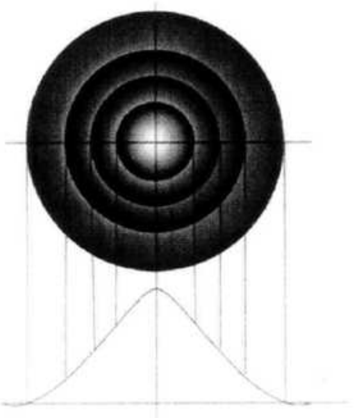
When the object is deformed, an arbitrary point (x, y) on the object surface is displaced to $(x+u, y+v, w)$, where u, v, w are the displacement components of x-, y- and z-axis, respectively. And a neighboring point $(x+\delta x, y)$ is displaced to $(x+\delta x+u+\delta u, y+v+\delta v, w+\delta w)$. Deformation of the object makes a phase difference between two neighboring points. In the optical set-up, the expression for the relative phase difference is given by eqn. (1) (Steinchen, 2003).

$$\Delta\phi(x, y)=\frac{2\pi}{\lambda}\left[(1+\cos\theta)\frac{\partial w(x, y)}{\partial x}+\sin\theta\frac{\partial u(x, y)}{\partial x}\right]\delta x \tag{1}$$

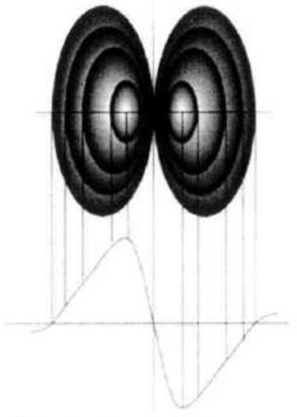
where, $\Delta\phi$ is the relative phase change between before and after the deformation, λ is the wavelength of light source, θ is the angle between illumination and the surface normal, $\partial w/\partial x$ and $\partial u/\partial x$ are the first-order partial derivative of the out-of-plane and the in-plane displacements of the deformed object, respectively, and δx is amount of shearing between two speckle patterns. The interferometric superposition of the two slightly sheared images makes a shearing interferogram. The shearing direction and the amount of shearing (δx) related to tilt mirror in Fig. 1 can be calculated from lens magnification and distance between object surface and the image plane. Shearing interferometry, due to the novel interferometer, measures the first derivative of static surface displacements directly instead of displacements. The surface displacement above inside defect is plotted in Fig. 2(a) and the sketch of phase map in out-of-plane displace sensitive interferometer in Fig. 2(b) and the sketch of phase map, displacement gradient, in shearing interferometer are shown in Fig. 2 (c). The size of inside defect is determined by measuring the length between two angular points of the line profile in shearing interferometer. The length between two peaks is related to the change of the effective factors. In order to evaluate the size of a defect quantitatively, phase shifting and unwrapping method has been used; where the 4 phase-shifted speckle interferograms are generated by PZT. The relative phase could be calculated from the 4 speckle interferograms (Cloud, 1990; Baek, 2002).



(a) Real displacement of an object surface



(b) Out-of-plane displacement sensitive interferometer



(c) Shearing interferometer

Fig. 2 Comparison of measurement result

3. Simulation by Pipeline System

A pipeline system with artificial inside defects was designed, which consists of a 100 mm diameter pipeline, pressure gage and nitrogen gas pressurizing system as shown in Fig. 3. The artificial defects were parallel to pipe axis with 12 mm in length and 1, 2, and 3 mm in depth from the inner surface of the pipeline. The pipeline to be inspected was loaded with inner pressure change. The pipeline would deform only by a few micrometers. In the areas with a weakened wall caused by crack or corrosion, the wall of the pipeline was deformed more by the inner pressure change than in the areas with no defect.

The difference between a loaded and an unloaded state provided the information about the surface displacement of the pipeline. The displacement gradient was obtained by deriving the line profile in the axis of the pipeline with speckle shearing interferometry. An image of the unloaded pipeline was recorded and stored as a reference image by an image processor. All the following images of the loaded pipeline were subtracted from the reference image in image

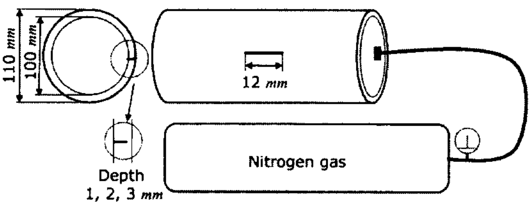


Fig. 3 Pipeline simulator

processor in real time and the result, speckle shearing interferogram, was displayed in a monitor. Fig. 4 shows the phase map of shearing interferometry according to amount of shearing. The defect size can be estimated by measuring the peak-to-peak of the line profile obtained by phase map. Fig. 5(a) shows the relationship between the estimated defect size and the amount of shearing. The size of defect is given as 12 mm in length. From the results, there is a critical point which is related to the fact that in the case that the amount of shearing was within the point, the size was evaluated very well. In the case that the amount of shearing is beyond the point, the size of defect was much overestimated. Therefore the amount of shearing should be an important effective factor and the size could be estimated exactly when finding the critical point. In addition, the depth of defect could not be evaluated with the surface information only and it appeared not to be related to the amount of shearing. Fig. 5(b) shows the relationship between the estimated defect size and the normalized pressure, which is given by the induced pressure divided by the allowable pressure of the pipeline. The out-of-plane deformation of object surface of defect with the same depth, according to the increase of induced load, is larger.

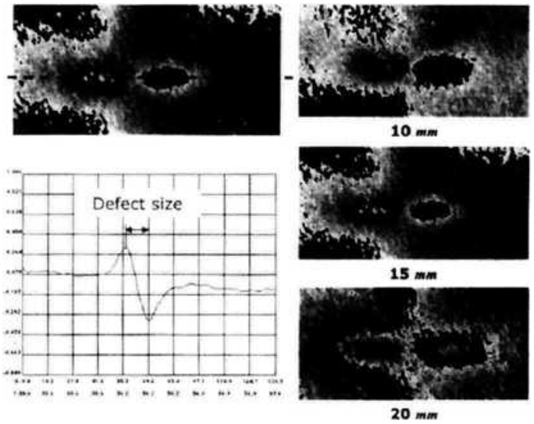
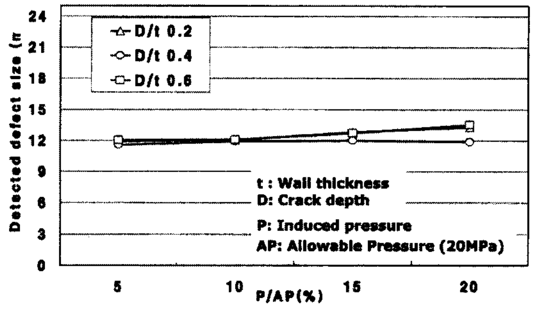
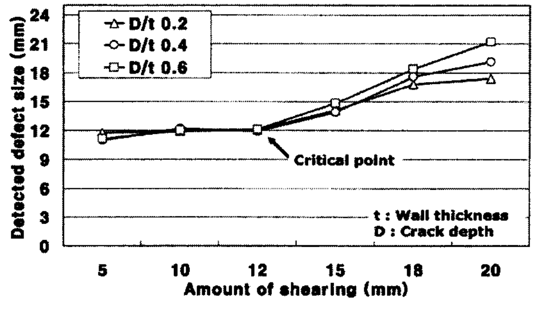


Fig. 4 Shearing interferometry phase map according to amount of shearing



(a) Estimation of inside defect with the amount of shearing



(b) Estimation of inside defect with the induced load

Fig. 5 Quantitative estimation of defect inside of pipeline (t : Wall thickness, D : Crack depth, P : Induced pressure, AP : Allowable pressure)

Therefore, the result has influence on the estimation of defect size, even though it is not too much. It is found from experimental data that optimal induced load is as low as possible. However, there are not any quantitative characteristic in determination of proper induce load.

4. Inside Defect Inspection of a Pneumatic Tire

The tire inspection system consists of shearing interferometry system and vacuum chamber. The automatic rotation of vacuum chamber allows for complete inspection of the entire tire. By vacuum stress, results of shearing interferometry appear out of the plane strain deformations wherever there is a weakened bond or small quantity of entrapped air within the structure of the tire. Fig. 6 shows the structure of pneumatic tire. Generally the air void, impurity and debonding defects are detected between the layer of belt and inside of tread. Delamination defects which will grow up separation defect are detected on belt edge, which is caused by frictional heat.

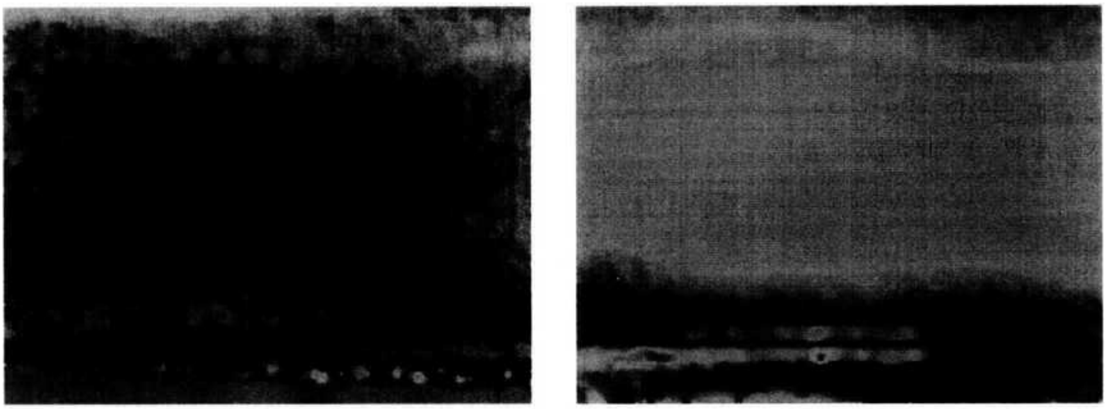
1. Tread 2. Carcass 3. Belt 4. Sidewal
5. Bead 6. Inner liner 7. Capply 8. Apex

Fig. 6 Structure of a pneumatic tire

In this paper, a void defect on tread in abnormal manufacturing processing and a separation defect in actual traveling test with more than 20,000 km are inspected.

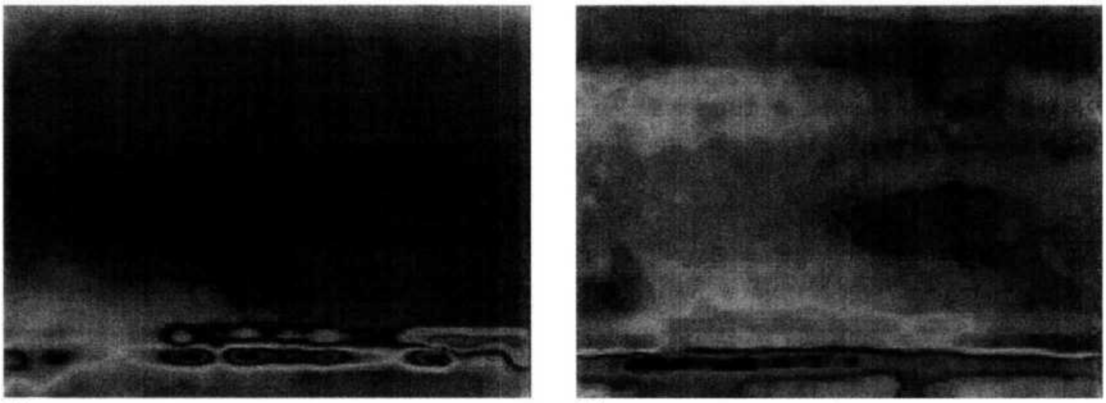
4.1 Monitoring on separation defect

Since it is a rare occurrence that separation is detected in the normally manufactured tire, a serious traveling test on highway is programmed. Generally, delamination defect with the type of point are started from belt edge and to progress a tread with separation. Finally, the separation makes the tread come off tire. The progress of



(a) First step : the separation appears as many points, which are started from sidewall of the tire. The cause of the initial point defects at first step is revealed as an abnormal heating generation of the fabricated steel wire

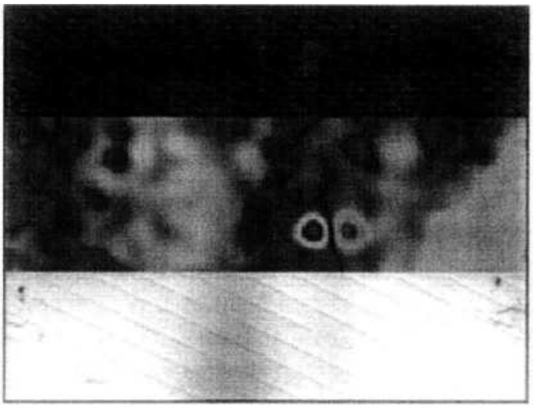
(b) Second step : one of many points grows up rapidly, which is regarded as a defect



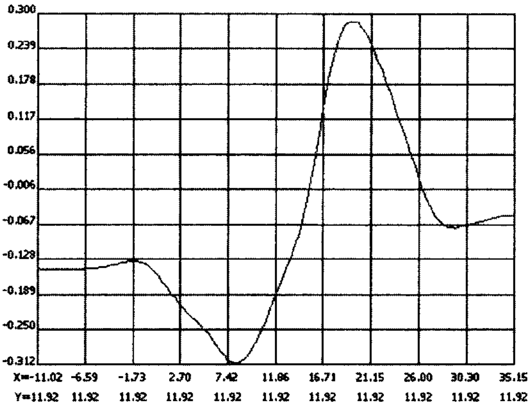
(c) Third step : the small defect is connected with each other, which is the starting point of a separation

(d) Fourth step : The defects are connected to make whole separation, which progress to a tread

Fig. 7 The progress of separation in actual traveling tire (The bottom of image)



(a) Qualitative estimation of inside void defect



(b) Quantitative estimation of inside void defect in x-direction

Fig. 8 Inspection result of void defect inside of tread

separation is monitored by shearing interferometry. Fig. 7 shows each step of separation.

4.2 The inside void defect inspection on tread

The void defects on tread are generally derived from water or an inclusion in manufacturing processing at the first production line setup. Since the defect stretches over all sections of a tire and the size and location of the defect are related to production control, it is needed to analyze the defects qualitatively as well as quantitatively. The size and shape of void defect in unknown void defect of inferior goods are estimated using shearing interferometry, based on proposed the technique. Fig. 8 shows result of shearing interferometry induced by void defect inside of tread. The defect size in x-direction can be estimated from the line profile of result, Fig. 8(b).

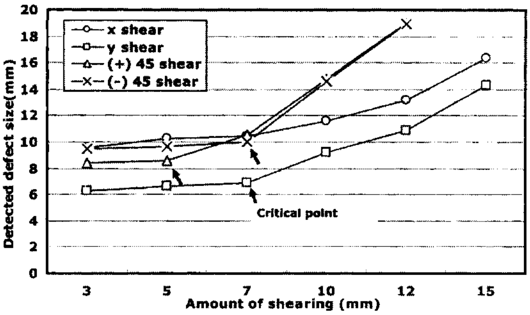


Fig. 9 Quantitative estimation of void defect inside of tread

The size and the shape of defect can be estimated from Fig. 9 as finding critical points. The size is estimated as 7 mm in x-direction, 7 mm in y-direction, 5 mm in 45-direction and 7 mm in -45-direction from the determination of the critical point on each shearing direction. The shape of void defect can be estimated from the size in each direction, and the section is cut open for visual inspection. The results are compared with visual inspection within the agreement of 5%.

5. Conclusions

The study describes the new technique of quantitative estimation of inside defect. Even though shearing interferometry has many advantages to non-destructive testing, many effective factors including the amount of shearing, shearing direction and induced load existed as barrier for the quantitative analysis of inside defects. To solve the problem, the pipeline simulator with artificial defects is inspected. Related to the details of a defect, factors are classified and optimized for quantitative estimation. The size and the shape of defect can be estimated accurately to find a critical point and was closely related with shearing direction. Even though it is not too much, induced load has influence on the determination. However, there are not any quantitative characteristic in the determination of proper induce load. It is found from experimental data that optimal induced load is as low as possible. The technique is applied for quantitative estimation of defects inside of a pneumatic tire. The actual traveling tire is monitored to reveal the cause of separation and the starting points. And also unknown void defects on tread is inspected and the size and shape of defects is estimated which is agreed with the result of visual inspection.

References

Baek, T. H., Kim, M. S., Morimoto, Y. and Fujigaki, M., 2002, "Separation of Isochromatics and Isoclinics from Photoelastic Fringes in a Circular Disk by Phase Measuring Technique," *KSME International*, Vol. 16, No. 2. pp. 175~181.

Berger, H., 1981, "An Overview : New Ideas in Nondestructive Evaluation," *Rubber Chemistry and Technology*, Vol. 54. Iss. 5, pp. 996~1002.

Borza, D. N., 1998, "Specialized Techniques in Holographic Non-Destructive Testing of Composites," *Composites Part B : Engineering*, Vol. 29, pp. 497~504.

Cloud, G. L., 1990, *Optical Methods of Engineering Analysis*, Cambridge University Press., England, pp. 477~491.

Ettemeyer, A., 1996, "Laser Shearography for Inspection of Pipelines," *Nuclear Engineering and Design*, Vol. 160, pp. 237~240.

Hung, Y. Y., 1974, "A Speckle-Shearing Interferometer : A tool for Measuring Derivatives of Surface Displacements," *Optics Communications*, Vol. 11, pp. 132~135.

Newman, J. W., 1993, "Advanced Shearography Tire Analysis," *Tire Technology International*, pp. 15~18.

Rastogi, P. K., Eds., 2001, *Digital Speckle Pattern Interferometry and Related Techniques*, John Willey & Sons Ltd., New York, pp. 179~203.

Shang, H. M., Toh, S. L., Chau, F. S., Shim, V. P. W. and Tay, C. J., 1991, "Locating and Sizing Disbands in Glass Fiber-reinforced Plastic Plates using Shearography," *Journal of Engineering Materials and Technology*, Vol. 113, pp. 99~103.

Steinchen, W. and Yang, L., 2003, *Digital Shearography*, SPIE Press., Washington, pp. 55~72.