The Electronic Laser Interferometry and Laser Heating Method for Residual Stress Determination

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Residual stress is one of the causes which makes defects in engineering components and materials. These residual stresses can occur in many engineering structures and can sometimes lead to premature failures. There are commonly used methods by which residual stresses are currently measured. But these methods have a little damage and other problems; therefore, a new experimental technique has been devised to measure residual stress in materials with a combination of electronic laser interferometry, laser heating and finite element method. The electronic laser interferometer measures in-plane deformations while the laser heating and cooling provides for very localized stress relief. FEM is used for determining the heat temperature and other parameters. The residual stresses are determined by the amount of strain that is measured subsequent to the heat-up and cool-down of the region being interrogated. A simple model is presented to provide a description of the method. In this paper, the ambiguity problem for the fringe patterns has solved by a phase shifting method.

Key Words : Residual Stress, Electronic Laser Interferometry, Laser Heating Method, Finite Element Method, Fringe Pattern, Phase Shifting Method

1. Introduction

Residual stresses have been defined as "those stresses existing without the loading of any intended, or unintended external forces" (Nickola, 1984), and they are produced by many material processing and joining operations such as welding, machining and rolling. These are mainly produced in them by compression and tension. Compressive residual stresses are sometimes purposely induced in materials by peening or rolling to reduce the potential for crack growth. On the other hand, tensile residual stresses can result in fatigue failures and promote corrosion. These residual stresses can occur in many engineering structures such as automobiles, airplanes and nuclear reactors, and sometimes lead to premature failures. So there are a lot of interests in the measurement of residual stress in many industries.

There are mainly two sorts of method used by which residual stresses are commonly measured. The method is distinguished into destructive or nondestructive. The famous destructive method is known as hole-drilling or blind hole-drilling. These methods take damage of specimen into disadvantage. The nondestructive methods are X-ray diffraction (XRD) and neutron diffraction. However XRD is able to give surface of testing specimen to a little damage, and neutron diffraction requires an intense neutron source. (Stanley, 1995)

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Therefore we devised a new experimental technique to measure residual stress in materials with a combination of electronic laser interferometry, (Kang and Kim, 1999) laser heating and finite element method. The electronic laser interferometer measures in-plane deformations while the laser heating and cooling provides for very localized stress relief. FEM is used for determining the heat temperature and other parameters. (Cook, et al., 1989) The residual stresses are determined by the amount of strain that is measured subsequent to the heat-up and cool-down of the region being interrogated. A simple model is presented to provide a description of the method. The technique is based on the idea that when stressed material is heated, the stress may be relieved to a certain degree and the force-displacement characteristics of the material. And this non-contact and non-destructive method can be measured at a real time for the whole area illuminated by laser beam.

2. Theoretical Model

The process to determine the residual stress can be described with the simple model. (Pechersky, et al., 1995) Consider a spring length, L which is initially relaxed at a room temperature T_L. F_1 is the force of unknown amount which is applied to the spring. A displacement of unknown amount, x_1 is applied to the spring and then the ends are fixed. The displacement and force are related through Hook's law by

$$F_1 = k_L x_1 \tag{1}$$

And the spring strain energy can be expressed as

$$U_1 = \frac{1}{2}\left(\frac{F_1^2}{k_L}\right) \tag{2}$$

where k_L is the spring constant at room temperature, T_L.

If the spring in tension is heated, the force will relax due to thermal expansion and plastic flow. Therefore this initial state is represented by point I, and the heated state of the spring is shown as point II in the force-displacement of Fig. 1. Point II is located on the force-displacement diagram

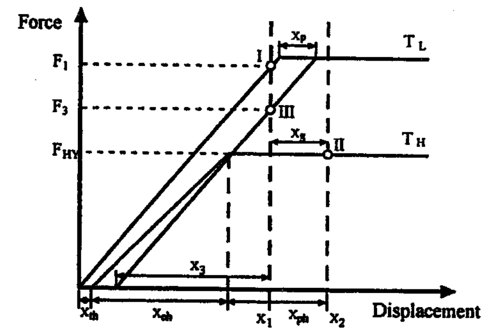

Fig. 1 Force-displacement diagram for the simple spring model

corresponding to the heating temperature, T_H, and though the ends of spring are fixed, the displacement, x_2 is increased in the environment. Then it is decomposed into four displacement components resulting in the virtual character. The thermal expansion component in the displacement, x_2 can be given by

$$x_{th} = \alpha(T_H - T_L) L \tag{3}$$

where, α is coefficient of thermal expansion of the material.

The elastic component at the elevated temperature in x_2 can be given by

$$x_{eh} = \frac{F_{HY}}{k_H} \tag{4}$$

The plastic component in x_2 is x_{ph}, and x_g is the gauge displacement in the environment. Where F_{HY} is the force on the yield stress and k_H is the spring constant of the spring at the heated temperature. The material of spring is assumed to be perfectly plastic. When the spring is allowed to cool down, the thermal expansion is reversed but the plastic deformation reserves. So point III is shifted due to the plastic flow. At this time, the force F_3 and the energy U_3 stored on the spring are

$$F_3 = k_L x_3 = k_L (x_1 - x_p) \tag{5}$$

$$U_3 = \frac{1}{2} x_3 F_3 \tag{6}$$

The amount of elastic energy dissipated as a result of the stress relief is

$$U_d = x_{ph} F_{HY} = \{(x_1 + x_g) - (x_{th} + x_{eh})\} F_{HY} \tag{7}$$

Where $x_2 = x_{th} + x_{eh} + x_{ph} = x_1 + x_g$, so $x_{ph} = x_1 + x_g - (x_{th} + x_{eh})$. For the law of energy conservation, the initial stored energy in the spring must be equal to the final stored energy plus the energy dissipated due to the plastic flow, or

$$U_1 = U_3 + U_d \tag{8}$$

To lead the equation for F_1 in terms of the physical parameters of the spring and the amount of plastic flow, Eqs. (9) and (10) yield Eq. (11).

$$x_1^2 k_L = (x_1 - x_p)^2 k_L + 2\{x_1 + x_g - (x_{th} + x_{eh})\} F_{HY} \tag{9}$$

$$\left(1 - \frac{F_{HY}}{x_p k_L}\right) F_1 = \frac{1}{2} x_p k_L + \{x_g - (\alpha \Delta TL + \frac{F_{HY}}{k_H})\} \frac{F_{HY}}{x_p} \tag{10}$$

$$F_1 = \frac{\frac{1}{2} x_p^2 k_L + x_g F_{HY}}{x_p - \frac{F_{HY}}{k_L}} - \frac{\alpha \Delta TL F_{HY} + \frac{F_{HY}^2}{k_H}}{x_p - \frac{F_{HY}}{k_L}} \tag{11}$$

where, x_p is in-plane displacement resulting from the stress relaxation.

In this example, the spring is assumed to be a constant cross section bar, Eq. (11) is replaced by an equation involving stress and strain as follows

$$\sigma_R = \frac{\frac{1}{2} \varepsilon_p^2 E_L + \varepsilon_g \sigma_{HY}}{\varepsilon_p - \frac{\sigma_{HY}}{E_L}} - \frac{\alpha \Delta T \sigma_{HY} + \frac{\sigma^2_{HY}}{E_H}}{\varepsilon_p - \frac{\sigma_{HY}}{E_L}} \tag{12}$$

Where,

σ_R : Unknown tensile residual stress
E_L : Young's modulus prior to laser heating
σ_{HY} : Yield stress at the heated temperature T_H
E_H : Young's modulus at the heated temperature T_H
α : Coefficient of thermal expansion of the material
ΔT : Temperature rise due to the laser heating $(T_H - T_L)$
ε_g : Strain resulting from the displacement, x_g
ε_p : In-plane strain resulting from the stress relaxation

Thus, if the material properties were known, we could determine the value of residual stress.

3. Electronic Laser Interferometry

Electronic laser interferometry (Butters and Leendertz, 1971) is an advanced technique in nondestructive testing of materials for deformation measurement in a submicron range. A beam of laser is divided into two, with one part, the object beam, and the other, the reference beam. When the beams are recombined, they interfere and provide fringes which allow visualization and quantification. Electronic laser interferometer is able to measure real-time, storage data and perform easily, because the fringes produced by interference are obtained using CCD camera, frame grabber and IBM PC. These fringes are determined by sensitivity vector $\vec{K}$ in the vector diagram of Fig. 2. (Rastogi, 1994) Sensitivity vector, vector $\vec{k_1}$ of incident light and observing vector $\vec{k_2}$ can be expressed as

$$\vec{K} = \vec{k_1} - \vec{k_2} \tag{13}$$

We used the optical method which is sensitive to in-plane displacement to determine the in-plane strain. With this type of interferometer the object is illuminated by two beams. (Jones, 1989) For the one dimensional situation described the in-plane strain ε_p is given by

$$\Delta x = \frac{\lambda}{2 \varepsilon_p \sin\theta} \tag{14}$$

where, λ : the wavelength of laser
Δx : the measured fringe spacing

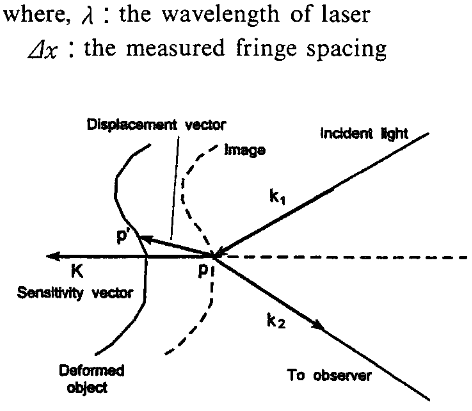

Fig. 2 Vector diagram showing sensitivity to displacement in ESPI

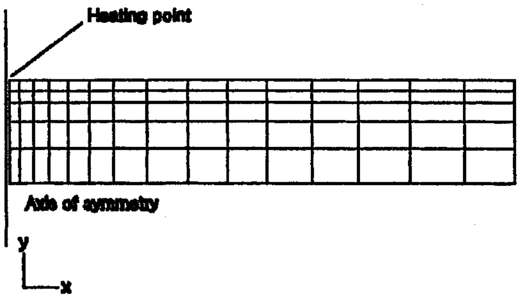

Fig. 3 Finite-element model of two-dimensional, axisymmetric plate
θ : the angle of incidence

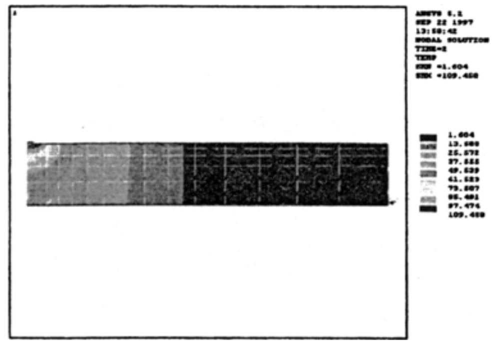

Fig. 4 Distribution of temperature after heating for 3 seconds

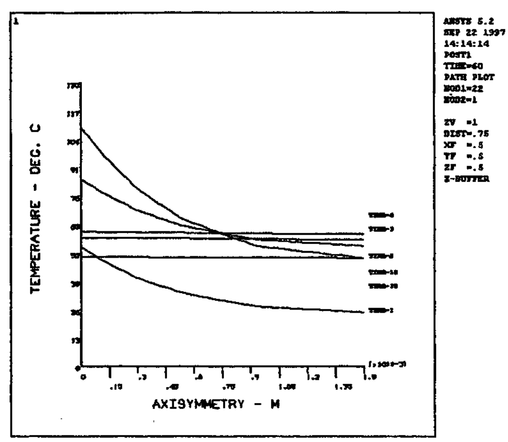

Fig. 5 Temperature rise graph of specimen center after heating and cooling

4. Finite Element Analysis

The analysis is based on spot heating method that is to stimulate on surface of specimen using laser. The heating process is accomplished in order that the stress may be relaxed. But the specimen is affected by heating spot size, heating time and heat fluxes. Thus it is important to determine the parameters for experiment. The model is that of two dimensional plate of 304 stainless-steel, which was heated at its center, on the top surface. (Swanson Analysis Systems Inc., 1993) The model is shown in Fig. 3. The functional relationship is between these parameters; therefore, the data include all of the different spot sizes, heating time and heat fluxes analyzed. The final heating cycle chosen in this analysis was a 1mm diameter spot with a peak intensity of 200 W/cm^2. The heating pulse was starting at no power, increasing to full power in 2 seconds and then falling off to zero in next 2 seconds. The laser power would have to be increased to take into account reflection. When the temperature rise of the specimen is over 50 degrees Celsius, the thermally induced stresses usually exceed the yield stress; therefore, the specimen starts to practically deform. (Pechersky, et al., 1995) The temperature rise of only 60℃ is required. Distribution of temperature after heating for 4 seconds shows in Fig. 4. In the analysis the specimens were assumed to be at various levels of uniform axial tension prior to the application of heat. The coefficient of thermal expansion of the SUS304 α is 17.2×10^{-6}/℃ and the Young's modulus prior to laser heating E_L is 193×10^9Pa. Young's modulus at the elevated temperarure E_H is similar to E_L.

Longitudinal distribution of temperature after heating and completely cooling for 60 seconds shows in Fig. 5. We could avoid time consumption for computer simulation, because the 4-node quadrilateral elements, one degree of freedom, were adapted. (Swanson Analysis Systems Inc., 1993)

5. Experimental Setup

Figure 6 shows a schematic of the laser heating apparatus, the electronic laser interferometer and the loading system used in this experiment. We used optical fiber to connect heat source with heating part, and the heat source is Nd: Yag laser

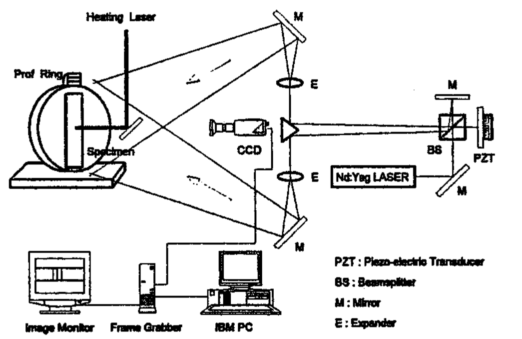

Fig. 6 Schematic of the laser interferometer and the image acquisition system used in the in-plane ESPI

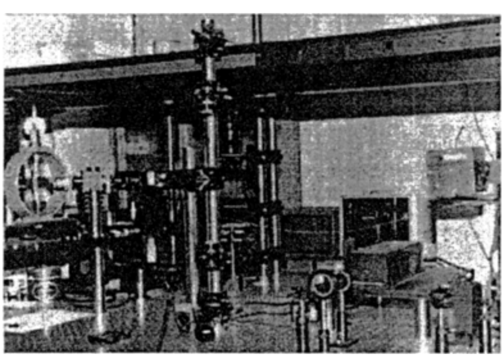

Photo. 1. Laser interferometer and the image acquision system used in the in-plane ESPI

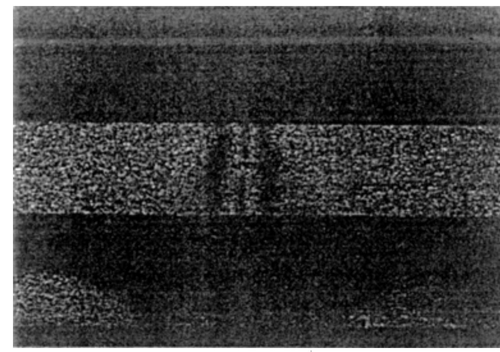

Fig. 7 Fringe pattern for a specimen

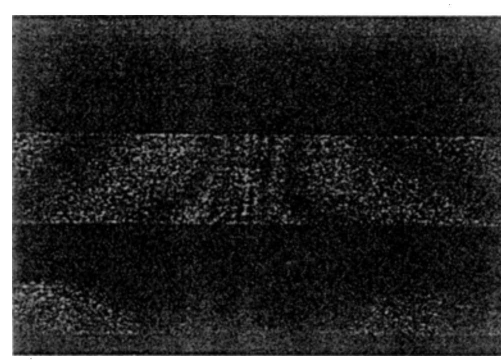

Fig. 8 Fringe pattern for a specimen loaded to 90% of its yield stress

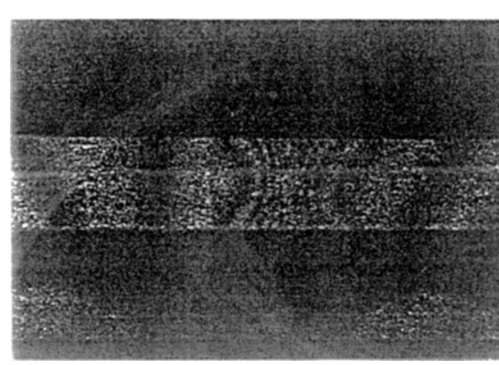

Fig. 9 Fringe pattern for a specimen loaded to 98% of its yield stress

that is able to control pulse width and energy level. The hot mirror at the CCD camera was used for applying the laser heating on the specimen and being able to see the fringe pattern of the specimen through CCD camera. Electronic laser interferometer used in the experiment is composed of in-plane interferometer, frame grabber and image processing system with IBM PC. The initial image is obtained prior to heating and stored in the memory of IBM PC. Heat is applied and then specimen is allowed to cool. After the cool-down the second image is acquired. The images are subtracted real time and the resulting fringe pattern, a function of residual stress, is displayed on a image monitor.

6. Results and Discussion

A whole system to measure residual stress is shown in Photo 1. A series of experiments were performed to demonstrate the validity of the approach described in the first part of this paper. Figures 7, 8 and 9 show the experimental results for the case when the preload were 80%, 90% and 98% of the normal yield stress of the specimen respectively. The heating laser used in the experiments selected 8ms in laser pulse width, 10Hz in frequency, 11.5V in input voltage and 10% in energy level. In these pictures the more residual

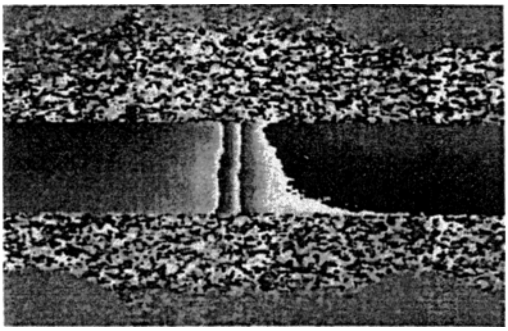

Fig. 10 Phasemap for a specimen loaded to 80% of its yield stress

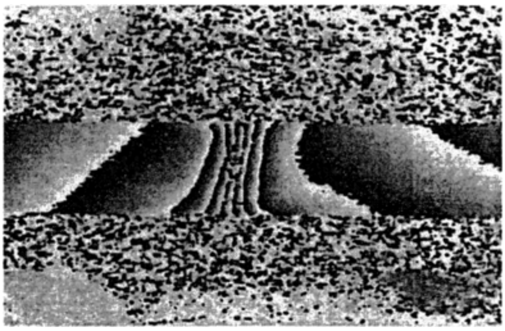

Fig. 11 Phasemap for a specimen loaded to 90% of its yield stress

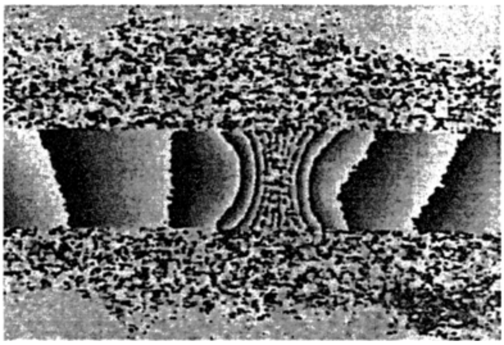

Fig. 12 Phasemap for a specimen loaded to 98% of its yield stress

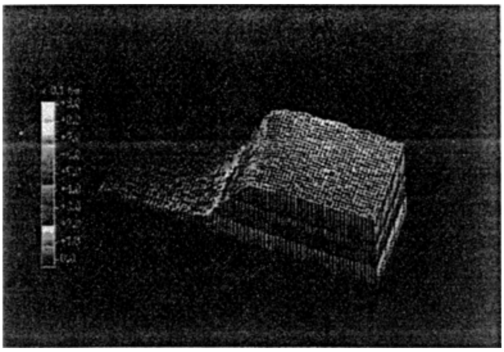

Fig. 13 3D plot for a specimen loaded to 80% of its yield stress

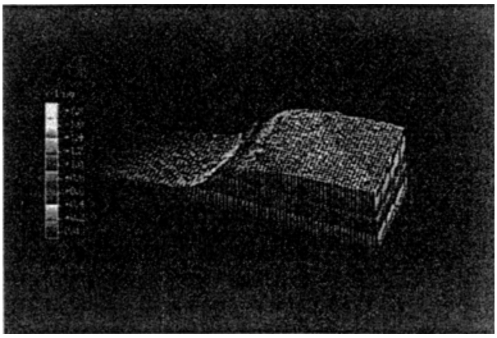

Fig. 14 3D plot for a specimen loaded to 90% of its yield stress

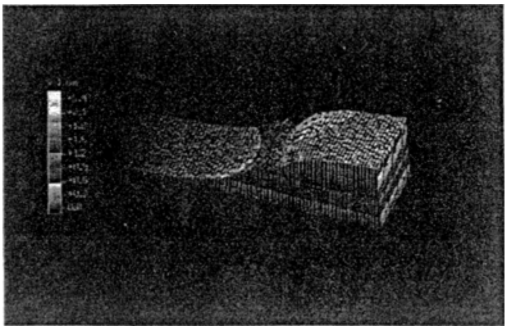

Fig. 15 3D plot for a specimen loaded to 98% of its yield stress

stress, preloading the test specimen in uniaxial tension, increase, the more the number of fringes increase and the interpretation becomes much more concrete.

Thus the value of the strain is determined to fringes, it is the in-plane strain ε_p resulting from the stress relaxation. In this case the center dark fringe is the zero order fringe. Figures 10, 11 and 12 show the phasemaps for the case when the preload were 80%, 90% and 98% of the normal yield stress of the specimen respectively. The fringe patterns were transformed into these phasemaps, which contain the phase information by using a phase shifting method. For the quantitative analysis of deformation the PZT (Piezo-Electric Transducer) was located in the optical path of electronic laser interferometer. Figures 13, 14 and 15 show the unwrapping images for the case when the preload were 80%, 90% and 98% of the normal yield stress of the specimen respectively. The displacements obtained for unwrapping images are about 0.9 μm, 1,8 μm and 2.4 μm respectively. The internal residual stress preloaded increase, the magnitude of displacement increase. The calculations and experimental results at strain ε_p agree to within about 20% from Eq. (12).

7. Conclusion

In this study, we developed a new technique to measure residual stresses with a combination of laser speckle pattern interferometry, FEM (Finite Elements Method) and spot heating. The process to determine the residual stress can be envisioned with the sample lumped-parameter model, which is discussed. From this model, finite element analysis was performed to determine experimental parameters for stress relaxation.

Then we used electronic laser interferometer and laser heating apparatus to obtain the fringe visualization of displacements parallel to the direction of the observation. In this theoretical, experimental method, we were able to obtain residual stress and present that it is possible to measure unknown residual stress.

To make this technique practical, several technical issues need to be addressed. One of the largest is the uncertainty in the yield stress of the material. The remaining issues are front surface temperature measurement, vibration isolation for measurement and heating cycles for depth profiling of the stresses.

Acknowledgement

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References

Butters, J. N. and Leendertz, J. A. 1971, "Speckle Pattern and Holographic Techniques in Engineering Metrology," *Optics and Laser Technology*, Vol. 3, No. 27.

Cook, R. D., Malkus, D. S. and Plesha, M. E., 1989, "Concepts and Application of Finite Element Analysis," *John Wiley & Sons, Inc.*, New York.

Jones, R. and Wykes, C., 1989, "Holographic and Speckle Interferometry, 2nd ed.," *Cambridge Univ. Press*, pp. 146～182.

Kang, Y. J. and Kim, K. S., 1999, "Experimental Analysis of Vibration Modes of Plates Using ESPI," *KSME International Journal*, Vol. 13, No. 10, pp. 677～686.

Nickola, W. E., 1984, "Weld Induced Residual Stress Measurements Via the Hole-Drilling Strain Gauge Method," *American Society of Mechanical Engineering*, Report 84-WA/DE-25.

Pechersky, M. J., Miller, R. F. and Vikram, C. S., 1995, "Residual Stress Measurements with Laser Speckle Correlation Interferometry and Local Heat Treating," *Optical Engineering*, Vol. 34, No. 10, pp. 2964～2971.

Rastogi, P. K., 1994, "Holographic Interferometry," *Springer Series in Optical Sciences*, pp. 27～31.

Stanley, R. K., Moore, P. O. and Malntire, P., 1995, "Nondestructive Testing Handbook," *ASNT*, Vol. 9, pp. 2～13.

Swanson Analysis Systems, Inc. 1993, "ANSYS Solid Modeling User Guide for Reversion 5.0."

Swanson Analysis Systems, Inc. 1993. "ANSYS Verification for Reversion 5.0."

Swanson Analysis Systems, Inc. 1993. "ANSYS Heat Transfer User Guide for Reversion 5.0."