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# Determination of Residual Stresses by Local Annealing to Laser Speckle Pattern Interferometry

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by

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# *Determination of Residual Stresses by Local Annealing and Laser Speckle Pattern Interferometry*

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One of the most common methods of experimentally determining residual stresses is **Blind Hole Drilling** [1], **BHD**. A new method which is a thermo-optical analog to BHD is being developed. This method uses local heating to anneal a tiny spot and uses laser speckle interferometry to measure the strain that results. This strain is used to determine the state of stress prior to heating. The peak temperatures are on the order of 200 Celsius so that for most metals, there will be no changes in phase or other material properties except for a slight reduction in yield stress. Preliminary experiments with type 304 stainless steel were performed using resistance heating The experimental results were in excellent agreement with finite element model predictions of the process [2]. Subsequently, the resistance heating was replaced with laser heating [3]. The heat input (22.5 Watt peak) from a small sealed radio frequency (RF) excited Carbon Dioxide laser was used. In order to both control the heating temperature and efficiently couple the infrared photons from the laser into the test specimen, a substance known as Liquid Temperature Indicating Paint was used. Without this substance the laser power would be so large as to make this approach impractical. Furthermore the measurement and control for the heat input would be very complicated. This laser heating approach was successful in obtaining similar results to those obtained in reference 2.

Since this laser based technique is a thermo-optical analog to blind hole drilling, a simple stress model is required to interpret the measured results. This simple stress model is presented below. As in BHD, the simple model must be modified by empirical coefficients to be useful. These empirical coefficients must be determined by experimentation and/or numerical analysis.

The approach for this laser method is similar to that used in BHD. There are major important differences however. The BHD model is based on the solution of linearly elastic, plane stress field equations for the stress and strain in the vicinity of a through hole in a flat plate. The stress model presented here is based on a lumped parameter model in which elastic-perfectly plastic deformation is assumed to occur as a result of heating. Consider the lumped parameter model of a general solid as shown in **Figure 1**. This figure represents an elastic body in plane stress as being composed of four springs. The bulk of the body has a stiffness, **k**. The region where this stress is being measured is comprised of a series/parallel combination of springs which itself is attached in parallel to **k**. The heat is applied to the spring designated as $k_i$ which can take on values of $\mathbf{k_C}$ or $\mathbf{k_H}$ depending on whether the spring is cold or has been heated, respectively. In principle one could characterize the spring constants of the solid by finite element analysis but we are seeking a simple model which can the be modified empirically. To simplify the analysis we assume that the residual stress or force, **F** remains constant. This leads to the lumped parameter model as shown in **Figure 2**. The system is shown at its initial position with a total displacement $\mathbf{X_1}$, with a corresponding force **F**. **F** and hence $\mathbf{X_1}$ are unknown. In **Fig. 2B**, $\mathbf{k_i}$ is heated and deforms due to: thermal expansion ($\mathbf{x_{th}}$), and elastic ($\mathbf{x_y}$) and plastic ($\mathbf{x_p}$) deformation. When the system is allowed to cool, some permanent deformation has occurred due to plastic flow. Spring $\mathbf{k_i}$, has a permanent deformation and the total deformation is $(\mathbf{X_3} - \mathbf{X_1})$. The object of the analysis based on this simple model is to express the unknown force, F in terms of the measurable displacement $(\mathbf{X_3} - \mathbf{X_1})$. The results of this analysis yield the following equation:

$$F = \hat{k}\cdot\left[1+\frac{\hat{k}}{\tilde{k}_C}\right]\cdot(X_3 - X_1) + \left[1+\frac{\hat{k}}{\tilde{k}_H}\right]\cdot F_y + \hat{k}\cdot\alpha\cdot\Delta T$$

$$where: \frac{1}{\tilde{k}_H} = \frac{1}{k_H} + \frac{1}{\bar{k}} \quad and \quad \frac{1}{\tilde{k}_C} = \frac{1}{k_C} + \frac{1}{\bar{k}}$$

and:

- $\alpha$ = thermal expansion coefficient
- **L** = length of heated region
- $\Delta T$ = Temperature rise due to heating
- $\mathbf{F_Y}$ = The yield strength at the elevated temperature
- **F** = the unknown residual force
- $(\mathbf{X_3} - \mathbf{X_1})$ = the measured displacement..

This equation can be transformed into an equation for a continuous solid by considering square of dimension **L** with the heated spot being a smaller square of dimension **d** at the center of the larger square. The heated spot is heated to temperature, $\mathbf{T_H}$ from the ambient temperature, $\mathbf{T_L}$ Shearing forces between the heated region and the surrounding region are neglected. The results of this transformation is:

$$\sigma=\left[\frac{L-d}{d}\right]E\cdot\varepsilon+\left[1-\left(1-\frac{L}{d}\right)\left(\frac{d}{L}\right)^2\left(\frac{E}{E_H}-1\right)\right]\cdot\sigma_{YH}+\left[\frac{L-d}{L}\right]\left(\frac{d}{L}\right)E\cdot\alpha\cdot\Delta T$$

where:

$\mathbf{E_H}$ = Young's Modulus at $\mathbf{T_H}$,
**E** = Young's Modulus at $\mathbf{T_L}$,
$\sigma_{\mathbf{YH}}$ = Yield Stress at $\mathbf{T_H}$
$\varepsilon$= strain relief near heated spot

For **d/L << 1**, the above equation reduces to:

$$\frac{\sigma-\sigma_{YH}}{E}=A\cdot\left(\frac{L}{d}\right)\varepsilon+B\cdot\left(\frac{d}{L}\right)\alpha\Delta T$$

where **A** and **B** are included as dimensionless empirical constants. The results of the calculations presented in reference 2 are plotted in **Figure 3**. A linear regression fit yields a correlation of 0.92 and the **A** and **B** are computed to be **0.00652** and **0.363** respectively. With these constants the above equation can now be used to measure residual stresses for other materials. Naturally there is much work left to verify this result and apply it to general residual stress situations.

## References


(1) "Determining residual stress by the hole- drilling strain-gauge method," ASTM Standard E837-92, American Society for Testing and Materials, Philadelphia (1992).

(2) Pechersky, M.J., R.F. Miller and Chandra S. Vikram, "Residual Stress Measurements With Laser Speckle Correlation Interferometry and Local Heat Treating ," **OPTICAL ENGINEERING,** Vol. 34, No. 10 pp. 2964-71.

(3) Vikram, C.S., M.J. Pechersky, C. Feng and D. Englehaupt, "Residual Stress Analysis by Local Laser Heating and Speckle-Correlation Interferometry," **Experimental Techniques**, Vol. 20, No. 6, pp. 27-30.


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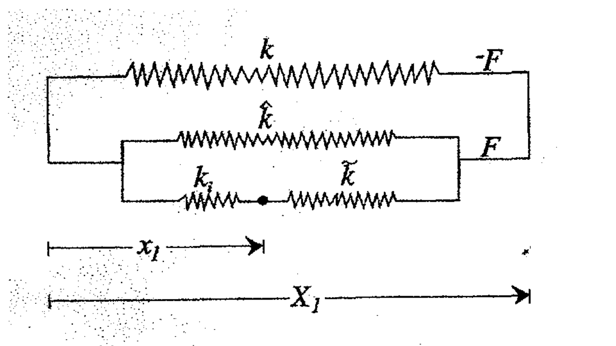


**Figure 1 - Generalized Spring Model**

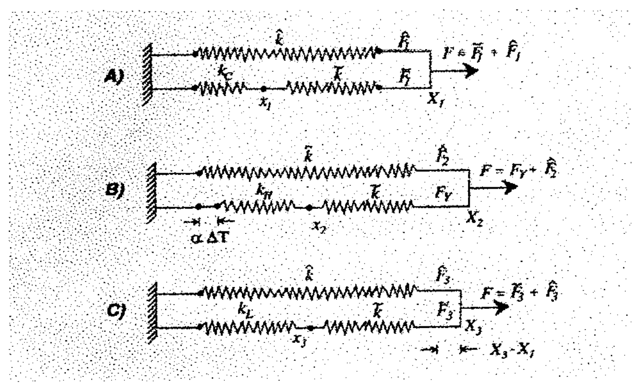


**Figure 2 - Constant Force Model**

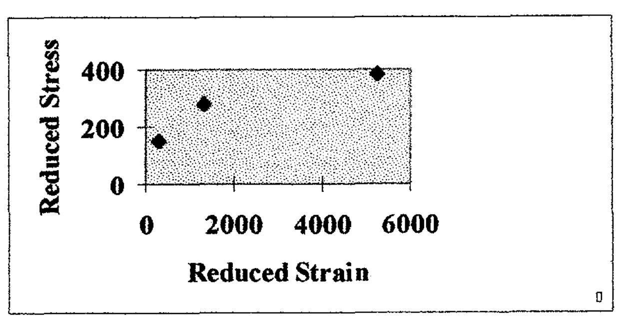


**Figure 3 - Reduced Stress versus Observed Strain where:**
**Reduced Strain = $1000(\sigma - \sigma_{YH})/E$**
**Reduced Strain = $1000(L/d)\varepsilon$**