Measurement and Effect of Residual Stresses on Turbine Components

Sharon L. Cole*
University of Missouri, Columbia, Mo.
Glenn E. Bowie†
Lockheed-California Company, Burbank, Calif.
Kevin R. Kondas‡
U.S. Navy, Washington, D.C.
and
David W. Hoeppner§
University of Missouri, Columbia, Mo.

Through the application of blind hole drilling techniques, the residual stresses in turbine components were determined. The equations used reduce the measured variance in strains to calculated residual stresses for both the on-center and off-center hole drilling procedure. Inherent residual stresses were observed in two turbine alloys, Ti-6A1-2Sn-4Zr-2Mo and Waspaloy. Residual stresses were found to be different in the forged turbine component and in the fatigue-crack growth test specimens machined from the component. Residual stresses of a material appear to be affected by its microstructure and crystallographic texture.

Nomenclature

a	= hole radius, in. or cm
E	= Young's modulus, psi or N/cm^2
r	= distance between rosette center and respective gage, in. or cm
R	= distance between hole center and respective gage, in. or cm
S	= distance between rosette center and hole center, in. or cm
u-v	= geometric axes through strain gage
$\alpha\beta\theta\gamma$	= angles for blind hold analysis, deg
ϵ	= strains and increments, in./in. or cm/cm
Δ	= difference; range
ν	= Poisson's ratio
σ	= stress, psi or N/cm^2

Introduction

MATERIALS development has played a major role in the advancement of gas turbine engine development and will continue to do so as the need for high-performance technology expands. Material fabrication is an important factor in the advancement of technology in the materials area. Residual stresses can develop during material fabrication, and these stresses can interact with expected design loads to affect fatigue-crack initiation and fatigue-crack growth from flawed sites.

Previous residual stress measurement by drilling techniques required drilling of the hole in the center of the strain gage rosette. This was the work originated by Rendler and Vigness in 1966.[1] For their procedure an alignment tool and drilling guide was necessary to insure that the hole center was within a tolerance of ± 0.001 in. (0.0254mm) of the rosette center. The center hole drilling process has since been modified by Bowie[2] to accommodate off-center hole drilling and in-field application without the use of an alignment tool and drilling guide. The modification has been done to extend blind hole residual stress measurements to structural components of various dimensions and shapes. This technique has become very important in measuring residual stresses in such components as compressor and turbine disks. The two turbine materials used in this study were the titanium alloy, Ti-6A1-2Sn-4Zr-2Mo, and the super-nickel alloy, Waspaloy, which are utilized in components of the NATO PHM hydrofoil turbines.[3]

Presented as Paper 77-364 at the AIAA/ASME 18th Structures, Structural Dynamics and Materials Conference, San Diego, Calif., March 21-23, 1977; submitted May 23, 1977; revision received Jan. 19, 1978.

Index categories: Structural Design; Structural Durability (including Fatigue and Fracture); Structural Design (including Loads).

*Graduate Student, Mechanical and Aerospace Engineering.

†Senior Research Scientist.

‡Technical Coordinator.

§Professor of Mechanical and Aerospace Engineering. Member AIAA.

Technical Discussion

Residual stress effects and accurate measurement of residual stresses are essential areas which must be investigated and studied. The knowledge of the magnitude and direction of residual stresses throughout a particular metal component is of continuing concern. Unless the component is used in the completely stress-relieved state, the residual stresses present may play a very strong role in the service life of the part. Residual stresses can have either beneficial or adverse effects and more than once have been of disastrous consequence on structural integrity.[4]

Residual stresses are defined as stresses that would exist in a solid body if all external loads were removed.[5] Residual stresses also are called internal stresses or locked-up stresses, since the stresses exist without any external force on the material. There are two types of residual stresses: macro and microstresses. Macro residual stresses, about which this investigation is concerned, vary continuously through the volume of the component and act over a large area in relation to atomic distances. When residual stresses exceed the elastic limit, plastic deformation occurs that may result in distortion or relaxation of stress.

The development of residual stresses can be affected by material processing and manufacturing. The sources of residual stresses can be mechanical, thermal, and chemical in nature. The forming operations needed to convert metals to a finished or semifinished shape rarely produce homogeneous deformation of the material.[6]

The effect of residual stresses can influence the reaction of a material to externally applied loads. A material under tensile residual stresses will increase the ease with which fatigue failure occurs. Conversely, compressive residual stresses may reduce the effectiveness of an applied tensile stress in producing fatigue failures. Depending on the magnitudes of the applied load, the residual stresses can be altered due to cyclic loading.

Unfortunately, residual stresses cannot be measured directly. Instead, residual stresses are measured indirectly by measuring strains that exist within a metal. Altering the state of constraint of the material allows the variance in strain to be measured and the resultant strain to be determined.

Though there are several different ways to measure residual stresses, the blind hole drilling technique was utilized in this investigation. Blind hole drilling is termed a semidestructive procedure but the "damage" that results from its use sometimes can be tolerated in a component. In this procedure a calibrated resistance strain gage rosette is placed on the component to measure accurately the residual strain. A circular hole is made in the material whereby the stress distribution in the neighborhood of the hole will change due to the change of constraint. The local strain relaxation that occurs during the drilling process is registered by the resistance strain gage. From these readings the magnitude and principal directions of the residual stresses can be determined at the surface and partially into the thickness of the material component. Details of the procedure employed herein are described in the following section.

Experimental Procedure

In order to get accurately measured strain, and therefore accurate residual stresses, one of the most essential factors is a good bond between the strain gage and material.[1] Through careful cleaning and proper application, the reliability of the results can be very good.[2]

The bonding technique followed was the procedure recommended by Micro-Measurements Inc., the manufacturer of the 0, 90, and 225 deg strain gage rosette used in this investigation. Some modifications of the procedure were necessary depending on the alloy and the area of application. The gages for the titanium alloy and nickel alloy, respectively, were selected such that the temperature compensating characteristics of the gage matched that of the material.

For both materials tested, Ti-6Al-2Sn-4Zr-2Mo and Waspaloy, the EA-06-062RE 120-ohm resistance strain gages were used—the recommended type for these materials. These gages have a 120-ohm resistance, a gage factor of 1.98, and are used with a 0.0625 in. (0.159 cm) drill bit.

To drill the hole precisely, a Bridgeport vertical milling machine was employed. A 0.0625 in. (0.159 cm) two-fluted carbide twist drill was used. A Daytronic unit (Model No. 300D), the transducer amplifier-indicator type 90, strain-gage-input module, was utilized in obtaining the strain measurements as the drilling took place. A Vishay switch-balance box, Model SB-1, was needed to have all three gages read on the same Daytronic unit.

Strain measurements were taken every 0.005 in. (0.013 cm) of depth drilled until a depth of 0.110 in. (0.279 cm) was reached. A Starrett dial depth indicator with graduations of 0.0001 in. (0.00025 cm) was employed as well as the calibrated depth gage on the Bridgeport. The hole was checked for being properly centered in the rosette.

Data Reduction Technique

Using stress analysis and theory of elasticity,[7] the equations are obtained for calculating residual stresses from measured strains. The calculations, due to their length, have been computerized.

The known values necessary for calculation of residual stresses are Poisson's ratio ν, Young's modulus E (10^6 psi), average hole radius r_h, and the distance between rosette center and gages $r=r_h/R$. Assume the hole is drilled on center. Figures 1 and 2 are diagrammatic representations of the gage layout and axes. The figure is for gage 1; similar layouts can be made for gages 2 and 3. To reduce the measured strains to residual stresses, the following equations were used.[2,8] By using the measured strains ϵ_1, ϵ_2, and ϵ_3 (μ in./in.), trial values of principal stresses $\sigma_{x'x'}$, $\sigma_{y'y'}$ (psi), and principal angle θ can be calculated by the following equations:

$$\theta = \frac{-\tan^{-1}[(\epsilon_1+\epsilon_3-2\epsilon_2)/(\epsilon_1-\epsilon_3)]}{2} \quad (1)$$

$$D1 = -r^2(1+\nu)/E \quad (2)$$

$$X1 = (\epsilon_1+\epsilon_3)/D1 \quad (3)$$

$$D2 = \left(\frac{-3r^4+4r^2}{1+\nu}\right)\left(\frac{1+\nu}{E}\right)\cos 2\theta \quad (4)$$

$$X2 = (\epsilon_3-\epsilon_1)/D2 \quad (5)$$

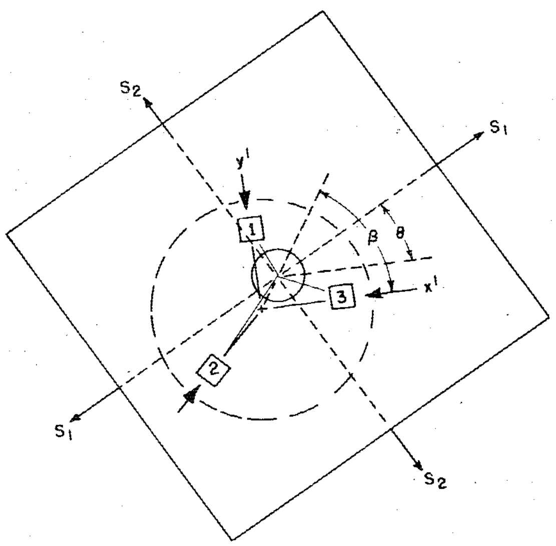

Fig. 1 Diagram of rosette center and off-center hole geometries.

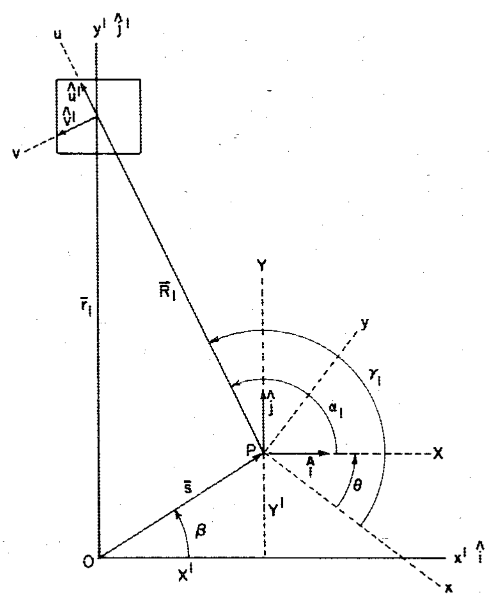

Fig. 2 Detailed axes and geometries of off-center hole in relation to gage 1.

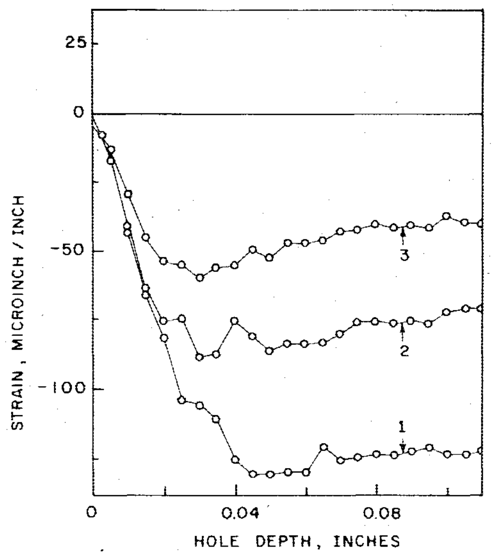

Fig. 3 Blind hole depth vs microstrain for the Ti-6A1-2Sn-4Zr-2Mo as-received forging.

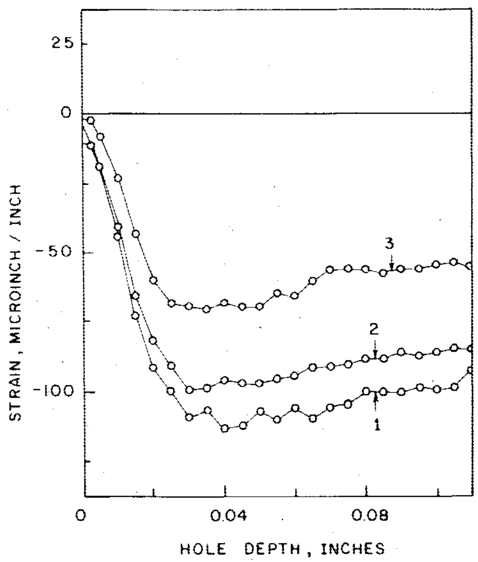

Fig. 4 Blind hole depth vs microstrain for the Ti-6A1-2Sn-4Zr-2Mo test specimen in through-the-thickness direction.

$$\sigma_{x'x'} = (X1 - X2)/2.0 \tag{6}$$

$$\sigma_{y'y'} = (X1 + X2)/2.0 \tag{7}$$

These values are trial values for the off-center hole.

For the off-center hole, the following values must be determined: the distance between rosette center and hole center S and angle β, and the trial values $\sigma_{x'x'}$, $\sigma_{y'y'}$, and θ. The distance between the hole center and the gage, and the angles α and γ, determined for the three gages were

$$R_1 = [(S\cos\beta)^2 + (r_1 - S\sin\beta)^2]^{1/2} \tag{8}$$

$$R_2 = [(S\sin\beta + r_2/2)^2 + (S\cos\beta + r_2/2)^2]^{1/2} \tag{9}$$

$$R_3 = [(r_3 - S\cos\beta)^2 + (S\sin\beta)^2]^{1/2} \tag{10}$$

$$\alpha_1 = \tan^{-1}[(r_1 - S\sin\beta)/(-S\cos\beta)] \tag{11}$$

$$\alpha_2 = \tan^{-1}[(-S\sin\beta - r_2/2)/(-S\cos\beta - r_2/2)] \tag{12}$$

$$\alpha_3 = \tan^{-1}[(S\sin\beta)/(r_3 - S\cos\beta)] \tag{13}$$

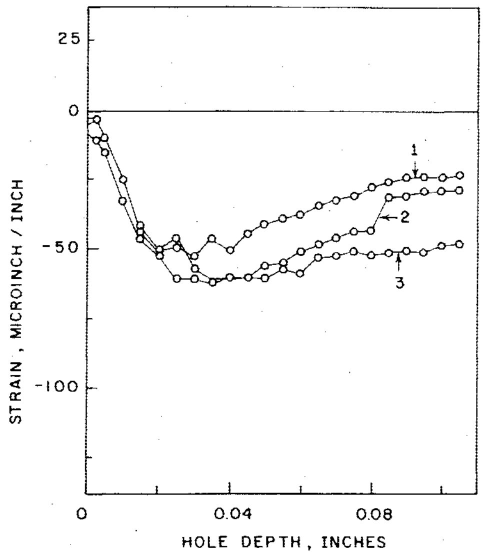

Fig. 5 Blind hole depth vs microstrain for the Ti-6A1-2Sn-4Zr-2Mo test specimen into the height of the specimen.

$$\gamma_i = \alpha_i + \theta \tag{14}$$

where $i = 1, 2, 3$.

The values σ_{uu}, σ_{uv}, σ_{vv}, $\sigma_{x'x'}$, $\sigma_{y'y'}$, and ϵ for the three gages can be put in an indexed format. Table 1 gives the coefficients to aid in indexing the equations.

$$\Delta\sigma_{uu\,i} = -\left(\frac{\sigma_{xx}+\sigma_{yy}}{2}\right)\left(\frac{a}{R_i}\right)^2 + \left(\frac{\sigma_{xx}-\sigma_{yy}}{2}\right)\left[3\left(\frac{a}{R_i}\right)\right.$$
$$\left. -4\left(\frac{a}{R_i}\right)^2\right]\cos 2\gamma \tag{15}$$

$$\Delta\sigma_{vv\,i} = \left(\frac{\sigma_{xx}+\sigma_{yy}}{2}\right)\left(\frac{a}{R_i}\right)^2 - \left(\frac{\sigma_{xx}-\sigma_{yy}}{2}\right)\left[3\left(\frac{a}{R_i}\right)^4\right]\cos 2\gamma \tag{16}$$

$$\Delta\sigma_{uv\,i} = \left(\frac{\sigma_{xx}-\sigma_{yy}}{2}\right)\left[3\left(\frac{a}{R_i}\right)^4 - 2\left(\frac{a}{R_i}\right)^2\right]\sin 2\gamma \tag{17}$$

$$\Delta\sigma_{x'x'\,i} = C1_i\Delta\sigma_{uui} + C2_i\Delta\sigma_{uv\,i} + C3_i\Delta\sigma_{vv\,i} \tag{18}$$

$$\Delta\sigma_{y'y'\,i} = C3_i\Delta\sigma_{uu\,i} - C2_i\Delta\sigma_{uv\,i} + C1_i\Delta\sigma_{vv\,i} \tag{19}$$

$$\epsilon_i = (\Delta\sigma_{x'x'\,i} - \nu\Delta\sigma_{y'y'\,i})/E \tag{20}$$

These ϵ_i values are then compared to the measured strains, and new trial values of θ, $\sigma_{x'x'}$, and $\sigma_{y'y'}$ are chosen. The computational process is repeated until the calculated ϵ_i values correspond to the measured strains.

Test Results

The blind hole drilling procedure was performed on both the as forged disk section and fatigue-crack growth test specimen machined from the component for two turbine materials, Ti-6A1-2Sn-4Zr-2Mo and Waspaloy. The measured strains vs depth at discrete points from the surface for Ti 6-2-4-2 forging and specimen are given in Figs. 3-5. (Note: the indicated numbers on Figs. 3-7 correspond to the strain gage rosette, Fig. 1.) The measured strains for the titanium forging were slightly greater than those obtained on either of the two tests performed on the machined titanium specimen. The maximum residual stress calculated from the measured strain was $\sigma_x = 13.3$ ksi (91.7 MPa) and $\sigma_y = 9.8$ ksi

Table 1 Indexing of coefficients

i	$C1_i$	$C2_i$	$C3_i$
1	$\sin^2\alpha_1$	$\sin 2\alpha_1$	$\cos^2\alpha_1$
2	$(\cos\alpha_2+\sin\alpha_2)^2/2$	$\cos 2\alpha_2$	$(\cos\alpha_2-\sin\alpha_2)^2/2$
3	$\cos^2\alpha_3$	$\sin 2\alpha_3$	$\sin^2\alpha_3$

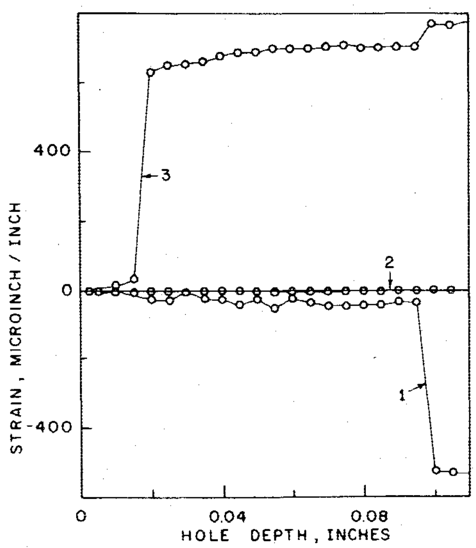

Fig. 6 Blind hole depth vs microstrain for the Waspaloy as-received forging.

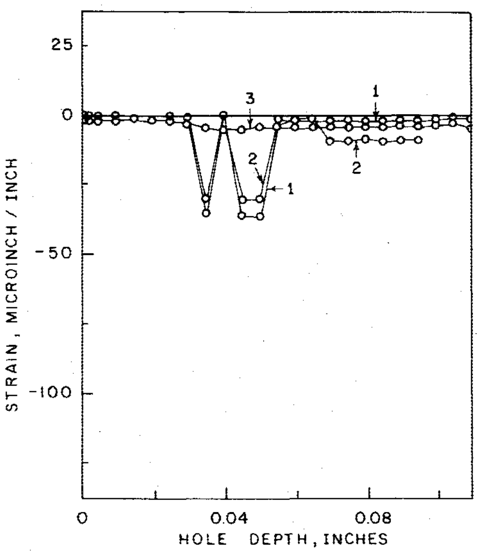

Fig. 7 Blind hole depth vs microstrain for the Waspaloy test specimen in the through-the-thickness direction.

(67.5 MPa) for the forging, while for the test specimen the values were $\sigma_x = 12.7$ ksi (87.6 MPa) and $\sigma_y = 10.6$ ksi (73.1 MPa). Since the gage readings were all compressive, the residual stresses observed were in a biaxial state of tension. In the titanium forging the maximum residual stress determined was 9.64% of yield strength in the σ_x direction and 7.09% of yield strength in the σ_y direction.

Conversely, the measured strain values for Waspaloy forging and test specimen were noticeably different, as indicated in Figs. 6 and 7. (Note: the ordinate axis in Figs. 6 is a larger scale than those of the other data plots.) The Waspaloy forging showed the highest response of all blind hole tests performed. The calculated maximum residual stress for the forging was $\sigma_x = -37$ ksi (-255 MPa) and $\sigma_y = 120$ ksi (-827 MPa) while for the Waspaloy test specimen the values were only $\sigma_x = 6.2$ ksi (42.7 MPa) and $\sigma_y = 3.2$ ksi (22.1 MPa). Differences in residual stresses observed in the Waspaloy can be due to variance in microstructure and surface condition between the forging and the test specimen. In the Waspaloy forging, a maximum residual stress determined was 24.2% of yield strength in the σ_x direction and 78.4% of yield strength in the σ_y direction.

The microstructure of both materials was observed under a microscope after having been polished and etched. In the titanium alloy the near-surface microstructure of the forged disk section was the same (grain size, etc.) as that found in the machined test specimen. However, in the super-nickel alloy the near-surface microstructure of the forged disk section was of much smaller grain size that observed in the machined test specimen taken from the internal portion of the component disk. Thus, the differences in microstructure suggest differences in residual stresses, as asserted in the preceding text.

Summary

Industrial forging and manufacturing practices were not controlled in this study, but are recognized as a paramount factor for microstructural alteration. In summary, the concluding points are

1) Residual stress measurements can be made through blind hole strain gage drilling procedures and can be adapted for in-field application.

2) Residual stress values measured for forgings are not the same as those determined for test specimens machined from the forging.

3) Microstructure appears to affect the residual stress of a material.

4) The internal residual stress can affect the fatigue life of a component since it can be considered a force on the component.

One obvious implication of this research is that residual stresses must be measured on actual components in which knowledge of their value is desired. Unless it is established that values of residual stress measured on specimens or blanks sectioned from a given component are representative of the values of residual stress in the component, the values measured (on the specimen or blank) are not necessarily related to the residual stress in the component. Thus, if greater insight into residual stress effects on material behavior and structural performance are desired, their values and distributions will have to be determined on the component of interest.

Acknowledgment

The forged components were donated by the Ladish Company. The study was funded by the U.S. Navy PHM Technical Design Directorate. The authors would like to thank E. Bruemmer, J. Yahl, D. Carpenter, and A. Braun for their time and efforts in completing this work.

References

[1]Rendler, N.J. and Vigness, I., "Hole Drilling Strain-Gage Method of Measuring Residual Stresses," *Experimental Mechanics*, Vol. 6, No. 12, Dec. 1966, pp. 577-586.

[2]Bowie, G. E., Sandifer, J. P., and Robinson, C. C., "Experimental Techniques for Structural Component Residual Stress Determination," Lockheed Rept. 27203, July 1975.

[3]DeRidder, A. J., Ladish Co., personal communication, 1975-1976.

[4]Lynch, J. J., *Residual Stress Measurements*, ASM, Cleveland, Ohio, 1952.

[5]Almen, J. O. and Black, P. H., *Residual Stresses and Fatigue in Metals*, McGraw-Hill, New York, 1963.

[6]Deiter, G. E. Jr., *Mechanical Metallurgy*, McGraw-Hill, New York, 1961.

[7]Timoshenko, S. and Goodier, J. N., *Theory of Elasticity*, 2nd ed. McGraw-Hill, New York, 1951.

[8]Cole, S. L., "The Effect of Mean Stress and R-Ratio on the Fatigue Behavior of Turbine Alloys," Masters Thesis, University of Missouri—Columbia, May 1976.