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Weili Cheng
Iain Finnie

Residual Stress Measurement and the Slitting Method

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Weili Cheng and Iain Finnie

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The Mechanical Engineering Series features graduate texts and research monographs to address the need for information in contemporary mechanical engineering, including areas of concentration of applied mechanics, biomechanics, computational mechanics, dynamical systems and control, energetics, mechanics of materials, processing, production systems, thermal science, and tribology.

Series Preface

Mechanical engineering, and engineering discipline born of the needs of the industrial revolution, is once again asked to do its substantial share in the call for industrial renewal. The general call is urgent as we face profound issues of productivity and competitiveness that require engineering solutions, among others. The Mechanical Engineering Series is a series featuring graduate texts and research monographs intended to address the need for information in contemporary areas of mechanical engineering.

The series is conceived as a comprehensive one that covers a broad range of concentrations important to mechanical engineering graduate education and research. We are fortunate to have a distinguished roster of consulting editors, each an expert in one of the areas of concentration. The names of the consulting editors are listed on page vi of this volume. The areas of concentration are applied mechanics, biomechanics, computational mechanics, dynamic systems and control, energetics, mechanics of materials, processing, thermal science, and tribology.

To
Weihsun and Joan

Preface

The early development of the slitting method is closely related to the work in Fracture Mechanics. G. Irwin's strain energy release rate is the foundation for computation of the crack compliance functions. H. F. Bueckner's principle for crack growth leads to the superposition principle for the release of the residual stresses. R. J. Hartrenft and G. G. Sih's, and G. Chell's expressions of K_I for shallow and deep cracks lead to an expression of K_I that works for both cases. The body force method introduced by H. Nisitani and his colleagues is a very useful tool for computing the compliance functions for a cut of finite width for near-surface measurements. The inherent-strain method developed by Y. Ueda and his colleagues has inspired the use of initial strains to approximate the residual stresses in the slitting method and the single-slice method.

The method of measuring residual stresses by a cut of progressively increasing depth was first tried in 1971 by S. Vaidyanathan and I. Finnie, who estimated the residual stress from a variation of K_I obtained by a photoelastic technique. It was not until fourteen years later that the method was extended by W. Cheng and I. Finnie in 1985 to measure residual stresses from a strain variation. In the years that followed a number of researchers around the world carried out similar measurements: D. Ritchie and R. H. Leggatt in 1987, T. Frett in 1987, C. N. Reid in 1988, and K. J. Kang, J. H. Song and Y. Y. Earmme in 1989.

Part of our early work was supported by Joe Gilman and Raj Pathania of EPRI and Wayne Kroenke of Bettis Laboratory. We appreciate the significant contribution of Mike Prime, who chairs the ASTM E.28.13.02 Task Group, and all Task Group members, Mike Hill, Gary Schajer, Yung Fan, Hans Schindler, and Can Aydiner, who have devoted their time to working towards a standard for the slitting method.

Our thanks also go to Öktam Vardar, Marco Gremaud, Glen Stevick, Ron Streit and Robert Ritchie for their contributions, friendship, and help over the years.

Fremont, California
Berkeley, California

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Iain Finnie
June 2006

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Introduction to Residual Stresses

1.1 What are residual stresses?

Residual stresses have been associated with humans ever since civilization began. The making of intricate clay components using fire in early days was actually an art that maintained the balance between reducing the residual stress gradient and achieving the desired shape of products. A stronger sword was often the result of a thin layer of compressive residual stress induced by repeated hammering at a controlled elevated temperature. Even today, the presence of residual stresses still dictates the design of many components, whether in a spacecraft or a tiny integrated circuit.

So what are residual stresses? In short, residual stresses are stress fields that exist in the absence of any external loads. All mechanical processes can cause deformation that may lead to residual stresses. For example, nonuniform heating or cooling causes thermal strains, plastic deformation induces incompatible deformation, and mismatched thermal expansion coefficients produce discontinuity in deformation under temperature change. Thus, the state of a residual stress depends on both the prior processes it has undergone, and the material properties that relate the current mechanical process/environment to deformation.

Figure 1.1 illustrates a thermal switch that makes use of residual stresses to produce desired movements. The switch arm is made of two layers with different thermal expansion coefficients, α_1 and α_2. At room temperature the length of the layers is the same and the arm is straight. Assuming $\alpha_1 > \alpha_2$, a temperature increase ΔT will make layer 1 expand more than layer 2. However, the bonding between the layers restricts layer 1 from expanding freely. The restriction can be visualized as a tension on layer 2 and a compression on layer 1, which are always in perfect balance. The resulting deformation controlled by the residual stress is an arm curved towards terminal 2. Similarly, a temperature drop $-\Delta T$ leads to an arm curved towards terminal 1. This simple example shows two fundamental features of residual stress: any

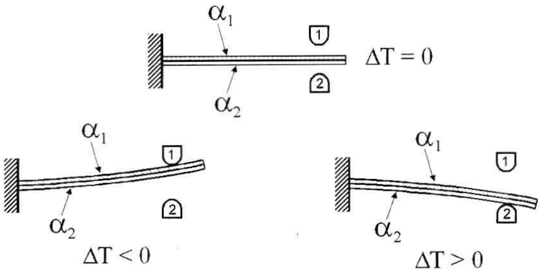

Fig. 1.1. A thermal switch that turns on/off depending on the temperature change.

tension/compression is always balanced by compression/tension, and the stress in the region restricted from expansion is compressive, and *vice versa*.

The study of residual stresses ranges from such common applications as the stresses existing in a bolted assembly to the special surface treatment by laser beams. Prediction and measurement of residual stresses in engineering components have been a constant pursuit of many researchers throughout the improvement of old or development of new components.

1.2 Influence of Residual Stresses on the Integrity of Mechanical Components

The mysterious cracking of a standing clay vase and a sudden tremor of the earth we live on have one thing in common: the releases of residual stresses cause deformation, whether it is an almost unnoticeable increment of cracking or a tremendous earthquake that topples buildings. A failure caused by residual stresses is often the most difficult to predict and least to be expected.

For mechanical components that operate in severe environments such as a nuclear reactor for an extended time or in safety-critical structures such as an airplane, the presence of residual stresses has a profound influence on the integrity of these components. It is known that one of the main contributing factors for slow-growing cracking in parts exposed to radioactive environments is the presence of residual tensile stresses near the surface. This is a serious issue for containers sealed by welding [77, 46] that contain nuclear wastes, whose radioactive level will remain dangerously high for many centuries. Most shafts or rods are machined by turning, a process that often induces tensile residual stresses near the surface [8], which are detrimental to fatigue life under cyclic loads. On the other hand, the presence of compressive residual stress near the surface is known to enhance fatigue life and inhibit stress-corrosion cracking. For this reason, a process known as shot-peening has been used widely to produce a layer of compressive surface residual stress. However, this process may have some unexpected consequence. Consider a part with a preexisting surface flaw of depth a as shown in Fig. 1.2. After shot-peening, a layer of compressive residual stress is produced in a depth of b, below which the stress becomes tensile. If $b > a$, the flaw under the compressive stress will be fully closed and will not grow unless a substantial external load is applied to open the flaw. The situation changes if $b < a$. The tip of the flaw is now under tensile stress and the compressive stress on the flaw faces up to depth b actually maintains the opening of the flaw. Thus, shot-peening in this case is harmful and the opening of the flaw tip makes it more susceptible to cyclic loading. Furthermore, the detection of the surface flaw by dye penetrant techniques [83] becomes very difficult due to closed flaw faces under compressive residual stress.

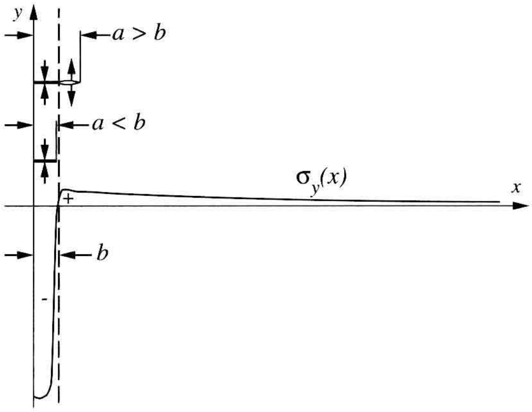

Fig. 1.2. Influence of surface compressive stress on flaws of different sizes.

Residual stress not only affects the initiation and onset of the propagation of surface cracks but also changes the path/growth of a crack as it grows below the surface. First, because the tensile stress near the surface is always balanced by the compressive stress below the surface, the growth of a crack is substantially slowed when it reaches the zone of compressive stress. Second, the growth of the crack often changes the stiffness or compliance of the part and relieves the locked-in load. As a comparison for the first case, a surface crack subjected to uniaxial tension will grow and penetrate a plate when the width of the crack on the surface is about 4 times the thickness [103]. For a crack under the same external load but with a substantial compressive residual stress below the surface, the crack will grow faster along the surface, and the ratio of the width to depth is typically larger than 10. As a consequence, the penetration of the crack is delayed, but the overall integrity of the component keeps weakening as the crack extends further along the surface. When this happens to a pressurized vessel, the occurrence of leakage may signal the onset of a fast moving crack that has already penetrated much of the thickness [53]. For the second case, consider a thin-walled cylinder with a circumferential weld, which introduces a locked-in moment M_o [40]. As a circumferential crack grows, the magnitude of the moment $M(a/t)$ reduces as the compliance of the cracked cylinder increases, as shown in Fig. 1.3. An assumption of constant moment due to residual stress as the crack size increases will certainly lead to an overestimate of the crack growth rate.

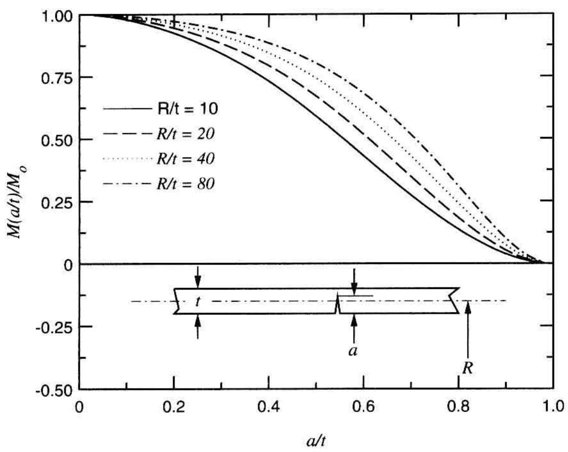

Fig. 1.3. Locked-in moment decreasing with the increase of crack compliance for thin-walled cylinders.

Moreover, the distortion of parts after heat-treatment or welding [77] is often so prevalent in manufacturing that it poses as the defining point that separates an experienced engineer from his peers. In the past century our understanding of residual stresses has been greatly enhanced by the analysis based on fundamental mechanics and the measurement of residual stresses that allow us to evaluate and improve the integrity of modern components.

1.3 Mechanical Methods for Residual Stress Measurement

All mechanical methods for residual stress measurement require measuring the deformation due to the release of residual stresses, which are then estimated by using an analysis based on linear elasticity. Therefore, the use of a particular method depends on the availability of not only the means for releasing the stresses and recording the deformation but also the solution and computation for the configuration of the measurement.