Residual Stress and Stress Relaxation

Edited by Eric Kula and Volker Weiss

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28

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Review of Progress in QUANTITATIVE NONDESTRUCTIVE EVALUATION Volume 1

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This volume provides a comprehensive review of the latest research in quantitative nondestructive evaluation (NDE) and brings together the work of leading investigators representing government agencies, industry, and university communities in the United States and abroad. The papers cover various areas of interest in quantitative NDE, including topics related to the development of quantitative ultrasonic and eddy current techniques, new and emerging techniques of flaw detection and characterization, considerations of improvements needed in the probability of flaw detection, and engineering applications that follow the transfer of research results to technology. The volume includes a presentation by Dr. Norman Tallan, Chief Scientist at the Air Force Materials Laboratory, concerning the importance of moving NDE inspection procedure forward to provide in-process inspection control for manufacturing.

Review of Progress in Quantitative Nondestructive Evaluation, Volume 1 will be of primary interest for those involved in NDE research and development. As NDE is a highly interdisciplinary subject, NDE research is of interest to those in materials science, electrical engineering, mechanical engineering, and related fields.

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PREFACE

The Army Materials and Mechanics Research Center in cooperation with the Materials Science Group of the Department of Chemical Engineering and Materials Science of Syracuse University has been conducting the Annual Sagamore Army Materials Research Conference since 1954. The specific purpose of these conferences has been to bring together scientists and engineers from academic institutions, industry and government who are uniquely qualified to explore in depth a subject of importance to the Department of Defense, the Army and the scientific community.

These proceedings, entitled RESIDUAL STRESS AND STRESS RELAXATION, address the nature of residual stresses and their measurements, the sources of residual stress, stress relaxation, sub-critical crack growth in the presence of residual stress, residual stresses and properties, and research in progress.

We wish to acknowledge the assistance of Mr. Dan McNaught of the Army Materials and Mechanics Research Center and Mr. Robert J. Sell and Helen Brown DeMascio of Syracuse University throughout the stages of the conference planning and finally the publication of the book.

The continued active interest and support of these conferences by Dr. E. Wright, Director of the Army Materials and Mechanics Research Center, is appreciated.

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THE NATURE OF RESIDUAL STRESS AND ITS MEASUREMENT

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ABSTRACT

The origins of residual stress and changes during fatigue are discussed. A new mechanism for fading is proposed. Pracitcal (destructive and non-destructive) methods for measuring this stress are critically reviewed. Each technique has major problems requiring further study, but acoustic, magnetic and x-ray methods are all poised for more widespread use.

INTRODUCTION

This is an important and timely conference because we are on the verge of making important steps in measuring residual stress, in standardizing the procedure and in understanding the role this stress plays in many processes, especially how it changes during use. This week, in these pleasant surroundings, we have the unusual opportunity to hear from people around the world about this subject and the responsibility to discuss key issues openly and vigorously; at such a meeting our participation is more vital than the presentations. In this introduction to the conference we hope to emphasize some of the issues. Fortunately, we do not also have to provide the answers.

THE ORIGINS OF RESIDUAL STRESS

We can define residual stress as the self-equilibrating internal stress existing in a free body when no external tractions are applied. At equilibrium the integral of this stress in the volume of the body must be null, and, as well, the integral over any plane through the specimen. In Fig. 1, two parts of such a body that we will refer to as "bulk" and "near surface" regions are shown separated. Suppose that for some reason the near-surface is elongated plastically. Then it is compressed elastically to join it to the bulk and released. The bulk puts this region under compression, while the near-surface exerts tension on the bulk. Bending can result, depending on the magnitude of the stress and relative thicknesses of the layers. In almost every real situation we can think of residual stress arises in this manner.

Residual stress can arise, for example, when a material is subjected to heat treatment or machining. Consider first a material that undergoes no change in crystal structure during heat treatment. If aluminum is cooled quickly from a heat treatment, the surface and the interior contract at different rates, as illustrated in Figure 2a. At some time, A, this difference, coupled with low material yield strength associated with the high temperature, induces plastic flow or permanent yielding. The surface region, which, because of the temperature gradient, contracts on cooling more than the interior, is extended by the interior and vice versa. (Note the increase in length in the surface, A in Figure 2a.) This is a real effect; for iron-base materials the product of Young's modulus and coefficient of expansion yields a stress of 3.5 MPa (.5 ksi) per°C difference in temperature between two such regions.

On continued cooling to room temperature, point B, the surface regions have been extended relative to the interior and consequently end up in compression. Residual compressive stress in the surface must be overcome by the applied load to initiate cracks, and thus the presence of surface compressive stress is a highly favorable condition.

Heat treatment does not always produce surface compressive stress. If a material undergoes a phase transformation, as in the hardening of steel associated with martensite, the local yielding is essentially masked by the volume expansion associated with the

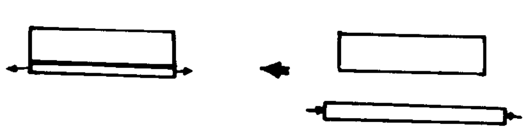
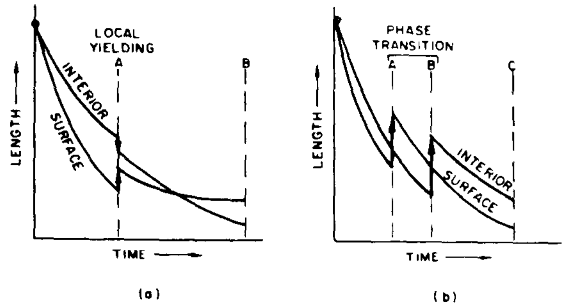
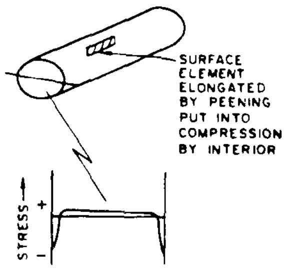


Fig. 1. If the near surface region is longer than the bulk compressive residual stress occurs at the surface, tensile residual stress in the bulk.

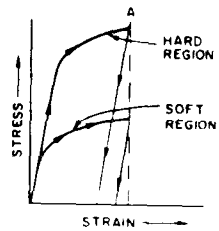
COOLING CURVES



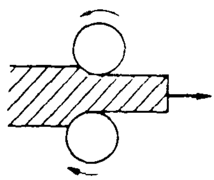
Schematic cooling curves during a heat treatment showing the difference in contraction of the surface and interior. In (a) there is no phase transition, whereas one occurs in (b).



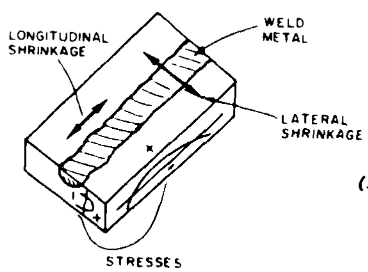
(c) - Surface deformation by peening elongates surface regions.



(d) - The harder surface regions contract more (on release on the load at A) than the softer interior.



(e) - Friction at the rolls in a rolling mill tends to extend surface regions more than the interior.



(f) - Stresses due to welding

Figure 2

austenite to-martensite phase change. The result is illustrated schematically by the cooling curve in Fig. 2b. At temperature A the surface region transform to martensite and expands, since it reaches the transformation temperature first. The interior composed of low strength austenite deforms plastically to accomodate this change. At B the interior transforms to martensite producing an expansion which is resisted by the high strength martensite surface. At C, near room temperature, the surface is thrown into tension by the interior, producing surface residual tensile stress, which can contribute to crack initiation and propagation. The origin of this stress is much more complex in a steel that is case hardened and undergoes different transformations at different temperatures during cooling. In Prof. Ericsson's chapter this is discussed in detail.

Stress relief annealing at moderate temperatures is often employed to allow local yielding to occur, thereby minimizing or eliminating residual stress. However, care is needed because even differences in the coefficients of expansion between the carbide and ferrite phases in steel can lead to significant stress if the parts are not cooled slowly after this treatment.

Another way to produce compressive stress in the near-surface region is to shot peen the surface. In this process, high velocity shot causes local plastic yielding in the surface, which is extended relative to the interior. The interior acts to constrict the surface, resulting in high, local compressive residual stress in the surface, balanced by tensile stress within the interior, Figure 2c. Prof. Wohlfart covers this topic, as well as Mr. Canmett.

In fact even a tensile extension of a specimen into the plastic region can produce stress. If the surface is harder than the interior because of defect pileup occurring during plastic extension, then on release of the load (at A in Figure 2d), elastic recovery leaves the surface shorter than the interior, resulting in surface tensile stress. (The reverse occurs when the surface is softer than the interior.) In a forming operation, such as rolling, the surface can be extended more than the interior due to friction at the rolls, as illustrated in Figure 2e, resulting in compression in the surface. The magnitude of the stress is a function of the thickness of the piece, the roll size and the degree of reduction.[1]

Another important cause of residual stress is welding, as illustrated in Figure 2f. Contraction of molten weld metal during solidification is resisted by colder surrounding metal resulting in the stresses illustrated in the figure. (For further information on stresses in this process see ref. 2.) Prof. Masubuchi reviews this matter in this volume. From these examples (see also refs. 3-5) it is clear that residual stress in materials arises not only in processing, but also in use. In Fig. 3, we show some examples of how even ordinary surface preparation can produce a large stress.

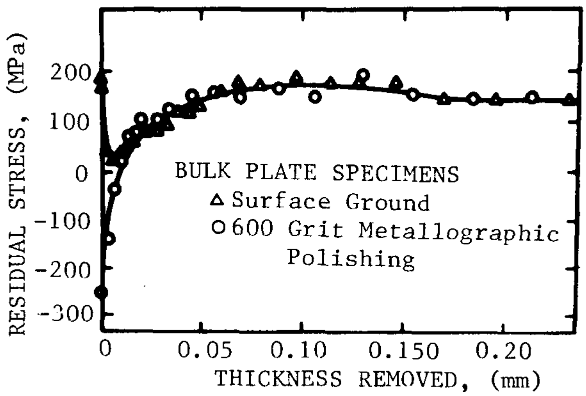


Fig. 3. Residual stress in an HSLA steel due to surface preparation. From ref. 6.

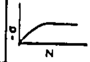
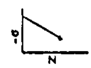
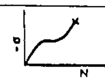
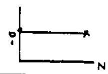
Unfortunately, in too many cases residual stress is ignored, or it is assumed that additional treatment has either eliminated it or introduced compressive stress. To further complicate the issue, not only will "macrostress" develop in different regions of the same piece, but "microstress" can arise in microscopic regions, such as the phases of a multiphase material. The magnitude of this stress can be a significant portion (half or more) of the ultimate tensile stress of the annealed material. Prof. Hauk presents information on this matter.

CHANGES IN RESIDUAL STRESSES DURING USE

Many of our speakers are concerned with this topic. As an example we will consider the fatigue process, first reviewing what is known, and then proposing a qualitative rationale for the observed behavior.

In low cycle fatigue of a rolled HSLA steel, Quesnel et al.[6] found that residual stress changed sign each half cycle, being opposite in sign to the sign of the applied load before load release. In Table I we summarize investigations on plain carbon steels in high-cycle fatigue. A clear pattern emerges. Below the fatigue limit with annealed specimens, compressive stress forms and saturates. In one study[11] this stress was found to occur only in deformation markings. Above the fatigue limit, this residual stress develops and then decreases until fracture. For specimens that are shot peened, relaxation occurs at all stress levels and is most rapid in the early stages of fatigue. In tension-tension fatigue of a shot peened piece the stress can even reverse sign and become tensile, a clearly detecterous effect. Much more work is needed with various

Table 1. Summary of Some Studies of Changes in Residual Stresses: Plain Carbon Steels During High Cycle Fatigue

Author	Material & Composition.	Heat Treatment & Mechanical work.	R ratio & Type of Fatigue Test.	Applied Stress (x Fat. limit)	Direction of residual stress	Results Fatigue below limit above
Taira & co-workers(7-10)	.07% C,.16%C, .28% C	Annealed	R = -1 Bending	.83-1.19	Axial and transverse in some cases	 
Taira & co-workers(7,8)	"	Cold-Worked	"	"	"	 
McClinton & Cohen (11)	.45% C	Annealed	R = 1 Axial pull-pull	Uncertain	Axial	
Terasawa et al. (12)	.16% C	Tufftrided	R = -1 Bending	1.10	Axial	
Ericsson (13)	.45% C	?	?	?	Axial	Compressive stresses reversed sign and became tensile.
McClinton & Cohen (11)	0.40% C	Normalized & peened	R = 1 axial pull-pull	at or above endurance limit	Axial	Compressive stresses reversed sign and became tensile.
Pattinson & Dugdale (14)	0.17% C	Normalized and straightened	Reverse bending, strain control	0.3	Axial	Fading
Kodoma(15,16)	0.17%C	Annealed & shot peened	R = 1 bending	above endurance limit	Axial	Fading in two stages, rapid at first.
Syren, Wohlfart & Macherauch(17)	0.45% C	Quenched in oil, shot peened	bending	above endurance limit	Axial	Subsurface cracking in peened specimens where stress profile changed sign.

load histories as most previous work is in bending or torsion. However we consider here the data currently available.

Fading is often attributed to microcrack formation, although there is as yet little evidence for this. Another interpretation by Taira's group[18,19] is that the residual stress forms in annealed specimens due to elongation of the near-surface region from excess vacancies formed during cycling. This continues until work hardening saturates, at which time the maximum compressive stress occurs. Additional cycles produce deformation of deeper layers, resulting in relaxation. Thus, relaxation should occur only in tensile cycles. However no relaxation is observed in this case; see Table I. James[20] suggest that stress can relax due to microplasticity in the near-surface region (see the chapter by James). As the surface is initially in compression, the relief would occur only in a compressive half cycle. However peened specimens do show stress relief in tensile cycling, Table I.

As an alternative to these theories, we propose the following qualitative rationale. Formation of compressive stress at the surface can occur only by:

1. Micro-plastic elongation in the near-surface region, with respect to the bulk; the bulk is stretched elastically, and places the near-surface in compression.

2. Alternatively, micro-plastic contraction of the bulk will cause the near-surface region to be placed in compression.

In tension-tension fatigue, compressive residual stress develops. As no contraction of the bulk is possible in this case, we can conclude that the dominant process causing the compressive stress is (1). Stress develops in the tensile portion of a cycle.

A maximum in the residual stress occurs during bending fatigue above the endurance limit, followed by fading. Fading can occur if:

1) the bulk elongates plastically or,

2) the surface contracts plastically.

As no relaxation appears to occur in tensile cycling of annealed specimens, we can conclude that relaxation occurs in a compressive half cycle and follows (2); surface elements are shortened.

The maximum in residual stress may occur because the surface can sustain only a certain plasticity without void formation, or because of local work hardening.

After shot peening, the observation that relaxation occurs in tensile cycling leads us to believe that the bulk is elongating plastically more than the (hardened) surface.

These simple qualitative ideas seem adequate to explain the known results and suggest a number of interesting experiments. For example, residual stress should be examined after each half cycle of fatigue, to see when formation and relaxation actually occurs.

Residual stress should be measured in the axial and transverse directions, and in a direction normal to the surface. Such results might lead to an understanding of why in some cases the sign of the residual stress is not important in fading[21], whereas in other cases it is clear that the algebraic sum of applied and residual stress is controlling.[22]

THE MEASUREMENT OF RESIDUAL STRESS

An entire session is devoted to this subject, so here we only briefly review procedures, emphasizing especially their limitations, as a basis for discussion in subsequent sessions.

1) Destructive Methods

One popular procedure is hole drilling or disection. The relief of stress distorts the region around the hole and the stress is obtained from measurements of this distortion with strain gauges. Care is needed to avoid producing large stress in the drilling operation. Also, the hole itself is a stress concentrator, and this can lead to unwanted local plastic deformation,contributing to the distortion.

Another common method is to remove material by boring or electropolishing and to determine the stress from measurements of strain on the surface opposite to the one where material is removed.[23] In applying such methods, problems can also arise. For example, if a soft material has a shallow heavily deformed layer, removing material may lead to plastic deformation of the interior. Furthermore, the principal stress axes are not necessarily in the surface, although this is usually assumed.

2) Non-destructive Methods

a. Acoustics[24]

The basic idea behind this method is that most solids are anharmonic; when a stress is applied there is a change in the elastic constants. Therefore the velocity of wave propagation is altered by stress. Popular methods of analyzing stress include acoustic birefringence involving the measurement of velocity or more precisely the transit time or phase difference in two directions with respect to the stress system. By varying the frequency, the depth of sampling can be varied. Surface elastic waves are also utilized. All such techniques suffer from the fact that the effective higher-order elastic Ionstants are sensitive to microstructure, texture, and in