COMPILATION OF STRESS-RELAXATION DATA FOR ENGINEERING ALLOYS
COMPILATION OF STRESS-RELAXATION DATA FOR ENGINEERING ALLOYS

Prepared for
The Metal Properties Council
and ASTM-ASME-MPC Joint Committee on
Effect of Temperature on the Properties of Metals
by M. J. Manjoine and H. R. Voorhees

ASTM Data Series Publication DS 60

ASTM Publication Code Number (PCN)
05-060000-30

1916 Race Street, Philadelphia, Pa. 19103
NOTE

The Society is not responsible, as a body, for the statements and opinions advanced in this publication.

This current project was sponsored by the Metal Properties Council, Inc. under the guidance of its Subcommittee 5 on Stress Relaxation. The data were compiled and analyzed for the Subcommittee by Dr. Howard R. Voorhees.

The Subcommittee acknowledges with gratitude those individuals and organizations who contributed data and services to this effort. The data sources are referenced in the tables, and those who contributed services can take pride from the result.

The members of Subcommittee 5 of The Metal Properties Council are as follows:

M. J. Manjoine, Chairman (Westinghouse Research Laboratories)
S. F. Collis (Alcoa Research Laboratories)
S. G. Epstein (The Aluminum Association)
R. F. Gill (General Electric Company)
F. Kull (SPS Technologies, Inc.)
R. W. Swindeman (Oak Ridge National Lab.)
H. R. Voorhees (Materials Technology Corp.)
R. C. Westgren (Wean United Inc.)
R. E. Zinkham (Reynolds Metals Company)
Related
ASTM Publications

Formability of Metallic Materials—2000 A.D., STP 753 (1982), 04-753000-23
Fracture Mechanics (13th Conference), STP 743 (1981), 04-743000-30
Stress Relaxation Testing, STP 676 (1979), 04-676000-23
Fatigue Mechanisms, STP 675 (1979), 04-675000-30
Formability Topics—Metallic Materials, STP 647 (1978), 04-647000-23
Selection and Use of Wear Tests for Metals, STP 615 (1977), 04-615000-23
1. Stress Relaxation of Metals and Alloys

A bar loaded to an initial stress of, say, 40,000 psi and then held at constant strain and temperature may after a time period have a remaining stress of only 30,000 psi. This time-dependent stress reduction of 10,000 psi is called stress relaxation. The total strain remains fixed but a part of the elastic strain is replaced with inelastic strain.

Examples of stress relaxation are:

a) loss of preload of a bolt in a rigid flange,
b) decrease of residual stresses, and
c) stress redistribution in a component with complex geometry.

This book compiles stress relaxation data for metals and alloys over a range of temperatures and initial stresses. A comparison of the 1000-hour relaxation strength for several classes of alloys has been shown in Figure 1. This comparison was made on an approximately equal basis in the earlier ASTM compilation. [D1] Relaxation characteristics of materials, methods of testing, and the utilization of relaxation data are reviewed in subsequent sections of this Introduction.

2. Relaxation Mechanics

In the stress relaxation process, the total strain is constant and the stress reduction at constant temperature occurs as elastic strain is converted to an inelastic strain. The types of inelastic strains described above are due to anelasticity, plasticity, microplasticity, and creep.

2.1 Anelastic strain, ε_a, is the transient strain for a stress change and it is recovered when the stress change is reversed. [R1] A simple model can be used to describe the general dynamics as follows:

\[ a_1 \sigma + a_2 \dot{\varepsilon} = b_1 \varepsilon + b_2 \dot{\varepsilon} \]

where \( \sigma \) is the stress, \( \varepsilon \) is the strain, and \( a \) and \( b \) are constants.

The anelastic strain is usually only 2 to 5% of the elastic strain. [R1, R3] It also influences the Young’s modulus; therefore, the dynamic modulus is called the unrelaxed modulus while the static modulus is the relaxed modulus.

The anelastic strain can be out of phase with the stress and it will contribute to internal heating during fatigue at high frequencies. [R4]

2.2 Plastic strain, \( \varepsilon_p \), is the permanent strain measured when a material is loaded to a stress above the elastic limit and then unloaded. Since the elastic limit is a function of the strain rate and the temperature, this strain for a given stress is also affected. The plastic strain range for a cyclic stress range is the difference between the strain range and the elastic strain range.

2.3 Microplastic strain, \( \varepsilon_{\mu p} \), is the transient strain for an applied stress and is not fully recovered when the stress is reversed. [R5] Together with the anelastic strain, it accounts for the time-dependent strain observed below the macro-yield stress and the recovery on stress reversal. The effects of temperature and strain-rate sensitivity on this strain are similar to those for the plastic strain, but the magnitude of the microplastic strain is usually only 5 to 15% of the elastic strain and reaches a finite limit at temperatures, \( T \), below 0.4 of the absolute melting temperature, \( T_m \), of a material. Since this strain reaches a limit, it will not be referred to as “creep” which is described below for temperatures above 0.4 \( T_m \), although it contributes to “primary” creep and recovery. [R6; D26]
2.4 Creep. For temperatures above 0.4 $T_m$, the thermal activation enhances the flow mechanisms. Creep is defined as the time-dependent deformation under applied stress, $\sigma$, which persists with time. Under constant stress or load, three stages of creep are identified for many materials: Primary, Secondary, and Tertiary.

2.4.1 Primary creep strain, $\epsilon_p$, is the limited strain which occurs (after loading) with a diminishing rate; $\epsilon_p$ can encompass some of the mechanisms described above. This limited strain has been expressed as \[\epsilon_p = A[\exp(-B/T)] (\sigma/\sigma_0)^m [1 - \exp(-Ct)],\]
where $t$ is the time and $A$, $B$, $C$, $\sigma_0$ and $m$ are constants.

2.4.2 Secondary creep, $\epsilon_s$, accumulates at a creep rate, $\dot{\epsilon}$, as long as a stress is applied. This strain, therefore, is:
\[\epsilon_s = \int \dot{\epsilon} \, dt\]
where $\dot{\epsilon}$ is a function of stress and temperature for a material in a given metallurgical state. Many mechanisms of creep have been postulated; one based on a diffusion process is:
\[\dot{\epsilon} = a[\exp(-Q_c/kT)] \sinh (\sigma/\sigma_0),\]
where $Q_c$ is the activation constant for creep, $\sigma_0$ can be a function of temperature, $T$, and $a$ and $k$ are constants.

2.4.3 Tertiary creep is one of increasing creep rate above the minimum secondary rate, up to rupture. It is a result of the damage processes which accompany the accumulated strain. The concern here is the reduction of local ductility which can occur in some materials under high constraint, especially multiaxial stress;[R9, 10, 11]. An example is "stress relaxation cracking" or "reheat cracking" when residual stresses in welds are relaxed.

3. Stress Relaxation Testing

Research on stress relaxation has been dictated by the following goals:
1. Design data for bolting and spring applications
2. Correlation of creep- and relaxation data
3. Fundamental studies for a given theory
4. Hold-time effects in creep-fatigue damage.

The American Society for Testing and Materials has developed standard recommended practices for stress-relaxation tests for materials and structures. [R13] which allow comparison of data from different sources. The "relaxed stress" is defined there as the initial stress minus the remaining (residual) stress during a stress-relaxation test. Tension tests have the advantage that the stress can be measured easily and the gage length can be larger for better sensitivity in maintaining constraint with a given extensometer. The relaxation test can be performed by differing loading procedures:

a) Initial stress at test temperature,
b) Initial total strain at test temperature,
c) Initial total strain at room temperature, followed by heating to a peak test temperature for a time period,
d) Repeated loadings to selected stress levels,
e) Holding at a given strain in a cyclic stress-strain loop.

The most common test employed to determine the stress-relaxation characteristics of materials is the tension test of a specimen with uniform cross section, instrumented with a sensitive extensometer, and employing procedure (a) above. When an initial strain results from service displacements, procedure (b) can be used to approximate service constraint.

Procedure (c) simulates the loading of a bolt at room temperature and the subsequent relaxation after elevated service temperature is reached. This type of loading is used in measuring stress relaxation by the compliance method.[D70] In many bolted flanges, multiple tightenings are employed to prevent leakage. Design data for frequency of tightening can be obtained for a given material from tests using procedure (d).

The "Bauschinger effect" demonstrates that after initiating flow in a forward direction, the flow stress in the reverse direction is lower. Therefore, the relaxation characteristics depend on the inelastic strain history.[R14] Reverse straining can occur from thermal transients; this type of loading can be studied by procedure (e).[D106]

The ASTM recommended practice suggests that the preferred method of relaxation testing should be similar to that of the intended application of the data. Thus, bending, torsion and compression data are identified in this compilation.

4. Analyses of Data

As indicated above, relaxation has been studied to understand the mechanisms of flow, so that analyses can be made for other loading histories or states of stress. The major effort has been to determine a correlation between creep and relaxation data, so that the contributions of the different types of strain of Section 2 could be evaluated. The early researches of Kanter [R14], Robinson [R14], Boyd [D17], Davis
4.1 Stress relaxation at temperatures below 0.4 $T_m$

The stress relaxation at temperatures below about 0.4 $T_m$ are a result of inelastic strains which after a time period reach a limit that is a function of the initial stress and the temperature. These inelastic strains were described in Section 2, and are due to micro- and macro-plasticity and anelasticity. The initial stress or strain can be induced in structures by fabrication loads or service thermal gradients.

An example of this relaxation limit is given in Figure 2 for an annealed Type 304 stainless steel for which $T_m$ is about 800 deg. F. The remaining stress reaches a limiting value within 100 hours for temperatures up to 600 F (315 C) and 90% of this relaxation takes place within 24 hours. The remaining stress is shown in Figure 2 as a function of the initial stress. This material at room temperature has significant relaxation which decreases with the initial stress.

Little relaxation is observed for stresses below about one-half of the yield strength for virgin monotonic loading. At 600 F (315 C) the amount of relaxation is greater than that above for a given initial stress, and no relaxation at stresses below one-half of the yield strength at this temperature. In this "lower" temperature range, sufficient stress must be applied to initiate micro-plasticity. However, after a reversed stress above the proportional limit (lowest curve in Figure 2) relaxation is observed for stress levels below one-half of the yield strength and negative relaxation (increase in stress) may occur at low forward stresses where the anelastic strain is dominant.

4.2 Stress relaxation at temperatures above 0.4 $T_m$

When creep strain is the dominate inelastic strain, stress relaxation occurs continually with time and as a function of the stress and temperature. The majority of the data tabulated in this book are in this "higher" temperature range, above 0.4 of the absolute melting temperature.

For a structure which is given an initial strain, the percent relaxation can be measured as a function of time at a given temperature, and the data analyzed to generate constitutive relationships for interpolation and extrapolation. A parameter $P = \log t - H/(T - 0.4 T_m)$ gives good correlation for a cold-worked Type 304 stainless steel in the creep range. [D71] The percent relaxation for specimens loaded to an initial 0.07 per cent strain and tested at several temperatures is plotted as the solid curves in Figure 3. The dashed curves were obtained using the above parameter with the constant $H$ being determined by the parameter method.

4.3 Loss of stress for a bar under constant total strain

The relaxation of the stress in a bar under constant total stress can result from a thermal expansion, inelastic flow, and metallurgical changes. The initial stress may be a result of an external load or displacement, or from a residual stress due to differential plastic strains. Since the initial strain in the bar is constant, the stress is a product of the elastic strain and the elastic modulus. This modulus decreases with rising temperature; therefore, the stress is reduced on heating. The initial stress under simple tension can be as high as the flow stress for the initial total strain.

The case for heating a bar of annealed Type 304 stainless steel with an initial stress at room temperature equal to the yield strength of 30 ksi (207 MPa) is illustrated in Figure 4. The top curve in that figure is the reduction of stress due to the change of the modulus with temperature. The yield strength curve for a given strain rate is marked $T_m$. This strength is less than that due to the modulus change, wherefor plastic flow will occur on heating and the stress will be reduced to a value near the yield curve. Since plastic flow is initiated, stress relaxation further reduces the stress to "the remaining stress for an initial stress equal to the yield strength".

Below 0.4 $T_m$ this stress reaches a limit value within 100 hours. The dashed and lowest curve indicates that if the initial stress is below this curve, no plastic flow is initiated and no relaxation will occur.

If the temperature is increased above 0.4 $T_m$, creep will continue with time and the stress will relax with time of exposure. In Figure 4 the zero-time curve is shown as the yield strength curve; additional curves are given for 100 and 1000 hours for temperatures up to 1900 F (104 C).

Similar curves can be generated for other materials by utilizing the data of this book. For materials which undergo a metallurgical change with time and temperature, the stress relaxation will be modified. If precipitation results in a volume decrease, the remaining stress will increase for a time, whereas volume increases (such as irradiation swelling) will cause an additional stress relaxation. Metallurgical changes also influence the creep strength and this in turn affects the rate of relaxation.

4.4 Stress relief by relaxation

The residual stress left in a structure from fabrication and processing can be detrimental in service because of corrosion, distortion, or reduction of the fatigue and rupture strengths.

[D26], Johnson [D51], Oding [D75] and others have been reviewed by Conway [R16].
4.4.1 Thermal treatment

The discussion in 4.3 illustrated how thermal exposure can reduce residual stresses and showed how the data in this book can be used to evaluate the magnitude of the reduction. Residual stresses can be eliminated by reheat treatment but in some cases this is not practical. Residual stresses may result from differential thermal expansion in dissimilar materials.

4.4.2 Mechanical and thermo-mechanical treatment

Residual stresses are self-equilibrated and can be reduced by imposing for a short time a monotonic uniform stress sufficiently high to cause plastic flow in the volumes where the peak stresses are of the same sign.

Since initiation of plastic flow in the forward direction lowers the yield stress in the reverse direction, cyclic straining with decreasing amplitude can be employed to reduce residual stresses. This process is similar to that for demagnetization. In roller leveling of plates or straightening of shafts, reverse bending with decreasing amplitude can reduce the residual stresses and redistribute the remaining ones over the entire cross section so that they will self-equilibrate over a short distance.

Mechanical and thermo-mechanical methods are used to add favorable residual stresses as well as to remove distortions or residual stresses. Surface compressive stresses improve fatigue strength and can be produced by shot peening, autofrettage or surface quenching.

Shafts can be straightened by local heating techniques to reduce residual stresses or to induce residual stresses which improve the straightness.

5. Utilization of Stress Relaxation Data

5.1 Bolting design.

A principal use of relaxation data is in the design of bolted structures. Leakage at bolted joints of pressure retaining structures can be prevented by adequate load of the bolts. The required preload and the allowance for relaxation can be calculated from the data presented here.

When a given bolt load is required to prevent fretting and wear of interfaces, then the allowance for relaxation must be calculated for the service period.

Adequate residual bolt loads are required in bolted assemblies subjected to vibratory loads to prevent joint opening and the associated higher alternating stress on the bolt.

5.2 Press-fitted joints, springs, and clamps

Other types of assemblies for which the success of a design depends on the analysis of the load or interface pressure and its relaxation under service loads and environment are: press-fitted joints, springs, and clamps. Uniaxial tensile relaxation data have been used in analyses of a cylinder on a rigid shaft [R10] and of a rolled-in tube. [R20]

5.3 Creep-fatigue damage

The stress-time history of a component for elevated temperature service can be very complex during start-up, operation and shut-down cycles. The damages from stress and strain histories are a function of the strain rate, stress state, temperature and environment. [R 9, 10, 11, 21, 22]. However, the stress redistribution under multiaxial stresses can be analyzed using uniaxial relaxation data. [R 22] The strain damage during relaxation under multiaxial stress can be more severe for some materials. [R10]

5.4 Constitutive relationships

Constitutive equations for a material describe the mechanical-thermal responses of plastic flow, creep, stress relaxation, and cyclic strain. The material models assume that the response can be formulated for multiaxial stress states using effective stresses and strains, and that the time independent part can be separated from the time dependent part. Relaxation data, therefore, are an important portion of the data base for a material. Comparison of the relaxation and creep data allow the assessment of the comparative roles of transient and steady-state creep in design and analysis. [D26; R8 and 22]

6. References


R 4. Manjoine, M. J. and Landerman, E. I., "Techniques for Fatigue Testing and Extrapolation of...


Fig. 1 - Comparative 1000-hour relaxation strengths for several classes of alloys
Fig. 2 - Relaxation of solution-annealed type 304 stainless steel
Fig. 3 — Relaxation of a 20% cold-worked type 304 stainless steel from 900 to 1300°F (482 - 704°C) for an initial inelastic strain of 0.07%
Fig. 4 – Remaining stress for an annealed type 304 stainless steel bar at constant strain as a function of temperature and time.