Stress Relaxation and Mechanical Behavior of Metals

D. LEE AND E. W. HART

Stress relaxation tests have been made in the temperature range 200° to 400°C on two materials, the Mg-Al eutectic alloy and commercial purity zirconium. The materials represent respectively high and low homologous temperature regimes. The novel features of the tests are the use of high speed, high sensitivity digital measurement techniques and the direct reduction of the data to stress-strain rate curves. It was possible in this way to obtain phenomenological information on the material behavior over a very large range of strain rate with very few specimens. Comparison was made with results obtained by more conventional differential strain rate tests. The test lends itself well to establishing the phenomenology of mechanical behavior of metals.

THE load relaxation test for metals in its most usual form consists in loading a test specimen in tension or or compression in a tensile testing machine to some predetermined load level, then stopping the crosshead motion, and subsequently recording the load as a function of time at fixed crosshead position. The resultant load-time record is dependent both on the plastic properties of the specimen and on the elastic properties of the testing machine and specimen. Although it is a straightforward procedure to extract the material dependent properties from the load-time record, this is rarely done in current uses of the test. Instead, a predicted load-time behavior is derived from some theory for the material behavior, and that behavior is then compared with the measured load time record. This procedure generally obscures the fact that the property that is measured in the test is in fact a material property that is independent of any special theory chosen to explain it. We shall demonstrate in this paper how the experimental data of the load relaxation test can be analyzed practically to yield explicit stress-strain rate data.

As it is generally done, the relaxation test yields results that cover barely two decades of strain rate in any one run. This can be seen in the exceptional published cases[1,2] where load relaxation data were converted into stress-strain rate results. The main reason for this limitation is inadequate instrumentation.

If it is desired to explore a range of strain rate for which the ratio of maximum strain rate to minimum strain rate is as much as 10^5, it is evident that a load-time record must be produced for which the slope can be measured with reasonable precision over the same broad range of strain rates. The necessary time resolution and precision for the load signal are difficult to obtain with the conventional analog recorders. The requirements are readily met, however, by the use of high-speed digital data recording. Collection of data in digital form has the added advantage that the data are already in form suitable for numerical calculation.

The method advocated here will be illustrated by the results of tests on two materials: Mg-Al eutectic alloy and commercial purity zirconium. The first of these exhibits high homologous temperature behavior at only moderately high test temperatures, while the second shows characteristic low homologous temperature behavior.

D. LEE and E. W. HART are Staff Members, Metallurgy & Ceramics Laboratory, General Electric Research & Development Center, Schenectady, N. Y.

Manuscript submitted September 14, 1970.

I. GENERAL MECHANICAL RELATIONSHIPS

The fundamental relationships concerning the loading of a plastic specimen in a tensile testing machine have been described recently by several authors.[3-6] We follow here the treatment given by Hart.[6] The model we follow is shown in Fig. 1. The specimen A is represented as a purely plastic element, loaded by the spring B that is in turn extended by the movable crosshead at C. The spring represents the combined elasticity of the specimen, the load measuring cell, and the connecting linkages. The instantaneous "plastic length" of the specimen, *i.e.*, the length of the real gage section less its elastic extension, is denoted by L. The load exerted on specimen and spring is P. We denote by L_1 the distance of the crosshead from a fixed fiducial point 0, chosen in such a way that, when $P = 0$, $L_1 = L$. With this choice of variables our fundamental equation is

$$P = K(L_1 - L) \qquad [1]$$

where K is the elastic constant of the spring. Any displacement of the crosshead by an amount X results in precisely that much change in the value of L_1.

It is convenient to adopt the following convention for any series of experiments on a single specimen. When the specimen is first mounted, and the crosshead has been moved to the point at which the slack is taken up but the load is substantially zero, L_1 will be assigned to have the value L_0, the initial specimen gage length. Since it is easy to keep track of the cumulative crosshead displacement from this point on, we shall call

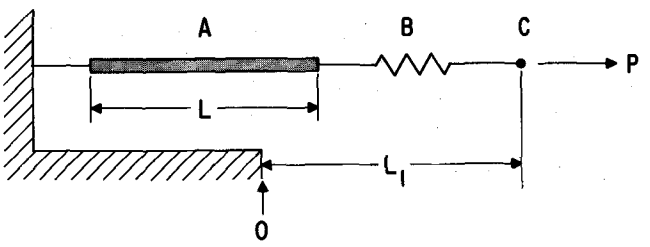

Fig. 1—Schematic diagram identifying various elements in the loading system.

that accumulated displacement X, and so at any time during an experiment

$$L_1 = L_0 + X \quad [2]$$

Then at any time, if the values of X and P are known, L is given simply by the relationship

$$L = L_0 + X - P/K \quad [3]$$

If we now differentiate Eq. 1 with respect to time t, and designate the time derivatives by dots over the respective symbols, we obtain

$$\dot{P} = K(\dot{L}_1 - \dot{L}) \quad [4]$$

Since the data that are collected are a record of P as a function of t and since $\dot{L}_1$ is known from the control settings of the testing machine (or optionally from auxiliary measurements), $\dot{L}_1$ and $\dot{P}$ are known at each point of an experiment. (The practical problems of obtaining $\dot{P}$ from $P(t)$ will be discussed below.) Then $\dot{L}$ can be determined at any instant as

$$\dot{L} = \dot{L}_1 - \dot{P}/K \quad [5]$$

It is now clear that any sufficiently precise experimental record of P and L_1 as a function of t can yield a record of material behavior for the test of the form: σ, $\dot{\epsilon}$, ϵ as a function of t, where σ is the true stress, $\dot{\epsilon}$ is the natural strain rate, and ϵ the accumulated natural plastic strain. We now derive the appropriate formulas.

If A_0 and A are, respectively, the initial and current specimen cross sections,

$$A_0/A = L/L_0 \quad [6]$$

then

$$\sigma = P/A$$

$$= PL/A_0L_0 \quad [7]$$

$$\dot{\epsilon} = \dot{L}/L \quad [8]$$

and

$$\epsilon = \ln(L/L_0) \quad [9]$$

Of course, L and $\dot{L}$ are obtained from P, L_1, and X by use of Eqs. [3] and [5].

Note, by the way, that our formulation to this point is applicable to any tensile testing routine. Specialization to the case of the load relaxation test is accomplished simply by setting $\dot{L}_1$ equal to zero and assigning to X the value it has at the beginning of the relaxation run.

There is one further point that should be considered here concerning the value of K. This is that the value of K can change during a series of relaxation runs on a single specimen if the specimen sustains considerable plastic deformation between any two runs of the series.

This is seen most easily in the following way. The spring B of Fig. 1 may be considered to have two components in series. One, the machine component, consists of the load cell and connecting linkages, and the other is the elastic contribution of the specimen. If C_m is the elastic compliance of the machine component, the total compliance of B is

$$K^{-1} = C_m + L/AE \quad [10]$$

$$= C_m + (L/L_0)\,(A_0/A)\,(L_0/A_0E) \quad [11]$$

$$= C_m + (L/L_0)^2\,(L_0/A_0E) \quad [12]$$

where E is the Young's Modulus of the specimen. Thus the compliance K^{-1} will increase with accumulated plastic strain of the specimen. In any particular experimental situation it is sufficient to measure K at a sufficient number of lengths L to establish the value of C_m. It is simple then to compute K for other values of plastic strain from Eq. [12].

II. EXPERIMENTAL

1) Instrumentation

The data presented in the present paper was collected in an Instron testing frame. The load cell signal at the output of the bridge and amplifier was measured by a Hewlett-Packard integrating digital voltmeter that was capable of forty readings per second. A maximum sample rate of ten per second was used, and the data were recorded by a high speed printer manufactured by the same company. The overall measuring system was capable of a precision of one-tenth percent.

2) Materials

The Mg-Al eutectic alloy with 67.7 pct Mg by weight was prepared from 99.99 Mg and 99.999 Al. The cast was extruded at 300°C, and heat treated at 400°C for 20 min in a helium atmosphere. This produced an equiaxed two-phase structure with a mean intercept length of 2 μm.

An ingot of commercial grade zirconium with major impurities of 1800 ppm by weight of Fe, 930 ppm O and traces of other elements, was rolled at 430°C. This was annealed at 550°C for 4 hr, resulting in the mean intercept grain size of 13 μm.

The gage sections of the test specimens were 0.1 in. diam and 0.5 in. long for the Mg-Al, and 0.160 in. diam and 1.0 in. long for zirconium.

3) Testing

An Instron oven provided the control of test temperatures. The maximum deviation in oven temperature was less than ±0.2°C throughout each test.

The differential strain rate test was made in such a manner that the crosshead speed was changed in increments where the ratio was not more than 2.5. The flow stress and the strain rate sensitivity were directly calculated from the load-extension record, following the extrapolation method outlined elsewhere.[8]

In the relaxation test, the accumulated crosshead motion was monitored through the crosshead control dials.

III. RESULTS

Typical load-time curves for the two materials are shown in Fig. 2. The loading portion of each curve yields a measure of the elastic constant K, while the remainder of the curve is the relaxation history at fixed crosshead position. The resultant material properties in the form of $\log \sigma - \log \dot{\epsilon}$ curves as computed from the formulas of Section 2 are shown in Figs. 3 and 4.

The outstanding feature of all the curves is the very large range of strain rate that is covered in each relaxation run.

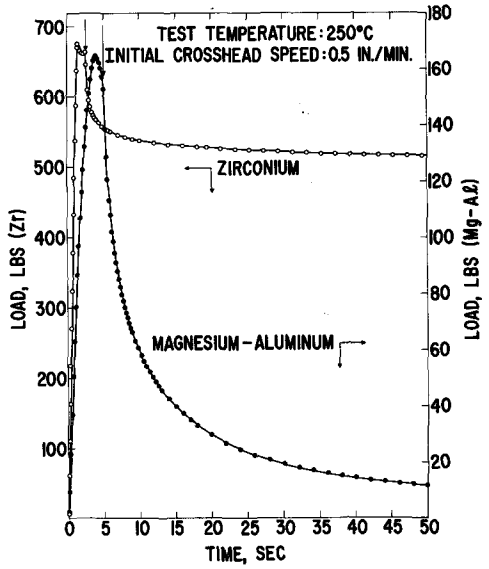

Fig. 2—Load vs time relationships for both Mg-Al and zirconium tested at 250°C. For the purpose of illustration, only the loading portion and the early stage of stress relaxation test are shown. The actual test time was more than 12 hr. The elastic constant, K, was 7890 lb per in. for Mg-Al and 63,950 lb per in. for zirconium at the crosshead speed of 0.5 in. per min. The arrows indicate where the crosshead motion was stopped.

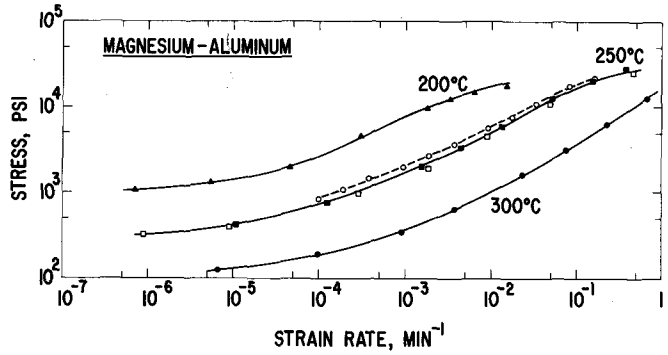

Fig. 3—Stress vs strain rate relationship for the Mg-Al eutectic obtained from a series of stress relaxation tests with a single test specimen. The result of duplicate tests (solid and open squares respectively) with the same specimen is shown for 250°C test. For the purpose of comparison, the result of differential strain rate test is also shown by the dashed line for 250°C test.

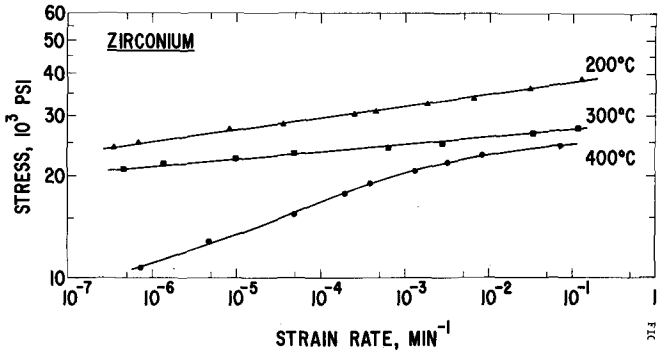

Fig. 4—Stress vs strain rate relationship for commercial purity zirconium obtained from a series of stress relaxation tests with a single test specimen.

An important practical feature of all the results is that many relaxation runs were possible with the same specimen even at different temperatures. The total plastic strain accomplished in each run was small and did not exceed $1\frac{1}{2}$ pct.

The plots in Fig. 3 also show points corresponding to independent measurements at 250°C obtained by differential strain rate tests.

The Mg-Al eutectic which is "superplastic" was shown by Lee[7] to exhibit considerable grain boundary sliding. In the work reported here repeated relaxation tests were insensitive to either the amount of plastic strain prior to each relaxation run or to intervening recovery intervals of up to 24 hr at test temperature but unloaded. In other words, the Mg-Al eutectic exhibited negligible strain hardening or static recovery.

The zirconium specimens, on the other hand, did show some strain hardening and so relaxation tests at different levels of strain hardening yielded different σ-$\dot{\epsilon}$ curves. The curves at different hardening levels were, nevertheless, parallel within the experimental error and at 250°C were straight over the entire strain rate range with a slope, $m = d \log \sigma / d \log \dot{\epsilon}$ of 0.02. The values of m obtained at the same temperature by differential strain rate tests varied from 0.02 at low $\dot{\epsilon}$ to 0.04 at high $\dot{\epsilon}$. A further anomalous feature of the zirconium is that m has a minimum value at a temperature intermediate to the highest and lowest temperatures investigated. It is probable that both of these phenomena are a result of strain aging as described by Lee.[8]

IV. DISCUSSION

We should like to emphasize that the purpose of this study was not so much an investigation of the particular specimen materials that were employed, but rather was to illustrate a different approach to the treatment of load relaxation data. The main point to be made in this connection is that the load relaxation test is a specially self-programmed sequence of stress-strain rate measurements carried out with very little strain. The proper presentation of the results is therefore the σ-$\dot{\epsilon}$ relationship that is so measured. We have demonstrated that, with proper instrumentation and control, such data can be generated for a broad range of strain rates with good precision. The "interpretation" of such data is a separate problem and is quite independent of the test itself. The measured σ-$\dot{\epsilon}$ relationship is a well defined property of the material whether or not the investigator has successfully explained that material property theoretically.

It is necessary at this point to make some comment about the effect of possible anelastic relaxations on the load relaxation test. The $\dot{\epsilon}$ that is deduced in the mathematical reduction of the data is a total strain rate and can include a contribution from anelasticity as well as the plastic deformation component. Since these two components generally have different stress dependence it is possible, and generally desirable, to identify them separately. This should be easily done by making similar tests at stresses so low that the plastic strain rate is negligible. Since anelastic effects are substantially linear in stress, the anelastic behavior should be easily measured at those low stress levels. Once determined, the high stress data can be corrected for the expected anelastic contribution. We have not done this

in the current investigation. The importance of anelasticity and the relationship of the load relaxation test to the general phenomenology of plastic deformation has been discussed recently by Hart.[9]

There was no difficulty in numerically differentiating the load-time data over most of the range to an accuracy of about 5 pct, which is quite adequate for most purposes. Somewhat poorer accuracy could be obtained at the very low strain rate end of the data because of temperature fluctuation. In the present case the situation was somewhat better than usual because of the high sensitivity and stability of the digital load measuring system.

The good time resolution and rapid response of the digital measuring technique permitted collection of data at rather high initial specimen strain rates. This made it possible to employ a maximum $\dot{L}_1$ as high as 1 in. per min. Of course the maximum value of $\dot{L}$ that can be explored in any relaxation run cannot exceed $\dot{L}_1$ in the loading.

It is worth noting that the value of K is controllable to some extent. Its value can be varied by varying the length of the specimen and the connecting linkages. A high value of K is desirable since the total strain during a relaxation run is then small. However, a high value of K results in a correspondingly high value of $\dot{P}$ for a given $\dot{L}$. Lower K values may then be desirable when the desired initial strain rates are so high that the rate of change of P would exceed the time resolution of the load recording system.

V. CONCLUSIONS

We have attempted to demonstrate in this study that the load relaxation test is capable of broader use than that to which it is currently put. Since each relaxation run employs only a small increment of plastic strain, the test is well suited to the investigation of the stress-strain rate behavior of materials that lack substantial ductility. The effect of strain and time histories can be investigated in detail by the use of many relaxation tests with the same specimen.

With this in mind we have presented a more detailed formulation of the mechanics of the load relaxation test than is usual, with emphasis on the deduction of the material properties that are measured by the test.

A high speed digital data recording scheme has been described and its efficacy has been demonstrated.

The method has been illustrated by tests on Mg-Al eutectic and zirconium specimens. The results were shown to be in good agreement with results obtained by differential strain rate measurements.

ACKNOWLEDGMENTS

We wish to thank R. L. Cook for his assistance in the mechanical testing.

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