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Measurement of stress relaxation strength in engineering materials for high precision mechanical applications

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Abstract

The problem of measuring relative relaxation strength of the order of 10^{-4}–10^{-2} has been solved by using an electrodynamic balance with a resolution of 10^{-6}. It has been modified in order to load the free side of a bending sample clamped on the other side by lifting or sinking the scale of the balance. The weight is fully supported by the scale and the sample. After loading the sample, its relaxing stress can be calculated using the time-dependent reading of the balance. This measuring technique is well suited to the problem of finding materials with low relaxation strength for balance applications, because the measuring conditions such as stress level, stress resolution, range of measuring time and mode of relaxation are nearly the same as the relaxation conditions in the balance.

1. Introduction

Mechanical relaxation of engineering materials in high resolution mechanical devices can be a serious problem. In electrodynamic balances, for example, it leads to a time-dependent drift of the electric current through a coil compensating the weight by a magnetic force. Without time-dependent correction of this signal the reading of the balance, which is proportional to this current, is also changing with time. This behaviour can be avoided by the use of materials with very low relaxation strength for certain elements in the balance.

The measurement of relative reversible relaxation strength of most metals, which is of the order of 10^{-4}–10^{-2}, is an ambitious task. Our original idea to solve this problem was the use of precision instruments in which relaxation of mechanical parts is detrimental. Thus a commercial electrodynamic balance has been modified in order to utilize the high force resolution.

2. Experimental details

Modern electrodynamic balances are force-measuring instruments with high resolution and extensive measuring range. The operation principle of such a balance [1] can be understood from the schematic drawing in Fig. 1. The mass m of a body lying on a scale exerts a force F on the system spring and a lever. The spring

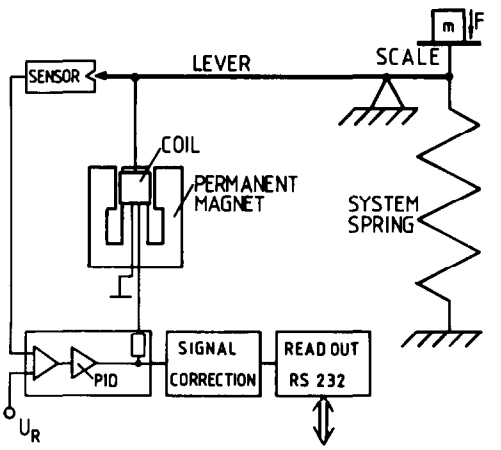

Fig. 1. Schematic drawing of electrodynamic balance.

is not compressed, because the force is compensated by the leverage of a coil in the gap of a permanent magnet. The activating electrical current flowing through the coil is adjusted by a control loop regulating the position of the lever via an optical sensor to be constant. In this way the current in the coil is approximately proportional to the force and can be used for analogue and digital correction procedures in order to obtain a digital read-out of the weight. The digital read-out via common interfaces is another advantage of modern balances, because the data can be processed on personal computers (PCs). The position of the lever and scale can be changed by changing the voltage U_R which is

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compared with the voltage of the sensor by the control loop. Owing to the force-compensating principle of the balance, it behaves like a very stiff spring and the spring constant is determined mainly by the electricity of the lever and its support.

In order to make stress relaxation experiments with engineering materials possible, a commercial balance (E1200s, Sartorius, Göttingen) has been modified by fixing a specimen holder on the balance system spring holder as demonstrated schematically in Fig. 2. At the sample holder a bending beam sample is clamped. The transverse beam (F_S) and the balance (F_B) are loaded by a weight (G) and the partition of the forces

$$G = F_S + F_B \tag{1}$$

can be controlled by a screw.

The position of the scale and thus the loading F_S of the sample is changed by an amount F_{S0} by changing the voltage U_R of the control loop via a digital–analogue converter (DAC). This is initiated by a PC and can be time programmed by using the clock of the PC. After changing the load on the sample by lifting or sinking the scale, the stress in the sample relaxes, causing a relaxation of F_S and, owing to eqn. (1), a corresponding change in the balance read-out

$$\Delta F_B(t) = -\Delta F_S(t) \tag{2}$$

Consequently, it is possible to determine both the initiated load change F_{SO} and the relaxing load change $\Delta F_S(t)$ of the sample by the balance read-out $F_B(t)$. At any point of the bending sample the change in the internal stress contributes to the change in the force. Therefore in the case of stress-independent relative stress relaxation the following equation holds:

$$\frac{\Delta\sigma(t)}{\sigma_0} = \frac{\Delta F_S(t)}{F_{S0}} = \frac{\Delta F_B(t)}{F_{B0}} \tag{3}$$

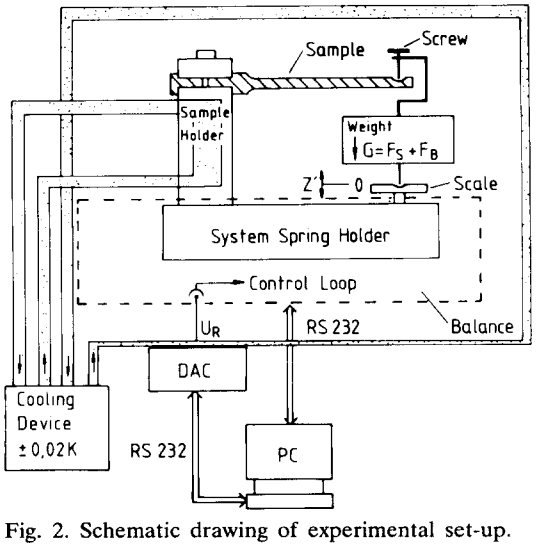

Fig. 2. Schematic drawing of experimental set-up.

For relative stress relaxation depending on stress, the measured relaxation strength $(\Delta\sigma/\sigma)_m$ can be corrected for the constant-stress condition using an equation developed by Lazan [2, 3] for cantilevers in bending:

$$\frac{\Delta\sigma}{\sigma}(\epsilon_m) = \left(\frac{\Delta\sigma}{\sigma}(\epsilon_m)\right)_m + \frac{7}{9}\epsilon_m \frac{d(\Delta\sigma/\sigma)_m}{d\epsilon} + \frac{1}{9}\epsilon_m^2 \frac{d^2(\Delta\sigma/\sigma)_m}{d\epsilon^2} \tag{4}$$

Here ϵ_m is the maximum stress in the cantilever, which can be shown to be [4]

$$\epsilon_m = \frac{3hz}{2l^2} \tag{5}$$

where h is the thickness and l the length of the cantilever bending beam and z is the stroke of the scale. With the maximum values $h = 3$ mm and $z = 0.12$ mm and a constant length $l = 80$ mm the maximum strain is 84×10^{-6}. At such low strains the relaxation strength is constant. Thus corrections due to the distribution of strains in the sample were not necessary.

After the load change initiated by the PC and during relaxation the position is held constant owing to the control loop. Because of this, only the stress but not the strain in the sample relaxes. If the relaxing part of the stress, $\Delta\sigma(t)$, is related to the relaxing part of Youngs modulus, $\Delta E(t)$, the following equation holds:

$$\sigma_R + \Delta\sigma(t) = [E_R + \Delta E(t)]\epsilon_0 \tag{6}$$

From eqns. (3) and (6) the relative change in Youngs modulus, also called the modulus defect, can be determined by the experimental set-up:

$$\frac{\Delta E}{E} = \frac{\Delta\sigma}{\sigma} = \frac{\Delta F_B}{F_B} \tag{7}$$

This in only possible with a bias stress, because the tip of the screw lies on the sample and would take off for upward-directed forces on the sample ($F_S < 0$). This is why strain and stress have to be changed around bias values (Fig. 3). For periodically altering strain levels a schematic drawing of strain and stress *vs.* time is shown in Fig. 3. It can be seen that reversible and irreversible stress ranges can be subdivided by using a bias stress and two successive stress relaxation periods. Only the reversible part of the stress relaxation has been determined in our investigations:

$$\Delta\sigma = \frac{\Delta\sigma_E - \Delta\sigma_B}{2} \tag{8}$$

The accuracy of the measurement can be increased by averaging more than two successive periods of the balance read-out. The irreversible stress relaxation is given by the drift of the whole relaxation curve. The

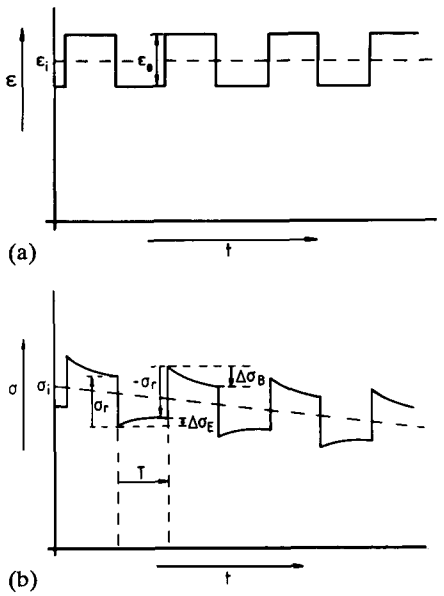

Fig. 3. Schematic drawing of (a) strain and (b) stress in bending beam sample.

drift is also very sensitive to other errors of measurement, *i.e.* very small temperature changes. Irreversible stress relaxation values could not be obtained for this reason. The temperature drift had to be reduced by isothermal (± 0.02 K) water cooling or heating of a case surrounding the whole modified balance and the sample holder (see Fig. 3) in order to obtain sufficiently accurate anelastic measurements. This is necessary in order to avoid non-linear drifting, because eqn. (6) only holds for linear drifting. Direct cooling or heating of the beam holder was essential, increasing the accuracy of earlier investigations. Before this the beam had been warmed up without control by the heat generated in the balance which had been conducted to the sample by the sample holder. The cooling case had to be as small as possible to minimize the convection of the air surrounding the sample. With an antifreeze agent in the water the temperature of the whole equipment could be changed from -20 to 40 °C without affecting the precision of the balance.

3. Results and discussion

One advantage of relaxation measurements compared with other methods of measuring anelastic properties is the usually extended range of measuring time, enabling the investigation of an extended spectrum of relaxation time constants. The first reliable read-out of the balance occurs 3 s after changing the load on the sample by altering the position of the scale. This is the lowest time value of the relaxation time spectrum and is

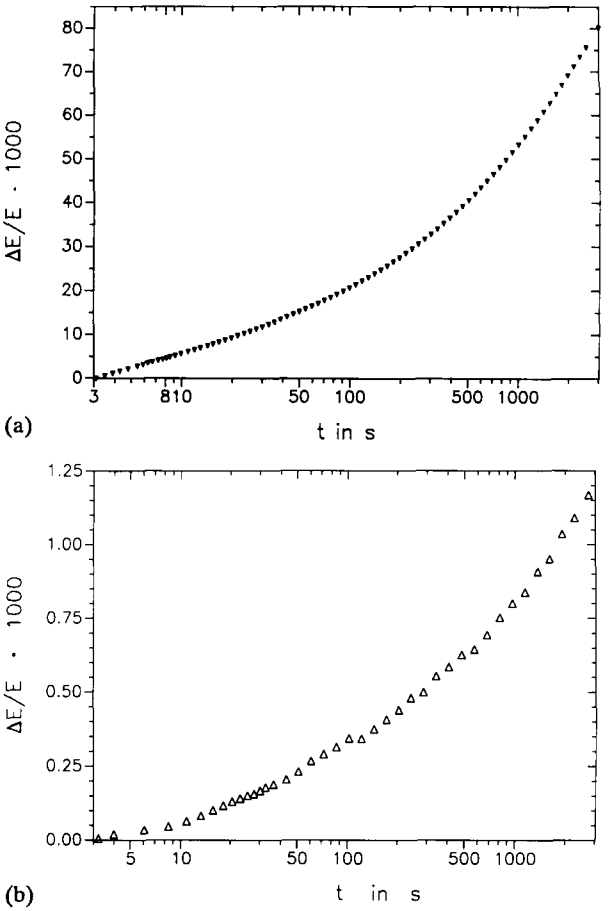

Fig. 4. Examples of modulus defect measurements by present experimental arrangement for (a) DISPAL and (b) CuBe2.

determined mainly by the time constant of the control circuit of the balance. The highest value depends on the time for which stable measuring conditions are possible, *i.e.* on the long-time periodic temperature drift, vibrations of the building and the stability of the electrical network. This time is also determined by considerations of time management. Taking into account that stress relaxation curves are plotted on a logarithmic time scale [5], the additional information provided by relaxation measurements after a certain time decreases rapidly with time. For our investigation we choose a maximum time of 3600 or 3030 s. In this way a time range of over three decades in covered. Taking into account that the measurements have to be averaged, two samples can be measured per day with these times.

In Figs. 4(a) and 4(b) results for two examples of engineering metals with high and low relaxation capacities are shown. They demonstrate that very high as well as very low relaxation capacities can be measured with the experimental arrangement presented in this paper. The curves show that the anelastic effects in the two samples cannot be explained by one mechanism with one relaxation time alone. This would cause an

TABLE 1. Relative reversible modulus defect from 3 to 3600 s, $\Delta E/E = [E(3\text{ s}) - E(3600\text{ s})]/E(3600\text{ s})$, at room temperature for various engineering materials ($\epsilon_m \approx 5 \times 10^{-5}$)

Metal	Condition	$10^3\ \Delta E/E$
Cu (99.9)	Cold rolled (105 HV 5)	4.8
CuBe2	Drawn, F600 (230 HV 5)	0.61
CuBe2	Peak hardened (410 HV 5)	0.27
Brass (CuZn40Pb2)	Drawn (175 HV 5)	1.9
Mg (99.5)	Hot swaged (146 HV 5)	73.0
AZ91	Cast (84 HV 5)	9.9
DISPAL (AlSi12C1)	Hot extruded	22.2
TiAlV65	Cold swaged (376 HV 5)	0.27
Steel (C100)	Cold swaged (247 HV 5)	0.74
Steel (St37)	(246 HV 5)	1.2
Alloy 400 (NiCu30Fe.5)	Heat treated 1200 °C/1 h (105 HV 5)	0.34
Alloy 75 (NiCr20Ti)	Cold worked (487 HV 5)	0.78
Alloy X (NiCr21Fe18Mo1)	Cold worked (354 HV 5)	0.97

S-shaped curve with saturation after a steep increase over about one time decade. The slow rise indicates a spectrum of time constants that can be estimated by the slope of the curve [5]. For a suitable choice of bending beam dimensions an absolute accuracy of about 3×10^{-5} is possible.

In Table 1 some relaxation strengths of engineering materials in the time range 3–3600 s at 20 °C are listed. Although these anelastic properties are very sensitive to structure, the table can serve as a rough guideline for long-time anelastic properties of some engineering materials at room temperature.

For the cast magnesium alloy AZ91 and for AZ91 with 20 vol.% alumina fibres the damping properties have been calculated from relaxation measurements compared with measurements of the logarithmic decrement [6] in the frequency range 30–50 Hz. The calculated and measured values agreed within the error limit of the relaxation measurements.

Acknowledgment

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