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Effect of microstructure on modulus loss at flexural mode and stress in sensor materials

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Abstract

Anelastic behaviour of metals, resulting from internal friction and responsible of modulus loss, is one of the major mechanical properties of materials considered in the design of high accuracy measuring devices and sensors which are generally used in mass, force, pressure and dimensional metrology. The level of modulus loss is important when high accurate measurements are considered in view of metrology. Hysteresis error is the main source of uncertainty in the measurement devices and related with loading and unloading. Modulus loss causes the hysteresis error on measurement when sensor or flexural element is made of anelastic material. The value of modulus loss of a sensor material can be changed by the application of proper heat and/or thermo-mechanical treatments. This study covers the attempts of determining the modulus loss values of copper–beryllium (Cu–Be), 17-4 PH stainless steel and AISI 4340 steel that are commonly used as material of sensor. An inverted pendulum system is used for the measurements of modulus loss and determining anelastic effects for the different sensor materials. Results show that modulus loss is influenced by microstructure of same material and differs form each other for different materials even when all are of the same hardness level. It was concluded that dislocation and precipitation mechanisms and their interactions can be assumed to cause modulus loss and its level.

Keywords: Modulus loss; Anelasticity; Cu–Be alloy; 17-4 PH stainless steel; AISI 4340 steel

1. Introduction

In view of metrology science, many metals show structural damping behaviour due to the modulus loss based on anelastic behaviour of material. On anelastic behaviour, energy is stored into the material but it is dissipated therefore the element is not returned to its original position. Anelastic behaviour of materials resulting from internal friction is responsible of modulus loss (ΔE) and it is defined as difference between stressed modulus (relaxed modulus) and non-stress situation (unrelaxed) of the material. It is proportional to stress applying on the material. Many crystalline materials exhibit anelastic behaviour, which is time-dependent and hence not purely elastic but completely recoverable. Anelasticity in metals resulting from stress and other thermo-mechanical changes in materials were emphasized as a source of internal friction and it was modeled the damping force as proportional to velocity of applied load on it by Zener [1]. Some mechanical models were used to describe damping as a sign of applied load in materials. Description of delayed response and damping can be determined by taking modulus of elasticity as a complex number by adding a damping term to the Young's modulus expression in the frequency-domain. The real part and the imaginary part of it represent in-phase restoring force and phase lag, respectively. The ratio of these values gives us modulus loss of the materials [2]. Yagmur et al. designed a new inverted pendulum can be used to measure modulus loss and determined anelastic effects of Cu–Be with different microstructures and mechanical properties [3].

2. Theory

Considering a spring, both the elasticity and damping in terms of a complex spring constant are expressed as "$\kappa[1+\mathrm{i}\phi(\omega)]$", where κ is the usual spring constant and the dimensionless parameter $\phi(\omega)$ is referred to as the "loss angle" due to internal friction of the material as a function of angular frequency [4,5]. In a material this type of loss is often characterized by adding a

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small imaginary part to the relevant Young's modulus [1,2].

$$E(\omega) = E_0[1 + \mathrm{i}\phi(\omega)] \tag{1}$$

In pendulum systems, quality factor (Q) involves the ratio of the maximum energy stored to the energy loss per cycle. In free vibration mode, Q is proportional to the ratio of amplitudes for two successive oscillations (A_n and A_{n+1}). Logarithmic decrement (η) in a damped but freely oscillation system is defined by $\eta = \ln(A_n/A_{n+1})$ and directly related (by a factor π) to measure of loss angle due to friction. i.e.; $\eta = \pi\phi$. Q of the resonance is equal to the quantity internal ϕ^{-1} and varies quite precisely as the square of the angular frequency (ω^2). Equation of Q is given by the ratio of the denominator's real part to its imaginary part of transfer function on resonance for the inverted pendulum and defined as follows [6],

$$Q = \frac{\omega_{\mathrm{p}}^2}{(\kappa/I) \times \phi(\omega)} \tag{2}$$

In this equation angular frequency is defined as $\omega_{\mathrm{p}} = 2\pi/T$ where T is the period of the pendulum and I is the inertia moment of the system with respect to pivot point of the flexure.

Relative modulus loss ($\Delta E/E$) can be determined using inverted pendulum and it is related with oscillation frequency, spring constant of the flexure, inertia moment and quality factor of the pendulum. In this study an inverted pendulum is used as a measurement device designed specially to supply work as torsion-strip pendulum [3]. The logarithmic decrement is related very simply to the modulus defect and stress is distributed uniformly along the length of the strip in this pendulum, i.e.; $\eta = \Delta E/E$. ΔE is the modulus loss and defined as $E_{\mathrm{U}} - E_{\mathrm{R}}$ which are unrelaxed and relaxed modulus, respectively [7,8].

The stiffness (κ) of the flexure element when under bending deformation is defined by

$$\kappa = \sqrt{WEI_{\mathrm{sec}}} \coth\left(L_{\mathrm{f}}\sqrt{\frac{W}{EI_{\mathrm{sec}}}}\right) \tag{3}$$

where I_{sec} is the inertia moment of cross-section, E is the Young modulus of the material, L_{f} is the effective length of flexure strip and W is the weight of overall pendulum, load acting on the flexure [8].

3. Experimental set-up

The measurement set-up is on a marble surface plate. A mirror is placed on the lateral surface of the rod. CCD camera and laser are set at correct angle using mounting post and its holder. A micrometer is placed for limiting stress. The pendulum rod was assembled to the samples, made of different material, at bottom. Oscillations were measured by using linear CCD camera, which monitored position of the laser beam reflected from oscillated pendulum. High resolution of laser beam spot position measured by "smart" CCD linear camera. A flatness mirror was attached to the lateral surface of the rod and "line generator" laser source was mounted to the base of the pendulum shown in Fig. 1 [3].

4. Details of samples

4.1. Design

Flexure elements were used as specimen. They were designed using ProEngineer CAD software, and were shown in Fig. 2. Screw threads and other geometrical features were machined using a CNC milling machine before cutting region of 320 μm (nominal value) in thickness. This part of the flexures was manufactured by using wire electro discharge machine (Sodick-AQ 325 L). Sand blasting as a surface treatment was applied after machining. Geometrical dimensions were determined using CMM after all machining process was finished. These dimension data was also used to determine effective length of the flexure in term of derivative changes along the critical length (Fig. 2b). The average thickness of the flexures (t) is about 320 μm ± 1.5 μm and length of the cutting section is 2.0 mm ± 1.5 μm. Surface roughness, R_{a} value was measured 1.8 μm ± 0.05 μm.

4.1.1. Microstructure and mechanical properties

The application of heat treatments on spring and flexure elements of transducers is a very effective method for attaining

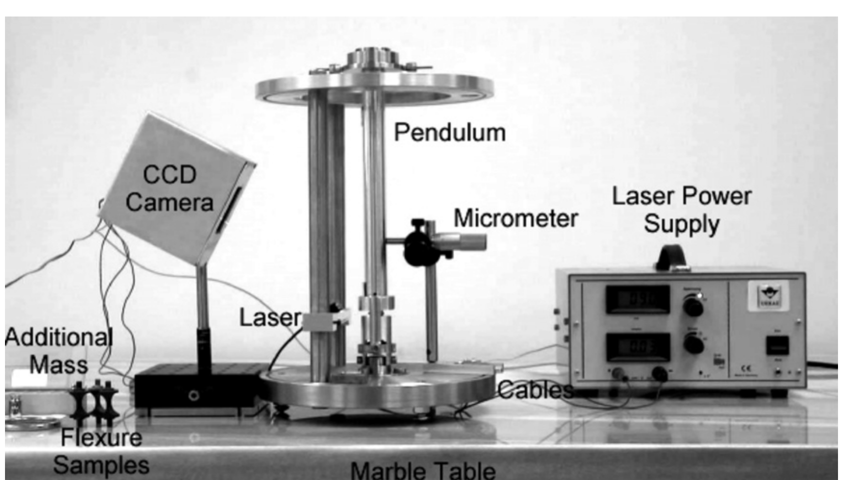

Fig. 1. The photography of experimental set-up both optical and mechanical parts mounted.