Impulse excitation technique for dynamic flexural measurements at moderate temperature

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(Received 30 December 1987; accepted for publication 29 February 1988)

The impulse excitation technique (IET), which is presently a precise and reliable technique for measuring dynamic moduli at room temperature, has been adapted to measure dynamic flexural modulus at temperatures in the range of 25° to 300 °C. This modified technique involves a sensitive microphone and electronics to record and analyze the sound waves emitted from a specimen vibrating in the fundamental flexural mode. The fundamental resonant frequency and geometry of the specimen are used to obtain the modulus. The location of the microphone relative to the specimen is critical and is a major factor once the specimen is placed within the heated environment. Problems were identified and solved, and test data for aluminum are presented to support the modification of the IET for use at elevated temperatures.

INTRODUCTION

Young's modulus is a property needed to describe a material's behavior in elastic deformation. Knowledge of a material's modulus as a function of temperature is particularly useful for designing parts for high-temperature applications. A new method has been developed to obtain dynamic modulus as a function of temperature by adapting an acoustic measuring device known as the impulse excitation technique (IET)[1] to measure flexural modulus at elevated temperatures. For materials that are essentially isotropic the values of flexural modulus and Young's modulus are equal. The IET is used to obtain dynamic modulus by measuring the fundamental resonant frequency of flexural vibration of a specimen after it has been excited by a light mechanical impulse (tap). The specimen is supported at its nodes of resonance (0.224L from each end, where L is the specimen length) and excited. A microphone located beneath the specimen receives the sound waves and passes the signals to the electronics box for Fourier analysis (Fig. 1). Within 3 s the fundamental resonant frequency is identified and then displayed in digital form. The frequency, and the length, thickness, and density of the material are used in the following equation[2] to calculate Young's modulus:

$$E = 0.94642 pL^4 f^2 T / t^2, \quad (1)$$

where p = density (kg/m^3), L = specimen length (m), f = frequency (Hz), T = a shape factor (dependent on Poisson's ratio), and t = specimen thickness (m). In this research, values of modulus at moderate temperatures were obtained by strategic placement of the microphone outside an electric furnace to analyze sound waves from a specimen tapped inside the furnace.

I. DEVELOPMENT OF THE MODERATE TEMPERATURE APPARATUS

The adaption of the IET to measure modulus at elevated temperature was carried out by obtaining an electric tube furnace and designing a special jig to hold the specimen with thin steel wires within the furnace. The furnace heating chamber was a 36-mm-diam horizontally split tube 300-mm long. The key factor in obtaining the modulus measurements successfully at moderate temperatures was the placement of the microphone outside the furnace. The routine arrangements for measurements at room temperature with the IET had the microphone located directly beneath the center of the specimen (Fig. 1). The distance from the microphone to the specimen was approximately 8 mm. The first question posed was whether the sound waves from a vibrating specimen inside a long cylindrical tube would propagate to the open ends without being altered. Several tests were performed with a cardboard tube (which simulated the furnace tube) and the microphone mounted securely on one end of the tube, and with the specimen and its support jig placed inside the tube. The results indicated that the waves would propagate with adequate intensity to the ends of the tube. The next step investigated was the performance of the same test with a furnace. The microphone was mounted at one end of the furnace tube (Fig. 2). A hole was drilled in the top of the furnace and a tube inserted to allow a means of exciting the specimen with small steel balls (of typical mass 250 mg). Again, several tests were performed at room temperature and these indicated that the detected signals were not consistent. Therefore, an L-shaped length of steel piano wire (1.6-

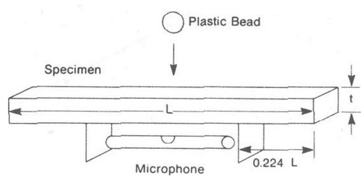

FIG. 1. The recommended setup for the operation of the impulse excitation technique (IET) at room temperature. The small projectile (such as a bead or small steel ball) causes the specimen to vibrate in the fundamental flexural mode and the microphone detects the resulting vibrations.

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mm diameter) was placed between the specimen and the microphone to act as a wave guide (Fig. 3). More testing led to the conclusion that the wave guide was incapable of carrying the sound waves to the microphone effectively. A decision was made to drill another hole in the furnace, directly beneath the specimen. This allowed the sound waves to travel on a straight, open air path to the microphone. The final arrangement of all the parts for the IET at moderate temperature is shown in Fig. 4. The distance between the microphone and the bottom surface of the specimen is approximately 12 mm. The tests showed that metallic specimens of approximate cross section 12×8 mm with lengths over 75 mm produced consistent results.

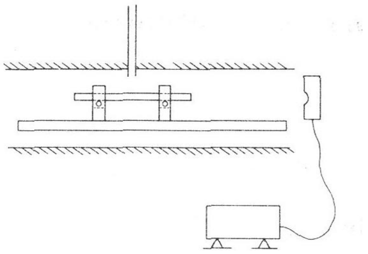

FIG. 2. The first arrangement explored for operation of the IET at moderate temperatures. The microphone is positioned on the end of the furnace tube.

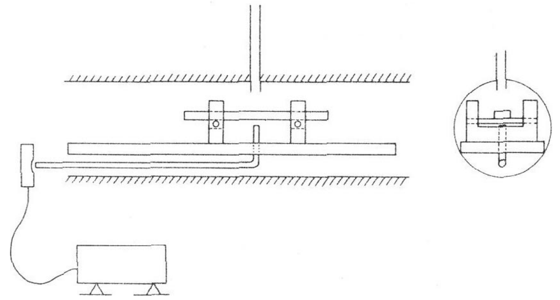

FIG. 3. Another test arrangement using a steel wave guide to transmit the acoustic vibrations from the specimen to the microphone outside the furnace.

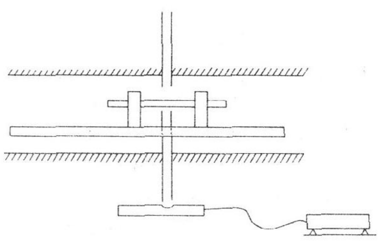

FIG. 4. The arrangement that proved to give the most reproducible results for dynamic modulus measurements at moderate temperatures with the IET. The microphone is located directly underneath the center of the specimen.

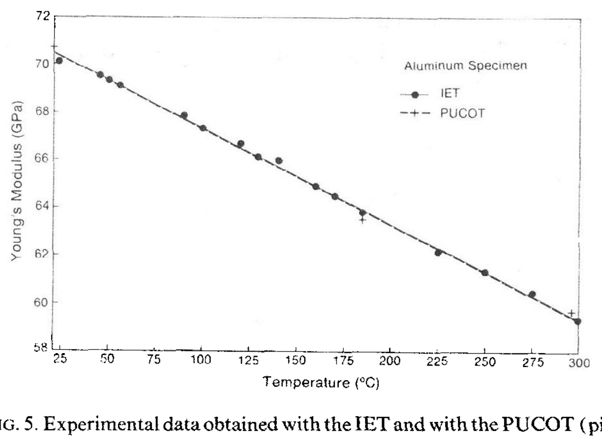

FIG. 5. Experimental data obtained with the IET and with the PUCOT (piezoelectric ultrasonic composite oscillator technique) for 99.99% pure aluminum over the temperature range 25° to 300 °C.

II. TYPICAL RESULTS

Measurements were made at room temperature with a pure aluminum specimen (99.99%). The results for Young's modulus agreed with published data[3] to within 0.25 GPa. Data at temperatures up to 300 °C were then obtained with the aluminum specimen and compared directly with data obtained on the same specimen using the PUCOT (piezoelectric ultrasonic composite oscillator technique).[4–6] A graph showing the results from both techniques and the linear relationship between modulus and temperature is presented in Fig. 5. Linear regression analysis for the two sets of data yielded

$$\text{IET: } E = 71.308 - (0.0398 \times T)$$
$$R = 0.994, \quad SEE = 0.125\ \text{GPa}; \qquad (2a)$$
$$\text{PUCOT: } E = 71.483 - (0.0406 \times T)$$
$$R = 0.990, \quad SEE = 0.550\ \text{GPa}; \qquad (2b)$$

with E in GPa and T in °C. The abbreviations R and SEE are the coefficient of correlation and the standard error of estimate, respectively. The imprecision in the value of the dynamic modulus obtained with the IET was estimated using a calculation method described by Kline and McClintock.[7] The results of this analysis showed that the imprecision in the value of the modulus was $\pm 1\%$.

ACKNOWLEDGMENTS

The authors are greatly indebted to Dr. Joseph Lemmens of Lemmens-Elektronika N.V., Leuven, Belgium for the loan of the GrindoSonic® instrument and for advice on its operation. Several colleagues have provided valuable suggestions and encouragement: M. R. Harmouche, S. J. Harbert, V. Cribb, J. Varughese, W. Chancellor, and S. Wickstrom. Great interest and encouragement have come also from R. C. Knight, M. Boyle, and R. Van Siclen of LTV Missiles and Electronics Division.

[1]The device used was the GrindoSonic® from Lemmens-Elektronika, N.V., Leuven, Belgium.
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