Pergamon

Scripta Metallurgica *et* Materialia, Vol. 31, No. 4, pp. 467-471, 1994

0956-716X/94 $6.00 + 00

NOVEL INSTRUMENTATION FOR QUANTITATIVE DETERMINATION OF ENERGY DAMPING IN MATERIALS AND STRUCTURES

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(Received April 4, 1994)
(Revised April 22, 1994)

1. Introduction

Damping refers to the ability of a solid to dissipate mechanical energy. For example, a billiard ball has a low damping capacity, since most of the kinetic energy is transferred from one billiard ball to another upon impact. On the other hand, a foam rubber ball has a high damping capacity, since most of its kinetic energy is dissipated upon impact with another object. Damping capacity may be characterized by the loss coefficient or loss factor, η, which is given by

$$\eta = \left(\frac{1}{2\pi}\right)\frac{D}{U} \tag{1}$$

where U is the total strain energy and D is the energy dissipated [1]. A factor of 2π exists in the denominator to normalize the value of η per radian, as most materials are tested for damping capacity under cyclic loading.

Damping test machines are generally large and bulky, and they require test specimens cut to specific dimensions. The method described in the present paper is able to test a specimen cut to practically any size and shape [2]. The present testing method was specifically designed for measuring the damping characteristics of teeth and dental implant structures, but can also be applied to a variety of other applications. This method is made possible by novel instrumentation and software that are used to determine the loss coefficient from the acceleration response of a mechanical probe.

2. Experimental Procedure

The present experimental system is interfaced to a Siemens Periotest, an instrument designed to make a qualitative assessment of tooth stability [3]. The Periotest has a hand-held probe that is used to tap a patient's tooth, denture, or dental implant with a force of approximately 5 N. The probe consists of a steel rod which is driven by an electromagnetic coil to impact the specimen 16 times in four seconds. An accelerometer at the back of the probe measures the acceleration of the rod during testing. The Periotest instrument averages the time duration of the stress wave pulse resulting from the impacts. The device then correlates this time to a numerical value corresponding a qualitative indication of tooth stability. In the present work, the accelerometer signal of the Periotest was interfaced to a 50 kHz A/D processing board housed in a personal computer (Figure 1). During testing, the Periotest and the specimen are clamped together horizontally, with the tip of the end of the probe casing placed against the specimen. The Periotest probe was also manually held up to the specimens for testing.

Using the acceleration data for the rod one can determine the loss coefficient of a specimen may be determined from an energy conservation approach. The total strain energy, U, is assumed to be approximately equal to the initial kinetic energy, E_k, of the rod just prior to impact. Upon impact, elastic strain energy, E_s, is returned to the Periotest rod in the form of a stress wave; the remainder of the initial kinetic energy is dissipated. Assuming that there are no significant sources of energy damping other than the specimen, we find that the energy dissipated, D, upon percussion is

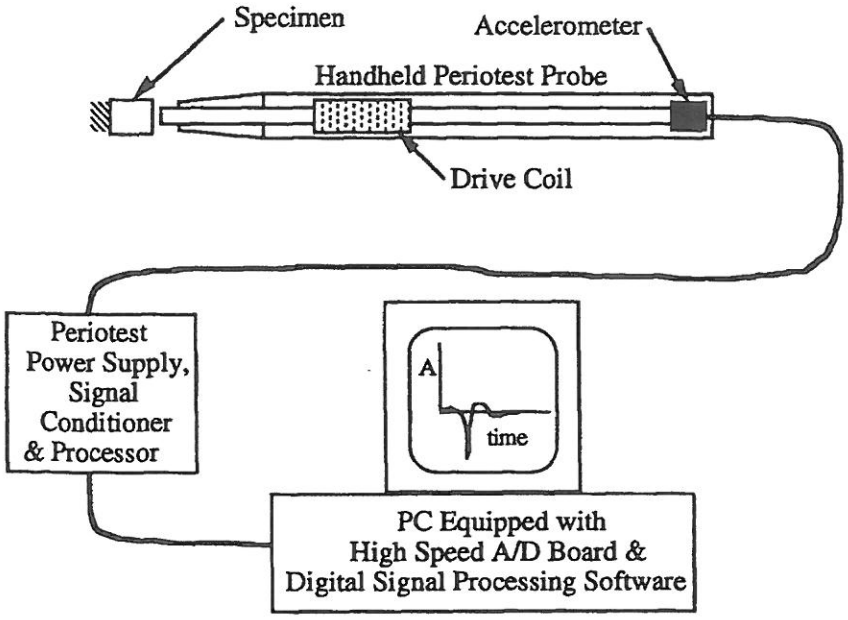

Figure 1. Schematic depicting the present material damping test system.

$$D = E_k - E_s. \tag{2}$$

Substituting Equation (2) and $U = E_k$ into Equation (1), we determine the loss coefficient for the specimen to be

$$\eta = \frac{1}{2\pi}\left(1 - \frac{E_s}{E_k}\right) \tag{3}$$

where

$$E_k = \frac{1}{2} m v^2, \tag{4}$$

$$E_s = \frac{1}{2}\left(\frac{m^2 a^2}{A^2 E}\right), \tag{5}$$

m is the mass of the Periotest rod, A is the cross-sectional area of the rod, E is the elastic modulus of the Periotest rod, a is the maximum acceleration of the rod as a result of the stress wave, and v is the velocity of the rod just before impact. The velocity of the rod is determined by numerically integrating the acceleration of the Periotest probe prior to impact.

The operator begins the test by actuating the Periotest and the computer gathers data as soon as the probe begins to accelerate the rod towards the specimen. The drive coil of the Periotest system automatically

shuts off as the probe approaches the specimen resulting in a probe velocity that is roughly constant prior to impact. The computer averages kinetic energy prior to impact and the maximum values of the kinetic and strain energies are determined from the data as illustrated in Figures 2 and 3. Specimens of carbon steel, teflon (polytetrafluoroethylene), and hard pine were used to evaluate the present technique.

3. Results

Figures 2 and 3 show the strain and kinetic energy versus time response for carbon steel and teflon, respectively. The average kinetic energy prior to impact, E_k, is calculated by the computer and is indicated by a horizontal line in Figures 2 and 3. The total strain energy, E_s, is equal to the maximum value of strain energy following impact. The values for E_k and E_s are then be substituted into Equation (3) to determine the loss coefficient. Typically, data from six to ten impacts are needed for adequate sampling of the loss coefficient for a given material.

Table 1 shows an example of data collected from a series of test runs with a teflon sample. The measured loss coefficients of carbon steel, hard pine, and teflon are given in Table 2 with their corresponding published values.

Table 1. Typical data for a teflon specimen.

Trial	E_s (J)	E_k (J)
1	1.05×10^{-5}	2.35×10^{-5}
2	9.2×10^{-6}	1.76×10^{-5}
3	1.04×10^{-5}	2.99×10^{-5}
4	9.0×10^{-6}	2.00×10^{-5}
5	7.2×10^{-6}	2.91×10^{-5}
6	7.3×10^{-6}	1.86×10^{-5}

Table 2. Comparison of loss coefficient values determined by the present analysis with η values published in the literature [4].

Materials	$\eta_{present}$	η_l
Carbon Steel	0.017	0.001-0.006
Hard Pine*	0.019	0.004-0.008
Teflon®	0.093	0.070-0.074

*percussion made parallel to the grain.

4. Discussion and Conclusions

The present damping measurement system was evaluated with the Periotest probe held horizontally and also with the probe held vertically. Values for the loss coefficient did not vary significantly for the different probe orientations. The present method has also been evaluated with the probe clamped in place and hand-held against the specimen. Again, the loss coefficient did not vary significantly for the two cases. Therefore, the present method is flexible in that it is not necessary to rigidly fix the probe or use it in a particular orientation.

It appears from the present results that better agreement with literature values could be achieved if

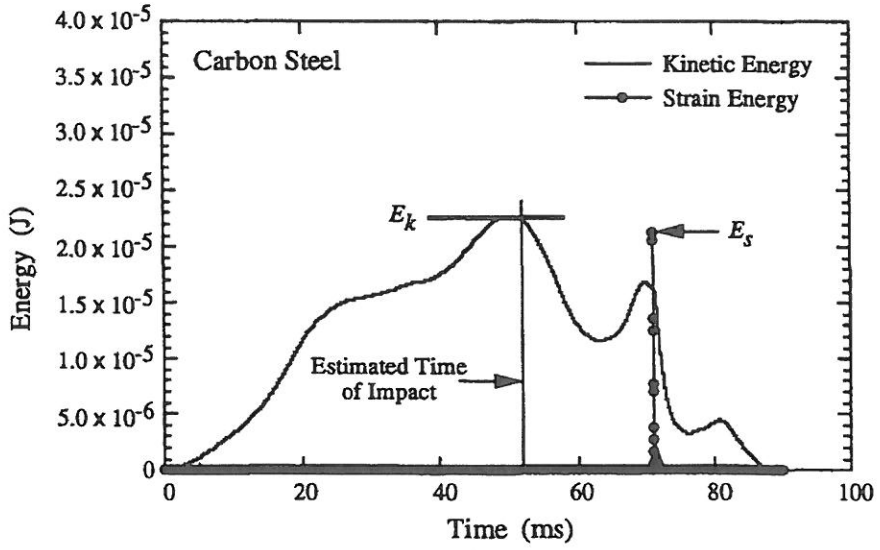

Figure 2. Kinetic energy of the probe and strain energy returned from a carbon steel specimen. versus time. The horizontal line corresponds to the average kinetic energy prior to impact.

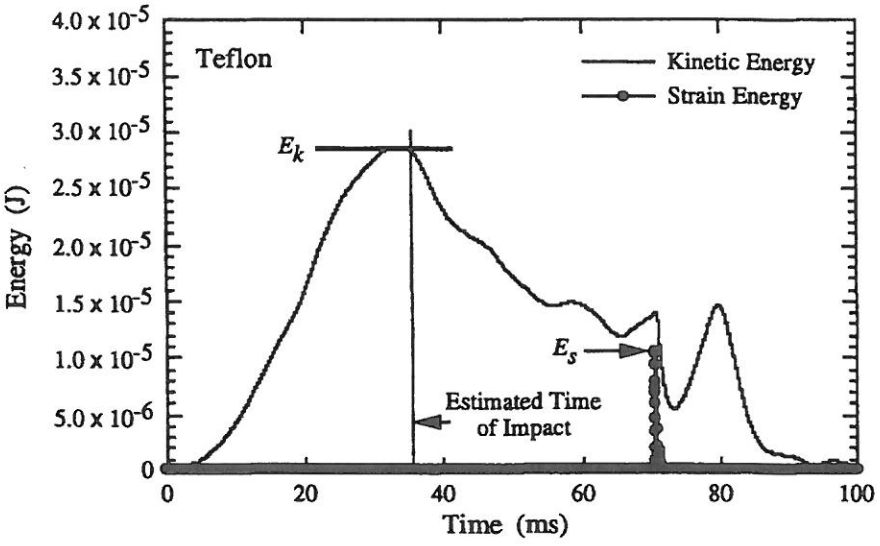

Figure 3. Kinetic energy of the probe and strain energy returned from a teflon specimen. versus time. The horizontal line corresponds to the average kinetic energy prior to impact.

energy losses due to other sources (D_p) were considered. For example, a small amount of energy is dissipated in the rod before the stress wave reaches the accelerometer. Therefore, Equation (2) can be rewritten as

$$D = E_k - E_s - D_p \quad . \tag{6}$$

Substituting Equations (6) and $U = E_k$ into Equation (1), we find the relation for the loss coefficient to become

$$\eta = \frac{1}{2\pi}\left[1 - \frac{\left(E_s + D_p\right)}{E_k}\right] \tag{7}$$

A calibration of the present technique for calculation of more accurate values of η would then consist of a determination of D_p. Accordingly, the calibration equation for the energy dissipated by the probe is

$$D_p = E_k\left(1 - 2\pi\overline{\eta}_l\right) - E_s \tag{8}$$

where $\overline{\eta}_l$ is the average value of loss coefficient reported in the literature for similar loading conditions. The value of D_p should not vary significantly with different material specimens since it primarily depends on energy losses in the Periotest probe. For $\overline{\eta}_l = 0.003$ for carbon steel (Table 2), Equation (8) gives a value of 2.0×10^{-6} J for D_p. Substituting this quantity into Equation (7) we find η equal to 0.005 and 0.079 for hard pine and teflon, respectively. A comparison of these values with the published η values in Table 2 indicates that much better agreement is achieved by including D_p in the analysis.

The accuracy of the η measurement technique could also be improved by an increase of the sampling rate of the data acquisition. This is evidenced by the relatively small number data points corresponding to the peak in strain energy shown in Figures 2 and 3. There is a distinct likelihood of underestimating the maximum value of E_s since there are only two discrete measurements near the top of this peak. This error is due to the relatively low sampling speed and is currently remedied by performing several tests with the same specimen to assure that a representative value of the strain energy is determined.

As stated in the introduction, materials are usually tested for damping under cyclic loading. The values of η typically depend on the loading frequency. The subject method only tests for damping under a single loading condition. Therefore, the present technique could further be refined if the loading was controlled and the values of η were matched with the published values for a corresponding frequency.

Acknowledgments

The authors would like to thank J. C. Radke of Bioresearch Associates Inc. and Drs. C. G. Sheets and M. C. Mensor for assistance in obtaining the Periotest instrument used in the present work. Support from the Committee for Instructional Development in the Office of Undergraduate Development at the University of California, Irvine is also gratefully acknowledged.

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