441. Vibroindentation tests for the determination of time-dependent mechanical properties

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Abstract. This paper is dedicated to the problem of nondestructive testing for determination of time-dependent mechanical properties of various materials. A new method, which is referred to as an adaptive contact impedance evaluation (ACIE) with respect to time, is considered herein. It is based on mechanical contact impedance evaluation (MCIE) at the local contact area between a piezoactive sensor and a specimen. The MCIA concept is based on the vibrational analysis of the motion response of a material or structure to a controlled excitation in the indentation. The opportunity of using vibroindentation tests to extract time-dependent flow property information was undertaken. These tests can be applied to various specimen geometries including small volume specimens. The fraction of specimens "damaged" in the test is small thereby enabling repeated or subsequent testing. Indentation creep and load-time measurements have been performed by using combined piezoelectric-magnetostrictive transducer. Composite transducers, consisting both piezoelectric and/or magnetostrictive materials with sectioned electrodes as well as divided winding coils and exploiting both direct and inverse piezoelectric and magnetostrictive effects were applied. These smart ACIE sensors are standing wave resonance devices and their design is based on changing modes and types of resonance vibrations in order to match contact impedance associated with different engineering materials. Dynamic response obtained from the experimental sensor highly correlates with time-varying mechanical and rheological parameters.

Keywords: Piezoelectric – magnetostrictive transducers, vibroindentation, contact impedance diagnostics, mechanical properties of materials, indentation creep and hardness.

1. Introduction

The life extension of fossil plants depends on the techniques for the accurate determination of time and service dependent material properties. A number of conventional nondestructive tests including X-ray diffraction, dye penetrate, ultrasonic and eddy current techniques have been successfully used in practice [1], therefore in recent years attempts have been made to apply these and other methods, based on the change of physical properties caused by material degradation, such as softening, embrittlement etc., for the prediction of remaining life. The characteristic feature of creep is the growth of carbides at the grain boundary and in the different phase composition. However at temperatures under 550°C the growth rate of carbides is very small so that the hardness measurement remains the most useful method [2-4].

One of the bases for the indentation test is the assumption that the mean contact pressure is independent of indentation time (i.e. the indenter comes to equilibrium with the solid being tested with the time that it takes to apply the full indenting load). If the indenter is still sinking

into the solid after application of the full load, the solid is said to exhibit indentation creep, which is therefore defined as the time-dependent motion of a hard indenter into a solid under constant load. Early recognition of damage primarily comprises the region of primary or secondary creep and the creep processes during indentation are dependent on indenter shape, and the behavior suggests comparable deformation patterns existing beneath all blunt indenters. Therefore, for indenters with indentation angles $2\theta < 120^o$ creep curves have a different shape, and it is known that the deformation patterns with sharp indenters tend to the theoretical plasticity mode of cutting and pushing sideways with no deformation beneath the indenter [2,4].
Although the fundamentals of the mechanical contact impedance evaluation (MCIE) method were first developed by Kleesattel and Gladwell 30 years ago [5], reliable systems based on MCIE have become available only recently due to advances in *mechatronics* [6], fast signal processing and new control algorithms. Consequently a new class of dynamic sensors made of piezoactive materials, e.g. piezoceramics and magnetostrictors, has been introduced [7-14].

The MCIE method is used for measuring the mechanical impedance at the driving point of a structure to be tested or the so-called contact compliance in the area of dynamic interaction between the indenter and the structure. The method is known as ultrasonic contact impedance evaluation, resonance sensing or acoustic flow detection. This method may be considered as a successful combination of existing classical methods and the ultrasonic technique. The method is applied under audio/ultrasonic resonance frequency for measuring the contact impedance and compliance that highly correlate with elastic constants of metals and mechanical properties, such as hardness [10-14] and contact force. Hardness testers have been marketed by Krautkramer (Germany) [15]. Cawley [16] reported the MCIE carried out at the audio frequency range and applied it to aluminium honeycomb structures.

Nowadays, a wide range of various materials having different properties has covered almost all engineering fields, from the automobile industry to space technology. Clearly, these materials require new testing methods and technical means. Elastic polymers, ceramics, steels, alloys and other engineering materials still lack sophisticated non-destructive and adaptive methods for detecting mechanical parameters on production line or during operation in the *time perspective*. For various materials with wide range of mechanical parameters conventional classical measuring methods are hardly applicable as it is very difficult to apply them to the time dependency to the evaluation of mechanical characteristics.

A new nondestructive testing method is proposed in the paper, which enables the extension of possibilities of MCIE. The method applies the basic principles of the MCIE. Based on the theoretical presumptions and experimental data smart ACIE sensors are proposed for measuring contact compliance and impedance simultaneously and adaptively adjust the measuring device to the structure to be tested. A dynamic response that is obtained from the sensor will be examined to determine if it correlates with Young's modulus, hardness, density and damping factor of different types of materials having different hardness.

2. Combined piezoelectric–magnetostrictive transducers and principles of the ACIE technique

Piezoelectric transducers employ the piezoelectric effect - direct conversion of mechanical energy to electrical via a material which changes its state, caused by polarization, when stressed (direct piezoelectric effect), or which changes its shape when an external electric field is applied (reverse piezoelectric effect). Magnetostrictive transducers are used to convert electromagnetic energy to mechanical or vice-versa. They are based on the phenomenon of a magnetostriction effect: when magnetostrictive materials are affected by the magnetic field, a change in their dimensions occurs. Conversely, mechanical stress causes a change in the magnetization. The direction of mechanical displacement depends on the magnetic field. Well-known magnetostrictive materials are such as: pure nickel, iron-cobalt alloys (e.g. Permendur), iron-rare earth elements (terbium, dysprosium) alloys, etc.

The generation of oscillations or static displacements in systems, consisting both of piezoelectric and magnetostrictive transducers is being carried on by both magnetic and electric fields or vice-versa. A multifunctional combined transducer - piezoelectric-magnetostrictive (PZMG) actuator/sensor represents a system with several input and output signals, which includes vectors of electric and magnetic fields (electric charges Q, magnetic fluxes W, electromotive UE(t) and magnetomotive UM(t) forces) and stresses or strains (displacements X(t)). By using this approach it is possible to combine low impedance input with the high impedance output, and vice-versa, in a single piezoelectric system. Such actuators/sensors can transform the frequency, amplitude and phase of the input signal, which can be magnetic or electrical, and mechanical parameters - stresses, strains, acceleration, temperature. In the simplest case, conversion between electric and magnetic energy is performed. This new class of transducers can be used in energy transformation, which plays a vital role in creating of piezomechanical devices. It combines fast dynamic response and opportunities applied to the flexible control in real time. Fabrication can be performed into complex forms, structures and arrays. Such piezodevices are ideal for precision mechanics, where incompatible requirements for accuracy, high speed, dexterity, efficiency and reliability pose a greater range of facilities applied to design. Important applications of combined transducers are sensorized piezoelectric - magnetostrictive actuators for microrobots, based on the transformation of high-frequency resonant mechanical oscillations into continuous motion, miniature pickups for magnetic field measurements, elements of intelligent devices and so on. It is also possible to create resonant sensors useful for the determination of time-dependent behavior of rheology, stiffness and hardness of materials. These measurements are based on the change of dynamic parameters in contact (amplitude, phase, frequency) of oscillating transducers in resonant and non-resonant frequencies, when they are applied to the surface to be measured [9-12].

The devices which are used to conduct a contact impedance evaluation consist of a vibroimpactor made of piezoactive material and an indenter which works as a waveguide. The vibroimpactor is supported at the nodes of resonance vibrations. The principle is shown in Fig. 1a schematically.

The vibroimpactor consists of piezoactive transducer(s): an actuator and a sensor. As it was described above, it can be made of piezoceramic and/or magnetostrictive material. The AC resonance frequency is maintained by the piezoactive actuator. The piezoactive actuator executes resonance oscillations and the piezoactive sensor senses an output signal due to interaction between a direct and inverse piezoelectric effect. The ACIE method uses an audio/ultrasonic technique which utilizes a standing wave. Various modes and forms of vibrations can be used. They can be generated either by selecting various topologies of electrodes (or active zones in the case of a magnetostrictor), or by sectioning electrodes on the same piezoactive material. As a rule, transducers are placed at the locations of maximum stresses associated with the utilized vibration mode. An output signal proportional to a change in contact impedance is obtained by measuring a change in amplitude (Fig. 1b), frequency and phase between an input and output signal. Various modes of vibration are applicable for the evaluation of the contact compliance in order to test mechanical properties of different materials. Only one important condition should be kept in mind: the stiffness/impedance of the vibroimpactor at the driving point should be of the same order of magnitude as the contact stiffness/impedance.

A concept of smart ACIE sensor implies the adaptivity of sensor to the structure to be tested [9-14, 17-18]. For instance, the range of adaptation in contact stiffness terms should cover the range from 200 N/m to 4000 N/m for the soft rubberlike polymers and hard steels, respectively. The smart ACIE sensor is illustrated in Figure 2.

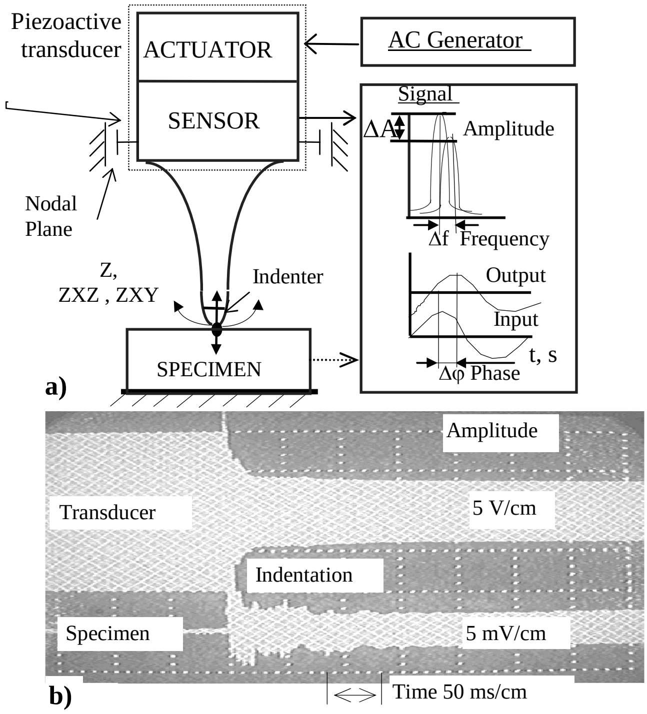

Fig. 1. Schematics illustrating the principle of mechanical impedance evaluation (a) and example of output response during indentation (b)

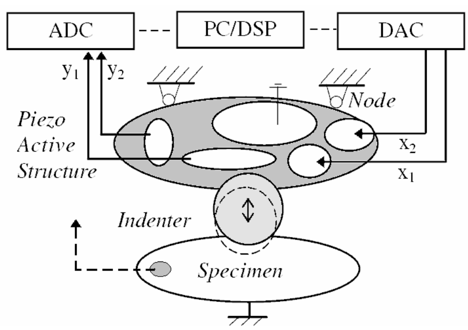

Fig. 2. Schematics of the smart ACIE sensor

The sensor consists of the piezoactive structure, where actuators and sensors have sectioned electrodes and/or magnetostrictive zones. Various modes of resonance vibrations can be generated in the piezoactive structures by executing actuators with the AC inputs $\{x_n, n=1,2,...\}$ and initial prestress could be adjusted via DC input ranging from 100 V to 200 V.

This allows us to build a smart ACIE sensor having mechanical impedances that differ several times. ACIE of different specimens can be performed within measuring trials by turning on the executing frequency. For example, rectangular shaped piezoceramic sensor could have four different mechanical impedances associated with longitudinal, flexural and rotational vibrations depending on excitation signals transmitted to various zones of the actuator. The challenge of the proposed new method ACIE is that smart ACIE sensors implies the adaptivity of the piezoactive transducer to the structure to be tested by its automatic selection of the vibration form and prestress range. In order to ensure ACIE stability, generation and control of resonance vibrations due to output signal $\{y_m, m=1,2...\}$ processing are performed numerically via PC/DSP- DAC-ADC circuit.

3. Analytical investigation

When plastic indentation is produced in a material, the latter must clearly experience some local permanent strain as a consequence of the deformation. Where geometric similarity holds, this representative strain will be independent of the size of the indentation; this is true of wedge, cone and pyramidal indentations. Indentations made with conical or pyramidal indenters differ in two ways from those produced with a sphere. First, the deformation patterns are geometrically similar whatever the size of the indentation, so that as the creep proceeds, the deformation pattern remains constant. With a spherical indenter the strains increase in magnitude as the indentation grows large. Secondly, for the more pointed cones the average strain produced during the indentation process is much higher than for a sphere. The effective included angle of an indenter plays a very important role in contact stress field. Following a suggestion by R. Hill [4], the indentation process is assumed to correspond to the plastic movement of a series of shells, concentric with the hemispherical core surrounding the indentation, into the bulk of the specimen. Strain hardening, while perhaps being the most familiar aspect of deformation from a qualitative viewpoint, is one of the most difficult to define quantitatively in a satisfactory manner that applies under all kinds of circumstances. In a creep test, a constant strain rate means that the creep strain is proportional to time, and so we see that when creep strain is proportional to time there is no strain hardening. Since stress is constant in a creep test, we must now ask what will happen to the creep rate when there is strain hardening. This question can be answered in terms of rate sensitivity. At least for metals, there is little change in the diameter of the indentation on unloading so that the conventional hardness test is essentially a test of hardness under load. However, since the depth measured during the indentation includes both plastic and elastic displacements, the elastic contribution must be subtracted from the data to obtain hardness. As illustrated in Figure 3, we have defined the plastic depth as the depth of indenter in contact with the sample under load. If the final depth rather than the plastic depth is used, a significant overestimate of the hardness will result due to the significant decrease in depth during elastic recover.

It is clear that when a conical indenter is pressed into a specimen, plastic flow occurs for the smallest loads and, on account of geometric similarity, the pressure will be constant whatever the size of the indentation. Some single measurements were conducted, which demonstrated that, although there was an appreciable recovery in depth, there was essentially no change in diameter of the indentation. Experiments indicate in a cross-section with an almost straight boundary its apical angle is slightly greater than that of the indenter. There is a difference in the increasing and decreasing part of the indentation. This is due to a slight creep during the repeated application of the load.

The position occupied by the different materials in the elastic-plastic spectrum, i.e. between the extremes of ideal elasticity (residual indentation parameter $h / a = 0$, $H / E = (\cot \theta) / 2(1 - \nu^2) = 0.15$ and ideal plasticity $h / a = \gamma (\cot \theta) = 0.26$, $H / E = 0$. It is important to reiterate that our analysis deals strictly with the mechanics of creep indentation. It is possible that different deformation mechanisms may have some influence on the similitude parameter γ. However, such effects are likely to be of secondary importance only, with all the more essential details of the micro-mechanical response concealed with the macroscopic parameters H and E. During loading the material deforms in a complex elastic-plastic mode. As can be observed in Figure 3, there are four main sub-processes in the deformation process of indentation testing: 1) load increasing region from zero to the total test force (force increasing process); 2) load holding (creep grow region) with the total test force (force holding-creep process); 3) load releasing region (force removed process); and 4) final region after load releasing (final process).

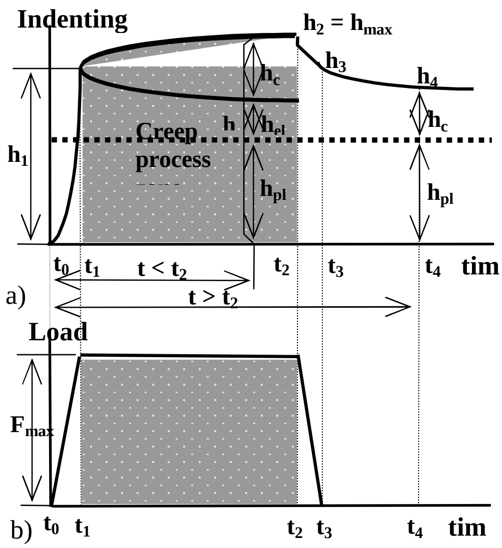

Fig. 3. Schematic indenting depth (a) and load (b) patterns versus time

Thus, over the loading path from the initial surface configuration at $h = 0$ to the maximum penetration at $h = h_2 = \gamma a (\cot \theta)$, the controlling material parameter in the deformation mechanics is the hardness H. The existence of a residual impression means that the load-displacement $F(h)$ curve must undergo some hysteresis on unloading and occurs elastically.

For creep analysis we measured the indentation depth at the end of the force increasing process h_1 and the indentation depth at the end of holding process h_2. In the force holding process, when the holding time increases, the indenting depth at the end of holding process, h_2, increases. The amount of creep during the loading process, $\Delta h = h_2 - h_1$, increases significantly when the indenting speed exceeds a certain value of speed V_0. The threshold value, V_0, differs for the hardness levels.

In indentation systems, increasing the “dwell time” - that is, the time over which the full load is applied to the surface-results in an increase in the size (depth) of the indentation and hence an apparent reduction in the hardness of the material. This effect is called indentation creep (Fig. 3).

Although strain hardening causes the creep rate to decrease in vibration indentation creep test, the rate of decrease is not controlled by the strain hardening alone. The constant stress prevailing in a creep test may be viewed as a balance between a tendency for increasing stress, because of strain hardening, and a tendency for decreasing stress, because of decreasing strain rate. The total distance moved down by the indenter h can be expressed as:

$$h = h_{el} + h_{pl} + h_c \,, \qquad (1)$$

where h_{el} - elastic component ($h_{el} = 2pa\,(1 - \nu^2 / E)$ and $p = E \cot \theta / 2(1 - \nu_1^2)$). It should be noticed that p depends only on θ and not on the size of the indentation; h_{pl} - plastic component, dependent on time but independent of the material; 2θ - apex angle of the indenter; h_c - time-independent creep component; $h_c = \int_o^\tau k\,(t - \tau)\ \sigma_c(\tau)\ d\tau$, where $k\,(t - \tau) = \gamma\, c\, e^{-\gamma(t-\tau)}$.

If in time t_2 the load is withdrawn, elastic recovery occurs, therefore in $t > t_2\ (p=0)$:

$$h = h_{pl} + h_c = h_p + \left(h - h_p\right) e^{-\gamma\left(t - t_2\right)} . \qquad (2)$$

In the vibroindentation tests we let load F be the harmonic longitudinal vibration of the support point and measure the displacement z of the indenter from an inertial reference. A static force is applied to make the indentation, but the contact area is measured by finding the increase in the resonant frequency of the resonator, which bears the indenter. Another measure to the specimen creep characteristics is the selection of proper mode of vibration. For sheet metal one will use tangential or torsional surface excitation instead of the normal one.

The measurements are made at the full load, while the indenter is in contact with the specimen. Therefore, no problems with the elastic recovery of the indentation are encountered. The indenters commonly used are not spherical, but conical or pyramidal therefore the corresponding problems related to irregular deformation process in contact for these indenters have been solved [3,4].

4. Experimental studies

Experiments were carried out in order to check the analytical analyses and dynamic vibroimpact model of the testing procedure. The main points of the experimental work were as follows: to find relations between electrical and mechanical parameters of the smart ACIE sensor as well as its output signal dependence on properties of testing material such as hardness, modulus of elasticity, stress, strain, density and loss factors; to obtain optimal parameters of the vibroimpact tester such as measuring accuracy, sensitivity range, measuring scale, reliability and stability of vibroimpact loading; the dependence of the output signal on geometrical shape of the indenter and applied load forces and time-dependence. Obtained results enable the selection of the best design of the sensor and adjust measuring and control algorithm for the ACIE [9,12].
An example of a typical output signal is presented in Fig. 4.

Curve 1 in Fig. 4b indicates the dependence of output signal on the input signal frequency when the indenter is not loaded F_{stat}=0 (the resonant frequency in that case is f_{R0}=76625 Hz). Curves 2÷7 show the change of the amplitude and resonant frequency of the output signal (input sinusoidal AC signal amplitude is constant - 10 V), when the indenter is loaded with the force F_{stat}=10 N to the specimens made of steel with different hardness values.

Transient period during the mechanical impedance test is illustrated in Fig. 1b. A sharp change in mechanical impedance is observed. A transient period was found to be less then 50 ms, when loading speed was 0.11 mm/sec. A compliance test should be performed by loading an indenter with a static force. The static force should be applied at a constant velocity. The optimum range of velocities was found to be 0.05 - 0.2 mm/sec.

Figure 4 illustrates the changes in the indentation depth according to the length of the force holding process time. As observed in figure 4, for both h_2 and h_3 (see Fig. 3) the indentation depth increases when the force holding process time increases. The data generated from the loading curves (see Fig. 3) deviate significantly from those obtained from individual indentations with optical measurements at small depths. The stress relaxation (under the indenter) during the various hold time is greatest for the smallest indentations with the highest strain rates. This clearly demonstrates that the strain rate sensitivity can contribute to the hardness size effect.

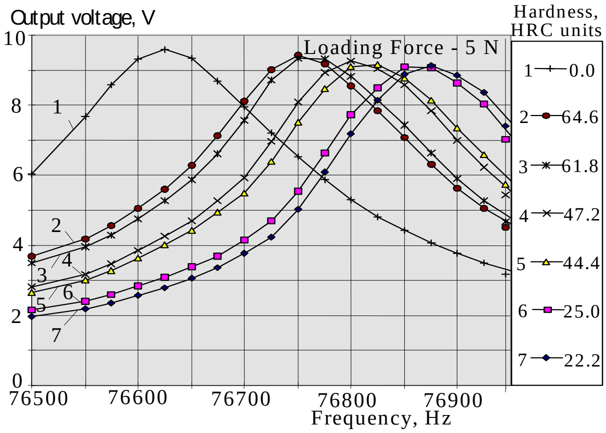

Fig. 4. Example of the dependence of output signals, obtained from the piezoactive sensor, on mechanical properties of specimens

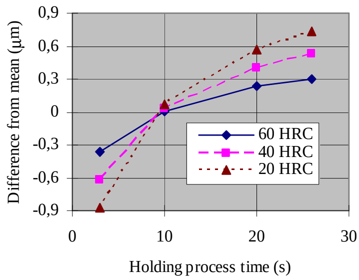

Fig. 5. The changes according to holding process (creep) time in indentation depths - residual indentation depth h_4 (see Fig. 3)

As is proven experimentally, impedance test should have a high sampling frequency in order to obtain reliable dynamic response caused by the vanished standing wave of free vibrations. Obviously, an impedance test should be carried out at the steady state of ultrasonic vibrations.

5. Conclusions

A new non-destructive testing method was developed in order to determine the temporal variation of mechanical characteristics of various materials. The method is based on the simultaneous evaluation of mechanical contact impedance and compliance at the local contact area of the dynamic interaction between the rigid indenter and the elastic specimen. Vibroimpact action is induced by a piezoactive transducer that oscillates in a standing wave manner. Mechanical impedance of the smart ACIE sensor is adjusted to the range of acoustic contact impedance associated with the specimen by utilizing different types and modes of vibrations. Several resonance frequencies of AC and DC input signals can be combined in order to obtain dynamic response from different piezoactive zones.

The ACIE method was proven to be a successful combination of the existing classical micro-hardness testing and ultrasonic techniques including control.

When this evaluation method is applied to various materials and/or elastic structures, it has a great potential to be used as intelligent tactile sensor for characterization of unknown specimens.

The MCIA technique is found to be a sensitive and direct means for in-process monitoring of the overall state of a structure and can be integrated in control system for composite fabrication. It is a highly versatile tool for the determination of time-dependent mechanical properties of various materials as a function of material physical properties and state. This method is not subject to any constrains on specimen geometry and dimensions.

The presented model provides a useful approach to investigate creep process for various materials. It is clear that useful information can be obtained by using indentation experiments on this scale. Because the contact pressure is computed from the indenter displacement under load, special operator skills in the optical measurement of the diagonals of the indentation area are not required. It is suggested that the behavior reflects the transient creep properties of the material and that the growth of the indentation with loading time is determined by the rate at which the plastic/elastic boundary can diffuse into the specimen.

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