Modeling and algorithmic provision of dynamic indentation process

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Abstract. Subject of Research. We study the methods for determination of the physical and mechanical characteristics of materials based on parameters recording of a solid body-indenter impact interaction with the surface of the material under test. Among the methods considered, the method of dynamic indentation was chosen for further research. With the development of computing devices and electronic element base this method acquires new opportunities and advantages over the other methods of nondestructive testing. They are: the possibility of portable implementation of the device, an unrestricted control of products, the possibility of \(F-h\) diagrams construction and others. Method. We consider the application of the developed algorithm for the primary processing of a measuring signal obtained from a primary transducer under dynamic indentation. The results of the algorithm are compared with the results obtained from the ISPG-1 dynamic indentation device, previously developed at the Institute of Applied Physics of the National Academy of Sciences of Belarus. The results of the measuring signal processing were also compared with the results of computer simulation of the process of shock contact interaction by the finite element method. Main Results. An algorithm for processing of dynamic indentation primary signals is proposed. A model of dynamic indentation process is proposed. It is shown that the developed algorithm and model are efficient and show similar results in comparison with the results obtained with the existing dynamic indentation device. Practical Relevance. The obtained results can be used in the development of the domestic analogue of the dynamic indentation device.

1. Introduction

At present, in the product production, it is necessary to determine and provide control over the mechanical characteristics of articles such as strength, hardness, modulus of elasticity. Traditionally, these properties are determined by direct methods of destructive testing on tearing machines or static hardness tester by the methods of Brinell, Rockwell, Vickers which include continuous insertion of the tip (diamond pyramid for the Vickers method [1], carbide ball for the Brinell method [2], diamond cone for Rockwell’s method [3]) to the test sample under the action of a smoothly increasing load, with the subsequent removal and registration of the displacement dependence from the load or other specialized installations for measuring the rate of incidence and rebound of the indenter by the method of Lieb [4], or measuring the height of the rebound by the Shore method [5].

At the same time, these tests necessarily require the production of witness specimens, which often leads to an inaccurate assessment of the product properties due to the inevitable difference in the material properties of the specimen and the material of the products under the test [6].

At present, the dynamic indentation (DI) is one of the most promising non-destructive methods for evaluating the mechanical characteristics of product materials, allowing to carry out non-destructive testing of not only mechanical, but also physical values of material properties.

The essence of this method consists in the shock introduction of a rigid indenter with a given kinetic energy into the test material with simultaneous registration of the implantation process [7]. The
registration of the implementation process means the continuous real time determination of the indenter motion parameters (speed, depth of penetration and contact force). The obtained changes in the values of the parameters of the indenter motion make it possible to make the transition to the contact force-introduction diagram $F(h)$ and to determine the mechanical characteristics of the material under study.

2. Methodology of measurements

The DI method is currently regulated by the standard\(^1\). It should be noted that the current standard does not establish certain methods for obtaining the primary measurement signal.

In this paper, the magneto induction method, which consists of recording the electromotive force (EMF) (Figure 1), induced in the sensor coil as a result of placing a magnet rigidly fixed with the indenter, is based on the device for recording the parameters of the indenter motion.

![Figure 1. A typical diagram of the change in electromotive force, obtained as a result of shock interactions.](image)

The values of $e_0$ and $e_{\text{min}}$ on Figure 1 characterize the speed of the indenter at the beginning moment of the contact interaction $t_0$ and the velocity at the end moment of the contact interaction $t_1$, respectively. The sections $\tau_{\text{act}}$ and $\tau_{\text{pas}}$ are called active and passive stages of impact. During the active stage of the impact, the elastoplastic deformation of the test sample occurs, and during the passive stage the indenter starts moving in the direction opposite to its introduction, under the action of the elastic forces accumulated in the sample.

The main advantage of this type of transducers is that their output signal - EMF $\varepsilon(t)$, in the permissible approximation, can be considered linearly dependent on the rate of penetration of the indenter $V(t)$ [7]:

$$\varepsilon(t) = kV(t),$$

where $k$ is the proportionality coefficient, which depends on the design parameters of the transducer.

The aim of this paper is to improve the accuracy of obtaining the dependences $V(t)$, $h(t)$, $F(t)$ from the primary transducer.

To achieve the goal, the following tasks were set:

1. The development of algorithmic support for the primary signal processing and obtaining the required dependencies;

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\(^1\) GOST R 56474-2015. Control of non-destructive physical and mechanical properties of materials and coatings of space technology by the method of dynamic indentation. It is adopted in 01/01/2016. Moscow: Standartinform, 2015. 22 p.
2. The development of the impact-contact model of the indenter interaction with the material;
3. Comparison of the results of the algorithm and the model with the results obtained from the ISPG-1 DI.

3. Material properties
As a material for the study, an exemplary measure of hardness MHB-1 66 HB was chosen. In the study of the material by the DI method, a spherical indentor made of tungsten carbide with a radius of 0.75 mm was used. The parameters of the material properties considered in this paper are given in Table 1.

| Parameters                  | Indenter          | Controlled material |
|-----------------------------|-------------------|---------------------|
| Material                    | Tungsten Carbide  | A measure of hardness |
| Material behavior           | Elastic           | Elastic-Plastic     |
| Density (kg/m$^3$)          | 15770             | 2640                |
| Young's modulus (GPa)       | 710               | 71                  |
| Poisson's ratio             | 0.31              | 0.3                 |
| Yield strength (MPa)        | –                 | 300                 |
| Tangent module (MPa)        | –                 | 500                 |

4. Algorithm for processing the primary signal
In this study, as the hardware implementation of the DI method, the ISPG-1 device developed at the Institute of Applied Physics of the National Academy of Sciences of Belarus is used. A transducer included in the ISPG-1 device was used to obtain the primary measuring signal.

The transducer is a device for curvilinear gravitational acceleration of the indenter and a measuring part consisting of a magnet rigidly fixed with the indenter and a measuring coil in which the EMF is induced in proportion to the speed of the magnet-indentor system [8].

![Figure 2](image)

Figure 2. Sensor with curvilinear gravitational acceleration: 1 - case, 2 - start button, 3 - swivel lever, 4 - indentor, 5 - magnet, 6 - coil, 7 - winding head.

An analog signal from the primary transducer was applied to the input of the WaveRunner WR 44Xi-A oscilloscope from LeCroy Corporation.

The signal was digitized at a sampling frequency of 5 MHz. In total, 10 measurements were carried out and digitized at the 66 HB exemplary hardness measure. The volume of each array was 10002 discrete samples. The oscilloscope worked in the mode of the increased resolution in 11 bits. The determination of the recording start time was carried out along the rising edge of the primary signal [9].
Figure 3 shows a set of 10 EMF curves obtained from the instrument transducer for a 66 HB hardness measure. All the dependences differ from each other in a random component (the noise of an analog-digital converter and others), as well as the insignificant difference in mechanical parameters on the surface of the hardness test piece [10].

Figure 3. Electromotive force variation curves for the hardness measure 66HB.

Figure 3 illustrates the input data in the form of 10 dependences of the EMF $E_i(t) - E_{10}(t+\Delta t)$, as well as the time difference $\Delta t$ between them. Despite the fact that in the course of obtaining experimental data the threshold value of the pulse front was a constant value, the beginning of the contact interaction for each curve occurs at different times.

The described inaccuracy in its majority is due to the imperfection of analog-to-digital conversion by an oscilloscope, and for its elimination it is necessary to center all the curves with respect to the transition through zero.

In the course of the experiment 76 hardness curves of EMF were obtained for a hardness measure of 66HB.

5. Algorithm for processing the primary signal

To identify an array of discrete values of the indenter velocity $V(t)$ from the EMF, the authors proposed an algorithm consisting of the following steps:

1. Analog-to-digital conversion of $e(t)$ at the output from the primary transducer and recording of the obtained discrete two-dimensional array in the computer memory.
2. Digital filtration of the received EMF array.
3. Approximating the discrete $e(t)$ dependence, preserving the coefficients of the approximating function, and generating a new two-dimensional array from the approximating function.
4. Selection and subsequent removal from the approximated array of areas that do not carry information about the process of contact interaction.
5. Reduction of the obtained dependence to $V(t)$ by elementwise division of the discrete dependence on the coefficient of proportionality (formula (1)).
6. Transition from the values of $V(t)$ to the dependences $h(t), F(t), F(h)$.

The last step of the algorithm is to apply the mathematical operations of differentiation and integration.

To determine the denting function of the indenter into the test material the integration operation should be performed:

$$h(t) = \int_0^t V(t) dt$$
To determine the dependence of the contact force on time, the previously obtained discrete array \( V(t) \) should be differentiated:

\[
F(t) = -m \frac{dV(t)}{dt}
\] (2)

Since all operations are performed with discrete arrays of numbers, then there is numerical differentiation, which is based on the approximation of a differentiable function. For the case of numerical integration, the method of rectangles is used in this paper.

The sign \(-\) in expression (2) indicates the direction of the applied force.

6. Modeling

The simulation of impact contact interaction by the finite element method is performed in an axisymmetric setting for a material with elastic-plastic behavior and a rigid hemisphere moving with a constant velocity at the moment of contact [11]. The results of the simulation allow us to construct an indentation diagram - the dependence of the contact force on the penetration depth of the indenter, necessary for calculating the physico-mechanical characteristics of the material being monitored.

Because of the axisymmetry of the problem along the symmetry axis (Y axis), the displacement in the X direction is zero (Ux = 0). The base of the material was fixed in the vertical direction (Uy = 0) [12] (Figure 4). The finite element grid consists of 6,500 curved isoparametric four-sided elements and is concentrated in the region of contact interaction [13]. In the study, when solving the modeling problem, bilinear kinematic hardening of the controlled material and elastic behavior for the indenter material are used [14]. As a result, the model of the shock contact interaction of a rigid sphere with an elastic-plastic material can be used to obtain mechanical characteristics of a material without carrying out full-scale tests, as well as to assess the requirements imposed on the controlled material: the minimum thickness of the controlled object, the roughness and the radius of curvature of the surface [15]. Modeling with different parameters of the indenter will increase the accuracy of data processing using the DI method.

7. Results

The implementation of the algorithm for processing the primary measurement signal was performed in the MATLAB software environment. As an input, 76 discrete samples of EMF values were used from the ISPG-1 primary transducer, previously obtained with an oscilloscope.

The algorithm performs the conversion of discrete EMF arrays that carry measurement results into sets of discrete velocity functions, contact force and the indenter intrusion in the test sample over time.
Also, the algorithm provides the possibility of constructing force–displacement curves for a series of measurements. Figure 5 illustrates the results of the algorithmic processing of 76 input data curves (figure 3) for a hardness measure of 66 HB. Due to the information overload of the picture, only the first 15 measurements are displayed.

![figure 5. Contact force-injection diagram.](image)

By analogy with figure 3, the curves in figure 5 illustrate the scatter of the maximum contact force, as well as an even wider spread for the values of maximum and residual intrusion. Such inaccuracies are primarily due to the imperfection of the primary transducer design and the error in performing the analog-to-digital conversion by the oscilloscope. The study of the influence of noise and quantization errors is not touched upon in this paper. It is assumed that there is a normal distribution of measurement results.

As noted earlier, the measurement results have a certain scatter value, which obeys the normal distribution law. On this basis, it is advisable to compare the results of the measurements processed by the algorithm and the results from the ISPG-1 DI instrument in terms of the standard deviation and expected value for the selected characteristic. As such a characteristic, the maximum injection was chosen. Thus, 76 maximal points were obtained from 76 discrete dependencies h(t). In the case of measurements on the ISPG-1 device, 40 values of h_max(t) were obtained.

For two samples of maximum values, the distribution density curves presented in figure 6 were constructed.
Figure 6. Density of distribution and expected values of simulation results.

It is not advisable to make a selection in the case of finite element modeling (FEM), since the results of the model depend only on the predefined characteristics of the material, and in the case of the invariability of these characteristics, the results will be repeated. Expected values and mean square deviation for samples of maximum implantations are given in Table 2.

Table 2. Values of statistical indicators.

|                   | Device ISGG-1 | Algorithm | Model |
|-------------------|---------------|-----------|-------|
| RMS deviation (μm)| 0,9308        | 1,023     | –     |
| Mathematical      | 36,31         | 36,02     | 35,96 |
| waiting (μm)      |               |           |       |

8. Conclusion

The algorithm of primary processing of signals of dynamic indentation is offered. A computer model of the process of shock-contact interaction of an indenter with a surface of a metal sample with a hardness of 66HB is obtained.

The results showing the operability of the developed model and the algorithm for processing the primary measurement signal are obtained. The expected value deviation of the maximal injections of the algorithm and the simulation from the expected value of sampling from ISPG-1 does not exceed 1%.

9. References

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