M. V. Lysyi, Cand. Sc. (Phys. and Math.), Ass. Prof.; A. I. Biliuk, Cand. Sc. (Phys. and Math.), Ass. Prof.; N. S. Kravchuk, Cand. Sc. (Eng.), Ass. Prof.; A. A. Biliuk

ESTIMATION OF YOUNG'S MODULUS, SHEAR MODULUS AND ELASTICITY LIMIT OF Al-Cu AND Al–Cu-Zn SYSTEMS USING THE MICROHARDNESS AND MECHANICAL SPECTROSCOPY METHODS

The paper estimates normal elasticity modulus E (Young's modulus), shear modulus G and proportionality (elasticity) limit σ_{pr} for aluminum alloys Al-2%Cu, Al-4%Cu, Al-4%Cu-1%Zn and Al-4%Cu-6%Zn using the microhardness and mechanical spectroscopy methods, which enables their wide application for obtaining standard as well as special mechanical characteristics of materials.

Keywords: *elasticity modulus, shear modulus, elasticity limit, microhardness, indentor, Poisson's coefficient, internal friction.*

Introduction

Elasticity modulus E (Young's modulus), shear modulus G and proportionality (elasticity) limit σ_{pr} belong to the most significant characteristics of the material elastic properties. They are widely used to calculate mechanical characteristics of springs, membranes, diaphragms, various aircraft devices and to evaluate wear resistance of operating components [1, 2]. However, for one and the same material these characteristics depend on a number of external and internal factors (thermal treatment, fiber direction, structure, chemical composition, etc.). E. g., aging of beryllium bronze leads to more than 20% increase of E [2]. For grey cast iron E could vary from 0.5·05 to 1.8·105 MPa (3.6 times) depending on the amount and nature of graphite, which plays the role of micropores [1].

The existing static means for determining these characteristics (tension, bending, compression) cannot be used for controlling finished products without breaking their integrity as it is necessary to cut out special samples for testing, i. e. to damage the component.

Therefore, to determine such characteristics as E, G and σ_{pr} of the finished product, it is expedient to use the contact deformation methods (the microhardness method) and the method of mechanical spectroscopy (internal friction).

Research materials and procedure

The paper investigates normal elasticity modulus E (Young's modulus) and proportionality (elasticity) limit σ_{pr} using the microhardness method as well as equations of Hertz and Mayer [3, 4]. Microhardness was measured by ПМТ-3 device. Shear modulus G (effective shear modulus f^2) was investigated by the mechanical spectroscopy method, using low-frequency device (~1 c-1) of the inverse torsional pendulum type [5, 6]. Dispersion-hardening alloys Al-2%Cu and Al-4%Cu, Al-4%Cu-1%Zn, Al-4%Cu-6%Zn, widely used in mechanical engineering, were chosen for the research.

Research results

The value of Young's modulus E was estimated by Hertz formula [4]:

$$d^3 = 6PR\left(\frac{1-\mu^2{}_i}{E_i} + \frac{1-\mu^2}{E}\right), \quad (1)$$

where P – indentor load (indentor is a diamond pyramid with an angle of 136° at the vertex between faces), d – diagonal of the indentation on the investigated part for given load P, μ_i – Poisson's coefficient of the indentor (μ_i = 0.07 [4]), E_i – Young's modulus of the indentor (E_i = 1140 GPa [4]), E – Young's modulus of the investigated material, μ – Poisson's coefficient of the investigated material, R – indentor radius at the vertex (R =0,7 mm [4]).

From equation (1) we find Young's modulus E of the investigated material

$$E = \frac{1-\mu^2}{\frac{d^3}{6PR} - \frac{1-\mu^2_i}{E_i}}. \tag{2}$$

Thus, to determine Young's modulus $\underline{E}$ of the investigated material for known values of μ, μ_i, E_i, and R, it is necessary to measure load P, acting on the indentor, and corresponding value of the indentation diagonal d. However, estimation of E for one load only will not always be reliable as the deformation / stress proportionality law is valid only in the first approximation. Therefore, E is determined as the mean value from a series of tests conducted in a certain range of loads. Thus, expression (2) could be rewritten as:

$$E = \frac{1-\mu^2}{\frac{1}{6Rn}\sum_{i=1}^{n}\frac{d_i^3}{P_i} - \frac{1-\mu_i^2}{E_i}}, \tag{3}$$

where n is a number of measurements.

Mean value of $\frac{d^3}{P}$ was taken from Table 1 and the mean value of Poisson's coefficient of the investigated material was determined according to Table 2 as the mean value, obtained from boundary values of μ for each material, which were collected from different sources [1, 4]. Averaging of μ was performed for alloy Al-4%Cu, which introduces an error ~1 – 4% in estimation of E for investigated materials (see Table 2).

Table 1

Load P, H		1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0
Al – 4% Cu	d 10^2, mm	9.03	10.55	11.98	13.19	14.19	15.94	17.55	19.04
	$d^3/P \cdot 10^4$, mm^3/H	7.36	7.83	8.60	9.18	9.52	10.13	10.81	11.50

Table 2

Poisson's coefficient of aluminum alloys [1, 4]

Material	Poisson's coefficient, μ		Boundary error $(1-\mu^2)$, %
	Boundary values	Mean value	
Aluminum alloys	0.31 – 0.34	0.325	1.1

Test values of E estimation by the microhardness method are presented in Table 3.

Table 3

Estimation of Young's modulus by means of static [7] and contact (microhardness) methods

Material	Static method $E_{st.}$, MPa	Contact method E_m, MPa	E_{st} / E_m
Al-2%Cu	78100	77000	1.01
Al-4%Cu	79200	78000	1.02
Al-4%Cu-1%Zn	79500	78400	1.01
Al-4%Cu-6%Zn	79550	78500	1.01

Procedure for determining proportionality (elasticity) limit σpr on the results of microhardness method application is based on different power indices in the dependencies of indentation diagonal d on load P in the elastic and plastic regions of Hertz and Mayer equations [3, 4], which are described by the following expressions:

$$P = \frac{1}{6R\left(\frac{1-\mu^2}{E}+\frac{1-\mu_i^2}{E_i}\right)} d^3, \;\; P = ad^n, \quad (4)$$

where a n – plasticity constants (the value of n is close to two).

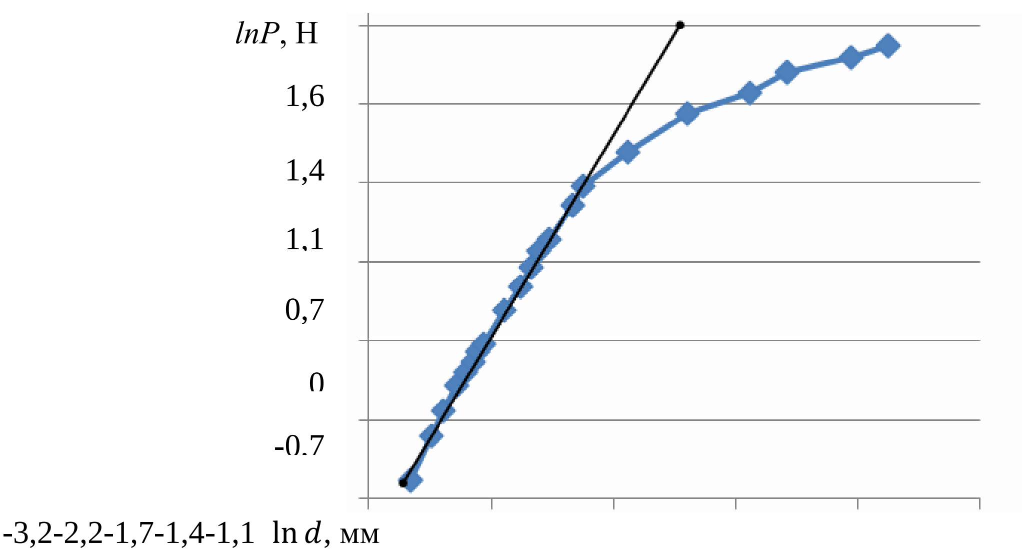

Fig. 1. Experimental diagram of microhardness of Al-4%Cu in logarithmic coordinates

Since power index in Hertz equation is equal to three and in Mayer equation – to about two, so if these dependencies are presented graphically in logarithmic coordinates, in the transition from elastic to plastic region an inflexion point will be observed due to different power indices in Hertz and Mayer equations. Then the load, which corresponds to the inflexion point, will match the boundary between elastic and plastic regions. The presence of inflexion point is confirmed well by the experiment (Fig.1). According to these diagrams P and d, corresponding to the first inflexion points, were determined. Elasticity (proportionality) limits σpr of the materials (see Table 4) were calculated by equations [7]:

$$\sigma_{\text{pr}} = 0{,}636 \cdot \frac{P}{d^2}. \qquad (5)$$

Table 4

Proportionality limits σ_{pr} for aluminum alloys

Material	Thermal treatment (hardening + tempering) K	$H\mu$, MPa	Microharness method, σ_{pr}, MPa	Tension method $\sigma_{\text{пр}1}$, MPa [1, 7]
Al-2%Cu	783+423	823	92	96 – 99
Al-4%Cu	783+423	930	105	110 – 112

Formation and stabilization of dislocation substructure in aluminum and its alloys [8, 9] is aimed, first of all, at improving their physical and mechanical properties. The use of these materials in mechanical engineering requires provision of improved and stable mechanical properties in wide temperature range.

Computation of shear modulus G was performed by the following expression [5]:

$$G=4\rho l^2 \frac{R}{n^2} K_T f^2, \qquad (6)$$

where n – the number of harmonics; R – calculation coefficient for samples with rectangular and round cross-section (determined in [10]), (R=1); KT – calculation coefficient taking into account temperature conditions of the experiments and geometrical relationships [10]; ρ – density of the material; l – the sample length.

Tables 5, 6 give the results of studying effective shear moduli $G \sim f^2$ for aluminum alloys and f^2 dependence on the temperature of the annealed alloy Al-4%Cu. According to dependence $f^2=f(T)$ reduction of f^2 after 573 K is observed. The studies [6, 8, 9] have shown that shear modulus undergoes significant changes at the temperatures of the hardening substructure formation and stabilization.

Table 5

Effective shear modulus f^2 for aluminum alloys

Material	Al-2%Cu	Al-4%Cu	Al-4%Cu-1%Zn	Al-4%Cu-6%Zn
f^2, c^{-2}	0.371	0.375	0.381	0.384

Table 6

Dependence of the effective shear modulus f^2 of the alloy Al-4%Cu on the temperature [6]

T, K	273	293	373	473	573	673	773
Al-4%Cu	0.405	0.375	0.364	0.356	0.345	0.347	0.338

Analysis of the results of studying effective sear modulus f^2, given in Tables 5, 6 and in [6, 8, 9], makes it possible to adjust thermal action on the material so as improvement of mechanical characteristics will be achieved, maintaining at the same time a sufficiently high level of damping properties, as well as to increase the structure homogeneity and to reduce warping of the components.

Conclusions

1. Mechanical characteristics of the aluminum alloys, measured by the microhardness method, are in good agreement with the results of mechanical characteristics estimation by the static method and errors of measurements with this method are in the range of 1 – 4 %.

2. Research results have shown that dependence of the indentation diagonal d on load P in logarithmic coordinates has an inflexion point due to the difference of power indices in Hertz and Mayer equations. Therefore, the load corresponding to the inflexion point will match the boundary between elastic and plastic regions.

3. Effective shear modulus f^2, measured by the method of mechanical spectroscopy, is in good agreement with this characteristic estimation by the static method since errors of measurements with these methods lie in the interval of 2 – 5%. In addition, investigation of shear modulus f^2 by the method of mechanical spectroscopy makes it possible to adjust thermal action on the material so that improvement of mechanical characteristics will be achieved with maintaining a sufficiently high level of damping properties as well as to increase the structure homogeneity and to reduce warping of the components.

Thus, the research indicates the possibility of wide use of the microhardness and mechanical spectroscopy methods in order to obtain not only standard but also special mechanical characteristics. This enables direct measurements of mechanical properties of the components without damaging them.

REFERENCES

1. Frantsevich I. N. Elasticity constants and elasticity moduli of metals and non-metals / I. N. Frantsevich, F. F. Voronov, S. A. Bakuta. – K.: Naukova dumka, 1982. – 286 p. (Rus).
2. Pastukhova Zh. P. Spring alloys of non-ferrous metals / Zh. P. Pastukhova, G. Rakhstadt. – M. : Metallurgiya, 1984. – 284 p. (Rus).
3. Mayer K. Physicochemical crystallography / K. Mayer. – M. Metallurgiya, 1972. – 21 p. (Rus).
4. Grigorivich V. K. Hardness and microhardness of metals / V. K. Grigorovich. – M. : Nauka, 1976. – 248 p. (Rus).
5. Mechanical spectroscopy of metallic materials / [Blanter M. S., Golovin I. S., Golovin S. A. et al]. – M. : MIA, 1994. – 256 p. (Rus).
6. Reguliarities in changes of mechanical characteristics of Al-Cu, Al-Zn systems during the substructure evolution / P. M. Zuziak, A. I. Biliuk, V. Y. Hodak [et al] // Physicochemical mechanics of materials. – 2002. – № 3. – P. 119 – 121. (Ukr).
7. Markovets M. P. Estimating mechanical properties of metals according to their hardness / M. P. Markovets. – M. : Mashinostroyeniye, 1979. – 196 p. (Rus).
8. Biliuk A. I. Impact of thermocycling under load on structural changes of precipitation-hardening aluminum alloys. / A. I. Biliuk // Physics of metals and innovative technologies. – 1997. – Vol. 19. – № 6. – P. 78 – 80. (Ukr).
9. Karbivskyi O. F. Impact of thermocycling on aluminum alloy polygonal structure / O. F. Karbivskyi, A. I. Biliuk, M. V. Lysyi, V. I. Savuliak // Technomus. – 2017, Romania. – P. 117 – 122.
10. Novik A. Relaxation phenomena in crystals / A. Novik, B. Berri. – M. : Atomizdat, 1975. – 472 p. (Rus).

Lysyi Mykhailo – Cand. Sc. (Phys. and Math.), Ass. Prof. of the General Physics Department.

Vinnytsia National Technical University.

Biliuk Anatoliy – Cand. Sc. (Phys. and Math.), Ass. Prof. of the Department of Physics and Methodics of Teaching Physics, Astronomy.

Vinnytsia Mykhailo Kotsubinskyi State Pedagogical University.

Kravchuk Nataliya – Cand. Sc. (Eng.), Ass. Prof. of the Department of Physics and Methodics of Teaching Physics, Astronomy.

Vinnytsia Mykhailo Kotsubinskyi State Pedagogical University.

Biliuk Anatoliy – Master's course student of the Department of Physics and Methodology of Teaching Physics, Astronomy.

Vinnytsia Mykhailo Kotsubinskyi State Pedagogical University.