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ENERGY CONCEPT IN COMPARISON OF STATIC AND DYNAMIC HARDNESS

Vytautas Vasauskas, Vytautas Čapas

Department of Mechanics, Kaunas University of Technology, Kaunas, Lithuania

Abstract – This paper outlines the development of a simple predictive model for comparison of static and dynamic hardness. The model is essentially based on the energy - balance considerations and uses work of indentation divided by deforming volume to define hardness. The dynamic hardness was evaluated from measurements of residual contact dimensions and continued force - displacement over the velocity range 1 to 10 m·s^{-1}, based on the energy loss models and the energy conservation principle. The total and reversible work of indentation, defined as the respective area under the loading and unloading curves, has also been studied. The correlation between the static and dynamic loading results is satisfying, indicating that the effect of velocity on the energy absorbing is negligible. The obtained value for several engineering metals of dynamic hardness was 1,12…1,40 higher than the static hardness.

Keywords: hardness, static, dynamic.

1. INTRODUCTION

Application of traditional indentation mechanics in the comparison of impact and quasi – static loading has been, for the most part, subject to limitations associated with difficulties in estimating impact loads and/or the dynamic hardness of the material. Static resistance to permanent deformation is described with the indentation Meyer's hardness, HM, which is defined as the ratio of the applied load, F, to the projected contact area, A, i.e. $HM = p_m = 4F / \pi d^2$. Consequently, at each load step beyond the onset of full plastic flow, hardness can be determined immediately from the load and the diameter of the circle of contact. Hardness HM also has a physical meaning, which has been recently explained as work to create a unit volume of elastic–plastic residual impression [1]. Since the deformation is volume process and it takes energy to induce it, the energy related definition of the hardness is more descriptive in particular in the dynamic hardness measurement, where the volume of the deformed material is hardly defined. An equivalent expression for the apparent hardness under conditions of impact loading is given by $H_d = W_o / V_o$, where H_d is the dynamic hardness, W_0 – initial kinetic energy absorbed in plastic deformation and V_0 is the volume of permanent indentation [2].

Some methods based on rigid body dynamics, elastic stress wave propagation phenomena, and microstructural analyses of the deformed regions [3-5] make it possible to get information about dynamic material behaviour. However, only in instrumented impact tests, the recorded force that the striker supports during the test allows the obtaining of information about the energy absorbed by the material [5, 6]. Dissipated energy is derived from of the whole load– displacement data obtained during the experiment by the described integration of force being a function of displacement. Elastic – plastic contact response produced under conditions of quasi – static and impact loading is quite similar, consisting of an approximately hemispherical region of irreversible deformation accompanied for brittle materials by median/radial or lateral cracks (Fig. 1). Volume of the indent is derived as an integral of the area of the indenter being a function of penetration depth and corrected by the factor of elastic recovery and the assumption that the total amount of material pile – up above the original surface is account in net volume V_d.

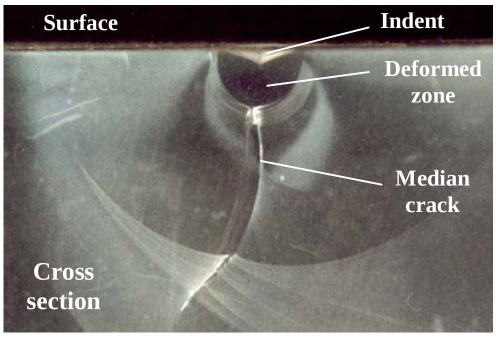

Fig. 1. Indentation zones in the sample of the PMMA

A complication arises, however, for soft materials, that exhibit strain hardening. Note that the diameter of indentation, d, is less than the diameter of the pile – up rim around the indentation, d^*, i.e. $d \approx d^* / c$, where c is depending on the work – hardening exponent of material n. The measured hardness of these materials typically increases with the indentation velocity. This may be the cause partly influenced by the fact that the geometrically necessary dislocation density decreases with increasing indentation size of the plastic zone beneath the indenter (Fig. 2). A simple argument reveals that the geometrically necessary dislocation density varies reciprocally with the strain rate and this can be used to explain the indentation velocity dependence on the hardness.

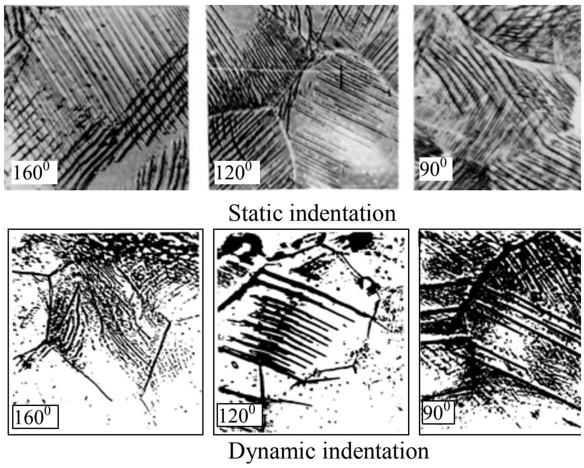

Fig. 2. Surface dislocation view of indentation in the static and dynamic loading for Armco – steel; cone $2\theta=160^0$, 120^0, 90^0.

In recently developed indentation testing methodologies loads and displacement are continually measured throughout an indentation process [7]. The contact time between the indenter and the specimen can also be precisely controlled and directly measured in this method to obtain an average strain rate during the dynamic indentation. Compared with the conventional hardness tests, it offers us complete information during indentation loading and unloading through the analysis of the measured indentation load – depth curve. Nearly all-standard instrumented indentation tests are carried out under quasi – static conditions. In the case of an impact problem, sample inertia and rate–dependent material behaviour adds to the complexity of the problem [8].

The purpose of this study is both to develop a method for determining the dynamic hardness that parallels the method for static hardness determination, and to verify the influence of the loading velocity on the constants appearing in the same cases of the indentation. As in the static hardness testing, load – depth is continuously measured and the dynamic hardness is determined by measuring the indentation volume on the specimen material.

2. BACKGROUND

In a conservative dynamic indentation system (Fig. 3) the total energy is constant, and the differential equation of the system striker – indenter – specimen can also be established by the principle of conservation of energy [9, 10]. The kinetic energy W_k is stored in the striker by virtue of its velocity, whereas the potential energy W_p is stored in the form of strain energy in elastic – plastic deformation or work done in a force field. The total energy being constant, its rate of change is zero, i.e. $W_k + W_p = \text{constant}$ and $d/dt\left(W_k + W_p\right) = 0$. There is a fundamental difference between static and dynamic hardness testing: in static tests the effective force acting on the penetration indenter is clearly and comprehensively determined throughout the entire process of indentation into the specimen [11]. In the case of dynamic indentation, however, the load (F) acting on the indenter changes during the course of the impact event (Fig. 6). To allow comparison between the kinetic energies at impact in various types of test the concept of the "equivalent impact energy" was introduced [10]. For a two-body impact problem this is defined as: equivalent impact energy W = energy input to the specimen up to the time when the masses m_1 and m_2 have a common velocity, where m_1 is the mass of the striker and m_2 is the mass of the indenter that is free to move (Fig. 3).

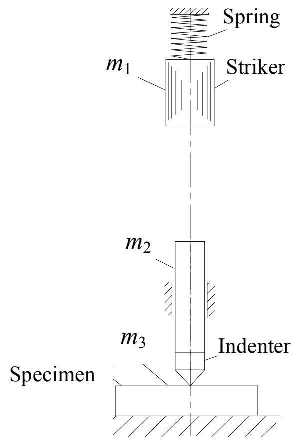

Fig. 3. Basic system for dynamic hardness measurement: striker – indenter-specimen system

Energy method is based on the analysis of the energy for the residual energy remains in the impact indenter of a spring activated device and present prior to impact

$$\frac{cs^2}{2} + mgs + W_f = \frac{mv_k^2}{2} \tag{1}$$

where $cs^2/2$ – potential energy of the spring system; mgs – potential gravitational energy; W_f – the energy consumed due to frictional effects along the path s, m – mass of impacting indenter, v_k -incident velocity.

Examining the case for progressively larger indentation depths, it is clear that energy for plastic deformation become increasingly significant and the energy balance will favour indentation more and more, i.e. the share of its contribution to the total energy will increase. The total energy expenditure will now be composed of two parts: the plastic work of deformation in the specimen (W_a), and the rebound energy, i.e.:

$$W_{tot} = W_a + W_{reb} \tag{2}$$

In the case of plasticity-dominated specimen response, the expenditure of energy may be assumed to be proportional to the plastically deforming volume. As the impact progress the pressure between the indenter-specimen increases until the peak pressure reaches the elastic yield limit of the specimen. In agreement with the introductory statements above the efficiency of the indentation process is defined as

$$\eta = \frac{W_a}{W_t} \tag{3}$$

where $W_a = \int F dh$ is the work performed on the sample as a result of a single representative impact, and W_t is the total kinetic energy of the striker. The kinetic energy of the rebounding is estimated from the measured coefficients of restitution depending on indentation geometry, impact velocity and specimen material. Thus, $W_t = W_t \cdot \eta_{tot}$, where W_a – all accumulated initial kinetic energy of striker, η_{tot} – total efficiency for the striker-indenter-specimen set is

$$\eta_{tot} = \eta_1 \cdot \eta_2 \tag{4}$$

where η_2 – loss of energy at the indenter-specimen impact for non-linear plastic deformation of cone indenter; for $k = m_1 / m_2 = 0{,}3 - 1{,}4$ and cone angles $2\theta = 80^0 - 160^0$ $\eta_1 . = 0.5 - 0.46$ [10]. According to Fig. 3, we have

$$\eta_2 = (1 - C_\theta^2)\frac{m_1}{m_1 + m_2} \tag{5}$$

where C_θ - restitution factor as function of indenter apex angle 2θ, m_1 – striker mass, m_2 – indenter mass. Then total efficiency of the dynamic system in our experiments was for various indentation angles in the ranges 0.33…0.50 [10].

The complete dynamic indentation procedure may be presented into the three following stages: starting phase, indentation phase and rebound phase (Fig. 3). During the striking phase the potential energy of the test specimen is converted into kinetic energy either by free fall or by a spring. Thus for a given contact geometry the intrinsic coefficient of restitution is uniquely determined by the degree of recovery and useful measure of the degree of reversibility of the contact deformation. The total work done by the indenter, W_{tot}, to cause and plastic deformation when the indenter reaches a maximum depth, h_m can be calculated

$$W_{tot} = \int_0^{h_m} Fh/3 = kh^3 \, H_M / 3 \tag{6}$$

where H_M is Martens hardness and is a direct measure of the total energy dissipated per indentation volume. Thus the force and work are proportional to h_m^2 and h_m^3 respectively [11]. The cross section view of deformed zones for static and dynamic indentation is shown in Fig. 4. The contours reveal that the plastic zone size is considerably smaller under dynamic indentation compared to the static indentation for similar loads. Furthermore, the width and depth of the plastic zone in static loading are one order of magnitude larger than the plastic zone in dynamic loading. This result shows that Johnson's cavity model about hemispherical plastic zone can be applied straightforwardly [9]. The agreement is consistent with the idea that the residual driving force for indenter is derived from an elastic accommodation of the hardness-impression volume and that the influences of indenter geometry and the indentation load on the residual driving force are completely characterised by the hardness-impression volume. Our deformation model assumes that the volume of impression produced by the impact indenter is proportional to the kinetic energy W, of the indenter and is dependent on its shape or tip angle, 2θ.

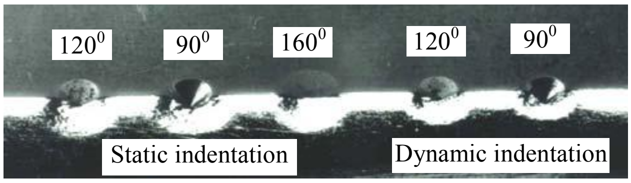

Fig.4 Micrographs of cross section view of deformed plastic zones for static and dynamic indentation for equal radii of indentation

The volume of a right cone with an apex angle of 2θ is

$$V_0 = \frac{\pi}{24}\cot\theta d^3 \tag{7}$$

where d is the diameter of the bottom of the right cone

$$W = V_0 \cdot w_o = \frac{\pi \, w_o}{24}\cot\theta d^3 = w_o k d^3 \tag{8}$$

where w_0 is the assumedly constant kinetic energy absorbed per unit volume of the deformed metal, and $k = \pi \cot\theta / 24$ is a geometric constant. Thus, the smaller plastic zones sizes (at given d) noted in Fig. 4 for impact loading suggest a dynamic hardness higher than the static value. However, a more complete analysis (a counting for strain hardening, nonproportional loading and far – field conditions) is needed in order to understand the full details about the active plastic zone.

3. EXPERIMENTAL

Static indentations were performed at fixed loads available on the standard static hardness machine. Loading and unloading were performed at a crosshead speed of $10^{-4}\, m/s$ and the load was held at its peak value for $10 s$. However, in the current dynamic setup, the load can be continuously varied between 0 and 30 kN by changing the striker mass m_1 and velocity. Six commercially metals were selected for the study. The specimen size was dictated by the supplied material thickness and also enough for load cell in dynamic loading. Similar to static testing, the indenter is placed in contact with the specimen before the striker is impacted. The indenter tip is made of a tungsten carbide cermet (85% WC and 15% Co compositions), which has a hardness of 80 HRA. Low – energy tests were carried out using a falling striker mass of 70, 127, 204, 503 g. The photodiode transducer that was used has a typical rise time of a few nanoseconds, providing adequate frequency response. Signal from the photodiode for measuring the intensity change was recorded using a two– channel Pico

ADC-212/100 PC digital oscilloscope at a 10M data points/s sampling rate, and analyzed by the computer. A good fringe contrast was achieved by making the fringe width slightly smaller than that of the diameter of the light beam from the input optical fiber.

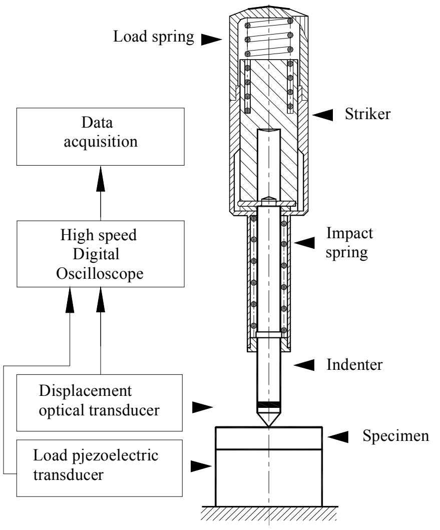

Fig. 5. A schematic illustration of the experimental set-up for dynamic indentation

For dynamic pulse measurements, the impact pulse length has to be significantly longer than the half-wave duration of the transducers lowest eigenfrequency, which amounts to roughly $2.5\ \mu s$ for $200\ Hz$. A high frequency piezoelectric load cell (0 – 30 kN load range), attached to a rigid support behind the specimen, is used to measure the dynamic load experienced by the specimen. At dynamic rates, a piezoelectric load cell is used. The resolution of the transducer is $\pm 1\ \mu m$. The computer controls the test data, controlling the different electrical subassemblies, and processing the data.

4. RESULTS AND DISCUSSION

A typical voltage signal generated in the load cell from a indentation experiment is shown in Fig. 6.

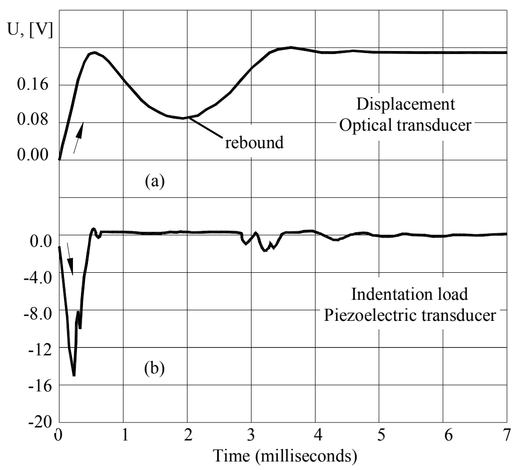

Fig. 6. Typical examples of (a) optical signal for the displacement and (b) piezoelectric force transducer signal for the load, during dynamic indentation

Unlike a nearly parabolic shape of the load – depth curve at the early stage of the indentation, the rate of increase in the load was substantially reduced at the later stages of the indentation. The rate dependence can arises from the sensitivity of flow stress to loading rate [3] or from environmental effects [9, 10].

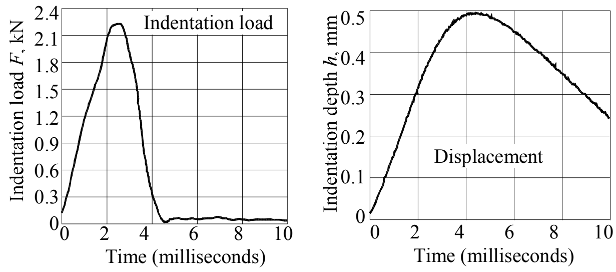

Fig. 7 Time – resolved signals for load and depth during dynamic indentation of aluminum impacted at $v = 2\,m/s$

To relate the hardness to plastic properties of materials, it is necessary to investigate plastic strain rate during dynamic indentation. As a second step to evaluate the strain rate sensitivity using dynamic indentation is load depth relationship due to sharp indentation

$$F = c\,h^2 \tag{9}$$

where c is a function or the indenter geometry and the mechanical properties of sample material. The work done by the indenter before the unloading is $W = 1/3\,c h_m^3$, where h_m is the maximum indentation depth at the corresponding impact velocity.

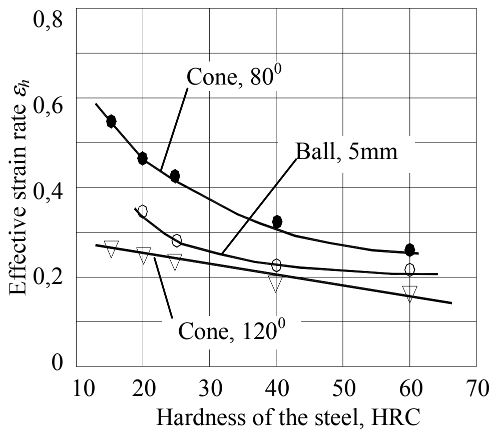

Fig. 8. Relation between hardness of material and effective strain rate for various contact geometry

The effective strain rate during dynamic indentation is defined as

$$\varepsilon_h = h_m / t \tag{10}$$

where h_m - maximum depth of indentation, t - impact duration time. The depth of indentation h when impact velocity is constant is great related to hardness of the material. The impact test is processed to determine the absorbed energy in the specimen through indentation. The energy equivalent of the difference between the starting and rebound phases is taken as a measure of the indentation characteristics in the specimen. Fig. 9 is a load versus displacement curves for the static indentation with various apex angles 2θ. The curve combines the results of loading and unloading the sample. Through use of load–displacement curves, indentation deformation energy can be portioned into its elastic, plastic and inelastic components.

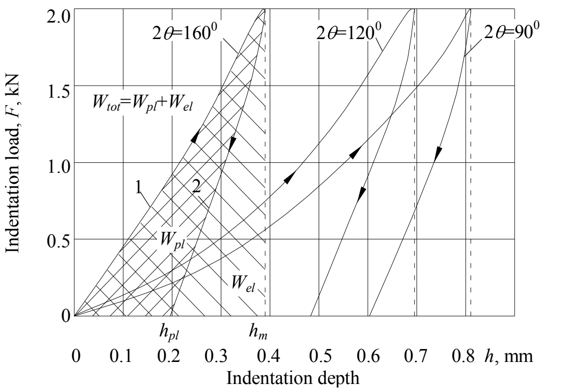

Fig. 9. Indentation curves of medium steel (AISI 1045) for different apex angles cone indenter: 1 – loading curves; 2 – unloading curve

Therefore for the giving constant values of the dynamic hardness for the testing specimen changes in kinetic energy of the impact could be not in changing of impact velocity of indenter's and height drop, but in changing mass of the impacting striker. This relation is constant of the impact velocity and verifies correlation between dynamic and static hardness values. Accordingly, our aim is to relate dynamic hardness at moderate velocities and compare the results with the corresponding static measures.

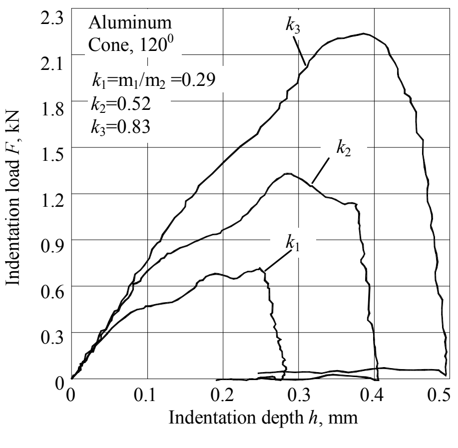

Fig. 10. Experimentally determined dynamic indentation response (load-depth, $F-h$) of aluminium subjected to various striker – indenter mass ratio

In Figs. 10 - 11, typical force – displacement $(F-h)$ curves recorded during the dynamic indentation tests carried out adopting the various indenters $(80^0 < 2\theta < 160^0)$, respectively, are shown. The different curves in each figure refer to different conditions of the impact. The effect of rate – dependent material response n dynamic indentation is to increase the materials resistance to indentation. This effect is illustrated in Fig. 11, which shows the dynamic $F-h$ curve for the case of steel AISI 1045. Rate – dependent plasticity has the effect of decreasing the peak depth compared to the rate – independent case. The reduction in peak depth, and thus in the final indentation size, shows how dynamic hardness values are higher under dynamic conditions. With the loads employed in our investigation, the diameter of the indentations is approximately 0.8…1.0 mm and the velocity of the indenter is around 2 m/s, giving a strain rate is $2 \cdot 10^3/\mathrm{s}$. In fig. 10 the load – depth curves are shown for different values of the parameter k defining the ratio mass m_1 and m_2.

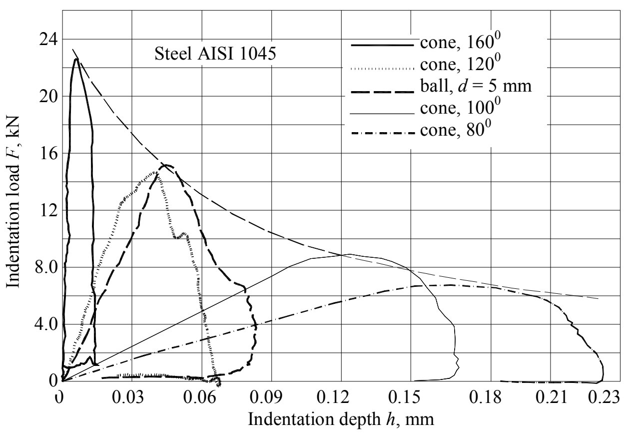

Fig. 11. Experimentally determined dynamic indentation response (load-depth, $F-h$) of medium carbon steel (AISI 1045 steel) subjected to various indenter geometry

There is no way of describing how to determine all these parameters in advance, thus the system can only be calibrated by comparing the resulting (F,h,t) diagrams with operator observations [7, 8].

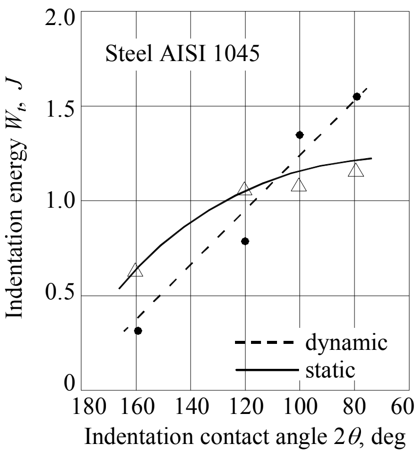

Fig. 12. Dependence of total indentation energy on the geometry of the indenter for static and dynamic loading

The total energy absorbed by the specimen is plotted in Fig. 12, where the plots are the average of three measurements. The energy is getting smaller to approach the value of the static case as the contact geometry decreases. The higher hardness in impact causes more extensive deformation, an increase in the elastic recovery of the depth of the residual impression, and a smaller plastic zone.

Dynamic hardness is 1,12…1,40 times higher the static hardness, because of the effect of strain rate on the deformation of material and friction affects. It was demonstrated [10, 11] that there exists an effective strain under sharp indentation condition for stress – strain characterization and that the effective strain is a function of indenter cone angle.

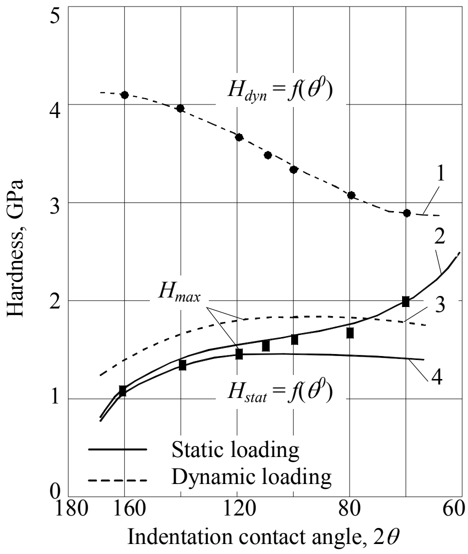

Fig. 13. Stress-strain curves (a) for static and dynamic indentation hardness: *1, 2*-contact friction unaccounted, *3, 4*-contact friction and efficiency of dynamic system striker-indenter-specimen set accounted

The dependence of hardness on cone angle is explained using the plastic zone size with respect to the contact area. The concept of representative strain is verified to be applicable to a broad range of materials.

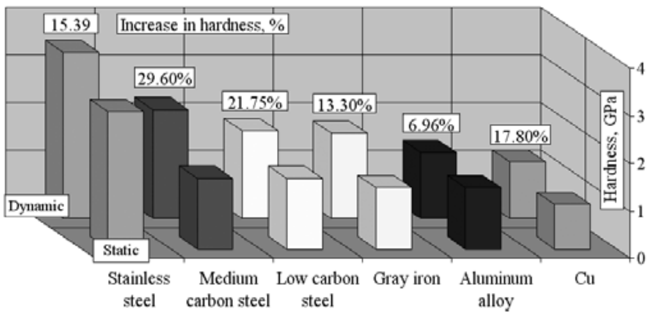

Fig. 14. Summary of static and dynamic indentation hardness maximum measurements for several commercial metals

The dynamic and static hardness measurements obtained from indentation diagrams for several metals are showed in Fig. 14. The percentage hardness increase in dynamic hardness maximum over the static maximum value, i.e. $\left(H_d - H_s\right)/H_s \times 100\%$, is also indicated on the top of Fig. 14. For steels this increase is between 13– 29% and for materials like aluminium and copper varies from 6– 7%.

5. CONCLUSIONS

The energetically evaluated indentation hardness measurement for static and dynamic loading has the same basis as the analysis of the conventional hardness. The dynamic hardness was found 1,12…1,40 higher than hardness determined by static indentation. Static and dynamic hardness test methods differ in principle only by the penetration velocity of the indenter, deformed zone size beneath the indenter and pile – up effect.

It is shown that the elastic and plastic properties in static and dynamic loading can be studied by deflecting energy balance method based on the measured load – depth response. The formation of impact indentations is much more complex than the formation of static indentation. The mechanism of impact-energy transformation seems to be more complicated than that of metal deformation.

REFERENCES

[1] D. Tabor, “The Hardness of Metals“, *Oxford University Press*, London, 1951.

[2] K.L. Johnson, “A Correlation of Indentation Experiments”, *J.Mech.Phys. Solids* 18, pp. 115-126, 1970.

[3] Y. Tirupataiah and G. A. Sundararajan, “Dynamic Indentation Technique for the Characterization of the High Strain Rate Plastic Flow Behaviour of Ductile Metals and Alloys”, *J. Mech. Phys. Solids*, vol. 39, no. 2, pp. 243-271, 1991.

[4] J.L. Bucaille, S. Stauss, E. Felder, J. Michler, “Determination of Plastic Properties of Metals by Instrumented Indentation Using Different Sharp Indenters”, *Acta Materialia*, vol. 51, pp. 1663-1678, 2003.

[5] E.W. Andrews, A.E. Giannakopoulos, E. Plisson, S. Suresh, “Analysis of the Impact of a Sharp Indenter”, *Int. J. Solids Struct.*, vol. 39, pp. 281-295, 2002.

[6] M.F. Doerner, W.D. Nix, “Method for Interpreting the Data from Depth Sensing Indentation Instruments”, *J. Materials research,* vol. 1, no. 4, pp.601-605, 1986.

[7] K. Herrmann, F. Pohlenz, K. Thiele, W. Würzner, “Calibration Methods for Universal Hardness Testers”, *Proc. of the Hardmeko 98, Standards Press of China*, pp.1-6. September 1998.

[8] ISO/DIS 14577-1.2, -2.2-3.2. “Metallic Materials – Instrumented Indentation Test for Hardness and Other Materials Parameters”, 2001.

[9] B.J. Koeppel, G. Subhash, “Characteristics of Residual Plastic Zone under Static and Dynamic Vickers Indentations”, *Wear*, vol. 224, pp. 56-57, 1999.

[10] V. Vasauskas, “Geometry Effect of Indenters on Dynamic Hardness”, *Proc. of the XVI IMEKO World Congress IMEKO – 2000, Vienna, Austria,* vol. III, pp. 343-348, 2000.

[11] Y. Cheng, Z. Li, “Hardness Obtained from Conical Indentations with Various Cone Angles”, *J. Mater.Res.*, vol. 15, no.12, pp. 2830-2835, 2000.

AUTHORS: V. Vasauskas, Ass. Professor. Kaunas University of Technology, Department of Mechanics, Mateikos 1-4, 50275, Kaunas, Lithuania, phone: +37037410707, E-mail: vytvas@ktu.lt; V.Čapas, Master of mechanics of engineering. Kaunas University of Techology, Department of Mechanics, Zuvinto 37-26, 51406, Kaunas, Lithuania, phone: +37061517105, E-mail: vcapas@ktu.lt