USE OF SEVERAL IMPACT PARAMETERS AT TESTING OF COMPLIANT AND ROUGH METALLIC ARTICLES BY THE DYNAMIC INDENTATION METHOD

A. Rabtchevich, P. Prokhorenko, O. Matsulevich, V. Rudnitsky, S. Starshinov
Institute of Applied Physics, Minsk, Belarus

Dynamic hardness meters are widely used in different branches of industry at present time. Dynamic devices are portable, easy to operate, accurate, allow to test large articles.

A principle of operation of dynamic hardness meters is based on applying impact of small energy with indenter against the material under test. The indenter has high value of hardness and during the process of its intrusion into article causes elasto-plastic deformation of metal. At the active stage of impact indenter moves with reducing of its speed into metal of a part under test. After a stop indenter begins moving outside under the action of indentation elasticity forces (passive stage of impact). A difference between indenter kinetic energies before and after the impact corresponds with the plastic deformation energy losses. Purchasable dynamic testers register impact and rebound velocity or only rebound velocity. A velocity restitution coefficient, which is calculated as a ratio of rebound to impact velocities, is a measure of article hardness (Shore hardness). A presence of stable relationship between static hardness of metals (Brinell, Rockwell) and velocity restitution coefficient allows to calibrate dynamic hardness meters directly in static hardness units.

Dynamic hardness meters have some shortcomings. Here we'll talk about restrictions, which limit dynamic testers on mass and thickness of the part under test. Modern devices provide specification precision only when testing articles have wall thickness in test area not less than 9-12 mm and local mass about 1.5-2.5 kg (depending on gauge parameters). Measuring of hardness of parts with lesser values of wall thickness or mass causes significant systematic error of measurement.

Significant contact forces in dynamic indentation, which are caused by short duration of impact process, are the reason of such limitations. E.g. for steels a duration of dynamic indentation process do not exceed 50 mcs. In case of applying impact with indenter with mass equal to 4 g and impact velocity equal to 2 m/s against article with hardness equal to 66 HRC maximum contact force reaches 700 N. Such significant forces causes an elastic sag of article wall when stiffness of the wall is limited. Some part of indenter kinetic energy spends on this process. It leads to device indication errors. It is empirically ascertained that if wall thickness is more than some value the influence of its limited stiffness on measurement results is negligible. Articles with wall thickness lesser that recommended value will be called compliant.

On purpose of testing of compliant articles by dynamic hardness meters in laboratory or plant environment attaching of tested part to massive base by means of consistent grease is used. If access to the opposite surface of tested part is lacking or this surface condition is too rough or has complicated profile, attaching of mass is impossible. Tubes is an example of such objects of testing. Attaching additional mass to working constructions like girders is also difficult. Solving of compliant objects testing problem is an important task from the point of view of working constructions safety, as well as for increase of productivity and manufacturing inspection possibilities of wide class of articles.

Investigations were made with the help of Impulse-2M device. Portable device Impulse-2M is designed for nondestructive express testing of hardness and ultimate strength of steel articles, it is registered in State list of measurement instrumentation (certificate № 3380) and is permitted to be used in Belarus. The device differs from other portable dynamic testers in method of initial data registration and processing, which makes it applicable both for investigations and for realization of techniques for minimization of negative factors influence. The device registers not a peak velocity values but the whole process of indenter intrusion into metal of article (fig. 1). A signal from gauge is converted into digital form with 5 MHz sampling rate and saved into device long-term memory. Then it is processed in a build-in pocket PC (PDA) by special algorithms. Processing involves noise filtration, reconstruction of amplitude continuous signal, integration and differentiation of the signal, calculation of elastic and plastic components of indenter displacement in accordance with the accepted model, calculation of indentation diameter and mean contact pressure in the indentation for every moments of measuring. The device keeps both a measurement results, which are accompanied by text comments, and indenter velocity array. The data can be transmitted into PC for unlimited storage in specially designed database and for monitoring the state of tested objects.

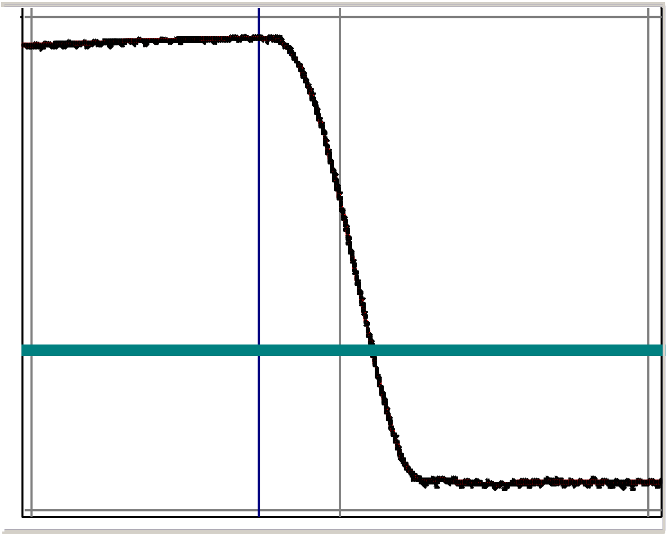

Figure 1. Dependence of indenter intrusion velocity on time.

It is obviously to suggest that decreasing of indenter impact energy leads to decreasing of device sensitivity to limited stiffness of article. Decreasing of the indenter kinetic energy decreases a contact force and accordingly article wall elastic sag. For investigation of an indenter impact energy influence on hardness measurement error sets of measurements were performed on samples in the form of tubes with different diameters and wall thickness (4-10 mm) with the help of devices Impulse-2M and TPC-4. Indications of the devices, obtained at limited stiffness of tested object, were compared with indications of the same device, obtained when tested object was attached to massive base. Systematic measurement error which was caused by limited stiffness of tested object was calculated as a difference between a means of sample. Tests showed that decreasing of the indenter kinetic energy from 9mJ (Impulse-2M) to 2 mJ (TPC-4) is not enough to get a significant decreasing of the systematic measurement error. At the same time indenter energy decreasing has a negative effect, which consists in increasing of requirements for quality of the article surface machining. Recommended values of roughness parameter Ra for device with impact energy of 9 mJ equals to 1.6-2.5 mcm, while the one for device with impact energy of 2 mJ cannot exceed 1.25-1.6 mcm.

Another way of the problem solving is a determination of relationship between true and measured hardness values of article with limited stiffness. A principle possibility of this approach results from monotonous character of relationship between hardness of article and error due to its limited stiffness. So it is possible to uniquely correlate device indications and true hardness of article. This approach has some significant defects. Main defect is a necessity of empirical relationship determination for every dimension-type of article. In the case of articles with inequable section profile a calibration relationship will be different for different test areas. Also our test experiments on a long-length tubes showed that device indications is very sensitive to an attachment of test article. I.e. measurement result depends on method and place of tested object fixation. These defects constricts possible application field of technique, which is based on device calibration by specific dimension-type of article.

Thus our investigations showed that approaches based on indenter energy decreasing or device calibration by specific dimension-type of articles with limited stiffness have insufficient effectiveness. It is preferably to find a more universal method, which is based on device-registered data about impact with minimum use of preliminary information about tested object parameters or without the one. It is obvious that use of indenter rebound velocity as a single registered parameter is not enough to realize such method because this parameter is sensitive to limited stiffness. Further investigations are based on the ground that device Impulse-2M allows to register a whole process of indenter intrusion into metal.

As an object of research steel tubes with diameters equal to 60-800 mm and wall thickness equal to 3.6-8 mm and plates with thickness equal to 4-10 mm were used. Tested area was finished to Ra1,6. Measurements were taken on the external tube surface and were subdivided into “compliance” – at cantilever fixing or without fixing (tubes lied on base) and “true” – when internal tube wall was attached to steel cylinder with lesser diameter. Also a special device, which allowed to take measurements on the cantilever fixed plate, was made. Plate stiffness was changed by changing a cantilever span. For an accidental error decreasing every test consists of 7 measurements, which were further used to calculate mean values of indentation parameters. Some characteristic hardness measurement results obtained with use a velocity restitution coefficient as initial data are showed in table 1. As follows from table limited stiffness of tested object can cause a significance systematic error of hardness measurement.

Table 1. Results of hardness measurement of limited stiffness articles.

N	Object of control	On massive base		Limited stiffness 1			Limited stiffness 2		
		Hardness, HB	Coefficient of variation	Hardness, HB	Error, HB	Coefficient of variation	Hardness, HB	Error, HB	Coefficient of variation
1.	Measure of hardness	232	0.0055	188	-44	0.051	161	-71	0.158
2.	Pipeline tube after 20 years of exploitation, wall thickness 7 mm	163	0.0567	154	-9	0.086			
3.	Tube ∅160, wall thickness 5 mm	130	0.3026	101	-29	0.0363			
4.	Tube ∅140, wall thickness 7 mm	156	0.0370	156	0	0.037			
5.	Tee 230x85, wall thickness 7 mm	166	0.0432	152	-14	0.093			
6.	Sheet, thickness 4 mm	128	0.0294	70	-58	0.046			
7.	Measure of hardness	269	0.0105	255	-14	0.008			
8.	Plate, thickness 4 mm	196	0.0165	176	-20	0.012	157	-39	0.030
9.	Continuation of p. 8	196	0.0165	147	-49	0.021	118	-78	0.048

Analysis of the indenter intrusion curves showed that a degree of limited stiffness influence on registered indenter velocity changes during impact. Active stage of impact is less sensitive to this factor than passive stage. Physically it is explained by different relation between plastic and elastic components of deformation on active and passive stages of impact. Phenomenological model of the process is shown on figure 2. As can be seen from figure at the active stage of impact elasto-plastic halfspace compliance C_1 is determined by sum of compliances: C_e –compliance of equivalent spring of indenter displacement elastic component, C_r – compliance of equivalent spring of indenter displacement plastic component, C_{eb} – compliance of equivalent spring of article wall elastic sag. Accordingly a halfspace compliance at the passive stage of impact – when elastic extrusion of indenter takes place: $C_2 = C_e + C_{eb}$. As $C_r > 0$, so $C_1 > C_2$ and

$$\frac{C_{eb}}{C_1} < \frac{C_{eb}}{C_2} \qquad (1).$$

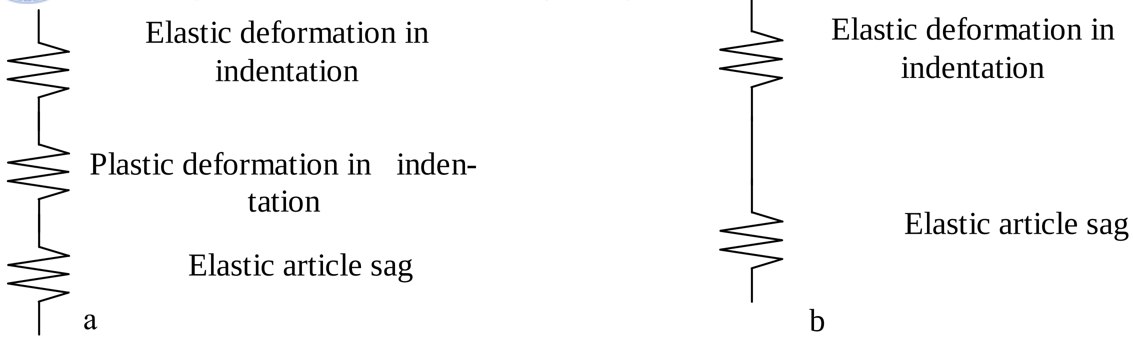

Figure 2. Simplified model of elasto-plastic halfspace.
a) active stage of impact; b) passive stage of impact.

Experimentally expression 1 is confirmed by course of dependence of indenter intrusion velocity on time at indentation of article with limited stiffness at free conditions and after attaching to massive base (fig. 3).

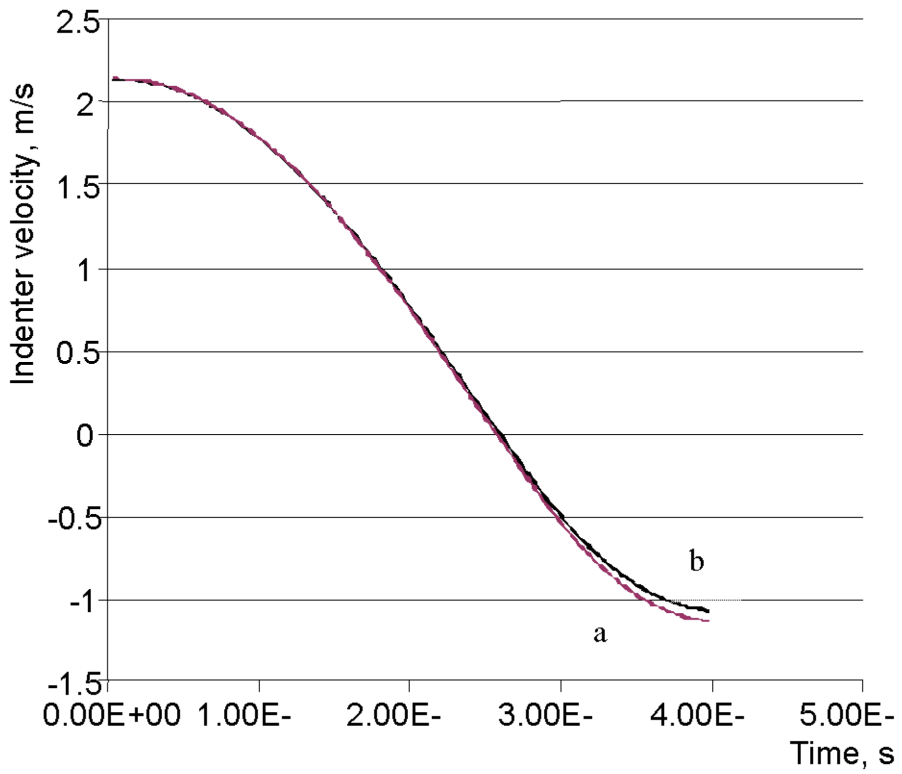

Figure 3. Dependence of indenter intrusion velocity on time.
a) infinite stiffness (halfspace), b) limited stiffness.

Analysis of 1500 measurements of low stiffness articles shows that dynamic Mayer hardness has minimum sensitivity to object stiffness and acceptable values of accidental error. Dynamic Mayer hardness is calculated as mean contact pressure in indentation at the end of active stage of impact.

On the basis of this fact a technique for minimization of influence of tested object limited (insufficient) stiffness was designed and built in device Impulse-2M. During a measurement device simultaneously calculates dynamic Mayer hardness and velocity restitution coefficient and computes a static hardness as a function of each of these parameters. If the difference between obtained values of static hardness is more than some acceptable value the device 1) shows that tested article has insufficient stiffness and 2) indicates static hardness, which is calculated by dynamic Mayer hardness. The build-in PDA power is enough to allow a comfort measuring time.

Table 2. Results of use of technique for limited stiffness influence minimization.

N	Объект контроля	On massive base		Limited stiffness 1			Limited stiffness 2		
		Hardness, HB	Coefficient of variation	Hardness, HB	Error, HB	Coefficient of variation	Hardness, HB	Error, HB	Coefficient of variation
10.	Measure of hardness	232	0.0055	211	-21	0.035	203	-29	0.051
11.	Pipeline tube after 20 years of exploitation, wall thickness 7 mm	163	0.0567	165	2	0.094			
12.	Tube ∅160, wall thickness 5 mm	130	0.3026	127	-3	0.0388			
13.	Tube ∅140, wall thickness 7 mm	156	0.0370	160	4	0.042			
14.	Tee 230x85, wall thickness 7 mm	166	0.0432	160	-6	0.071			
15.	Sheet, thickness 4 mm	128	0.0294	109	-19	0.025			
16.	Measure of hardness	269	0.0105	267	-2	0.026			
17.	Plate, thickness 4 mm	196	0.0165	177	-19	0.022	173	-23	0.038
18.	Continuation of p. 18	196	0.0165	161	-35	0.015	153	-43	0.039

The other defect of dynamic indentation testers is a restriction of surface roughness of an article. User faces this problem at incoming, outgoing and intermediate tests as well as in cases of field tests. For dynamic hardness meters, which calculate hardness as function of velocity restitution coefficient, the only way of reduction of surface quality requirements is to increase impact energy. It decreases a part of energy, which spends on deforming of roughness profile peaks and accordingly decreases a roughness influence on measurement results. To estimate an effectiveness of this method we compared hardness values measured on same samples by dynamic testers with different impact energies. Experiments were performed with the help of devices Impulse-2M and TPC-4. The results are shown in table 4.

Table 4. Influence of impact energy on hardness measuring error.

Hardness, HB	Ra, mcm	Error, HB	
		TPC-4	Impulse-2M
147	1,6	6,5	2,8
	2,5	9,5	5,0
	4,5	16,4	9,8
318	1,6	2,2	2,7
	2,5	17,9	13,4
	4,5	52,8	37,4

As can be seen from table 4, increasing of impact energy to 9 mJ (Impulse-2M) leads to significant decreasing of roughness influence on measured hardness values. It is obvious that further increasing of impact energy will reduce a restriction of surface roughness still more. For example an impact energy of hardness tester Equotip (Germany) with gauge G is 90 mJ. This device allows to test a surfaces with Ra7 but its application field is rather limited. This is caused by influence of local elastic deformations of article as a result of its limited stiffness or mass. For correct Equotip G application a local mass of article mast be at least 15 kg that makes using of this gauge practically impossible in majority of cases.

For estimating of surface roughness influence on the main dynamic indentation parameters a number of experiments were performed. The purpose of the experiments was to determine the potential of calculating of hardness as a function of the other indentation parameters besides a traditional velocity restitution coefficient. The results of experiments showed that velocity restitution coefficient and contact force at maximum displacement have a minimum sensitivity to surface roughness. Nevertheless hardness measurement error calculated as a function of these parameters exceeds the acceptable values. It follows that conventional method of hardness measuring as a function of only one parameter do not allows to test a rough surfaces with adequate accuracy.

With the purpose of estimating of effectiveness of hardness calculating as a function of two parameters a surface roughness influence on relation between the indentation parameters at different article hardness was investigated. As a result of performed investigations it was proposed to determine a hardness of rough articles in two stages. At first a value of hardness is measured as a function of one parameter, which is minimum influenced by roughness. This parameter is velocity restitution coefficient. Then obtained value must be corrected taking into account a parameter, which has high sensitivity to surface roughness. Our tests show that use of dynamic Mayer hardness is preferably, because this parameter allows to receive minimum accidental error. On the basis of obtained empirical relationships between velocity restitution coefficient and dynamic Mayer hardness algorithm of determination of static hardness of rough surfaces was developed. The algorithm allows to significant decrease a roughness influence on measured hardness (table 5).

Table5. Effectiveness estimation of two-parameters method of hardness measuring.

Hardness, HB	Ra, mcm	Error, HB	
		Determination of hardness as a function of velocity restitution coefficient	Determination of hardness as a function of velocity restitution coefficient and dynamic Mayer hardness
147	1,6	2,6	4,6
	3,2	5,4	6,8
	5,5	16,7	4,8
318	1,6	6,7	7,1
	3,2	23,5	4,9
	5	43,0	3,7
438	1,6	2,0	6,2
	2,5	4,6	6,0
	4,5	30,1	2,8

Conclusion:

Analysis of influence of limited stiffness and mass of tested articles as well as roughness of their surface on measured values of hardness is performed. Results show that conventional method of hardness determination by velocity restitution coefficient does not allow to test compliant or rough surface metallic articles with adequate accuracy because this parameter is very sensitive to mentioned negative factors. The area of application of dynamic hardness meters can be spread if the whole process of impact is recorded and used as initial data and the data is processed by the built-in PDA or similar high computation power chip. This approach is new to portable devices, it has been realized in portable hardness meter Impulse-2M. It allows to develop some techniques on accounting and minimization of influence of the negative factors. Using of developed techniques allows to test articles with wall thickness starting from 5.5-6 mm and surface roughness parameter Ra equal to 4-5 mcm with certification accuracy.