Article ID: 1003－7837(2005)02,03－0643－05

Miniaturized disk bend test－a new technique for monitoring the changes of mechanical properties of structural materials operating in extreme conditions

Tsepelev A. B.

(A. A. Baikov Institute of metallurgy and materials science of RAS, Moscow 119991, Russia)

Abstract: Method of Miniaturized Disk Bend Test (MDBT) originally designed for the tests of irradiated materials is a convenient technique for monitoring the degradation of mechanical properties of structural materials operating in extreme conditions. A small size of specimens (disks with 3 mm in diameter and 0.1－0.3 mm in thickness) as well as possibility to use the standard equipments for tension and/or pressure tests allow minimizing the financial charge for application of this method in practice and enable to keep up in the real time with (watch on) the changes of materials mechanical properties induced by the effect of unfavorable environment. Wide application of MDBT or other methods for miniaturized specimen tests does possible to inspect on the fly the changes of strength and ductility of the materials, and, of the expense of it, to prevent an alert conditions caused by the materials degradation, for instance, catastrophic embrittlement.

In the paper, methodical aspects of MDBT technique application for estimation of structural materials mechanical properties have been considered. By the example of own results and literature data, the possibilities of MDBT method are demonstrated as well as the correlation of obtained from this technique parameters with the standard mechanical properties such as strength, yield stress and ductility of metals.

CLC number: TB302 **Document code**: A

Forecasting of the exploitation characteristics of structural materials working in extreme external conditions, for example, at high temperatures, in corrosive environment, under radiation, etc, is usually based on the results of imitated or full－scale tests produced by the standard methods with the use of standard for each technique specimens. As a rule, a full cycle of such investigations requires a long time and a big cost. However, there are some cases when the carrying out of such tests is impossible.

So, for instance, conventional methods of the tests are no proper for the study of the effects of irradiation on the mechanical properties of metals and alloys because of the dig size of specimens. Neutron irradiation induced radioactivity of the specimens results in the number of technical and ecological problems, such as necessity the carrying out of postirradiation tests in special equipped "hot" laboratories, complexity of structure investigations for activated specimens, and need to bury of waste after the tests.

Besides, it is difficult to keep unchangeable conditions (neutron flux, specimen temperature) in the

Received date: 2005－08－29

full scale reactor experiments. A long duration of the reactor irradiation (2-3 years or more) implies a long term planning of the experiment and does not to conduct a prompt estimation of radiation resistance of promising materials.

Required radiation conditions can be realized much easily under the imitation irradiation with the use of charged particles accelerators. However, a large size of the standard specimens does not allow bringing about a uniform irradiation through the whole specimens area and volume in the accelerators, too. And a number of irradiated specimens will be low in this case that causes trouble to get statistical significant results.

For overcoming of these problems, the efforts were undertaken for development of new techniques for miniaturized specimen tests[1,2]. One of them, a Miniaturized Disk Bend Test (MDBT, or Small Punch (SP), or Microbulge) technique was proposed [3-17]. Such tests are carried out with the help of a simple device on a conventional testing machine in tensile or compression mode depending on the device design. Specimens are TEM discs 3 mm in diameter and 0.2-0.3 mm in thickness. As a loading member, a punch of various shape (cylindrical or conical with a flat, semispherical, or spherical end)[3-6,9,11,15,16], or steel ball ~1 mm in diameter[7,8,10,12,17], or loading ring [18-20] are used. As a result of MDBT, a curve "load—specimen deflection" is obtained, the form of which is determined by specimen materials properties and geometry of the test (specimen thickness, type of loading member, rate of deformation, etc.). On Fig. 1, a typical shape of MDBT-curve is presented for sufficient ductile pure metals and alloys, obtained at a flat-end cylindrical die application [11,13,15]. Extracted from such curve parameters, characterizing the material mechanical properties, are P_M — maximum load value; P_y — load of the curve deviation from linearity on initial stage of loading; W — the values of specimen deflections characterizing the material ductility. (W_0 — total deformation before specimen fracture, W_{pl} — plastic deformation, W_{el} — elastic deformation, W_{cr} —deformation connected with a crack propagation in the specimen fracture process).

One can see, simplicity of MDBT is complemented by clearness of the loading curves obtained that allows estimating qualitatively the strength and ductile properties of tested materials even without a quantitative treatment of the curves.

Unfortunately, a complicated stress state of disc specimens under the loading during MDBT does not allow doing a simple interpretation of quantity parameters extracted from MDBT—curves. But a number of experimental investigations of different metals and alloys show that, for instance, between strength MDBT—parameters and standard strength properties (tensile strength σ_B, yield stress $\sigma_{0.2}$) there are the simple linear correlations. Corresponding relations between W-parameters and, for example, elongation before fracture δ have a more complicated view, but in this case also a sufficient clear for practical application correlation dependencies can be obtained[5,7,9,12,14,21].

Area under the loading curve characterizes a specimen fracture energy J which by a simple way is correlated with a fracture toughness value obtained in the process of Sharpy tests[8,10,17,19]. When MDBT are carrying out at different temperatures, the change of J value allows determining a ductile-brittle transition temperature (DBTT), and on the base of this data one can estimate, for example, inclination of material to radiation embrittlement. Results of MDBT can be complemented with fractographic investigations with the help of scanning electron microscopy[8,10,18,20,22-25].

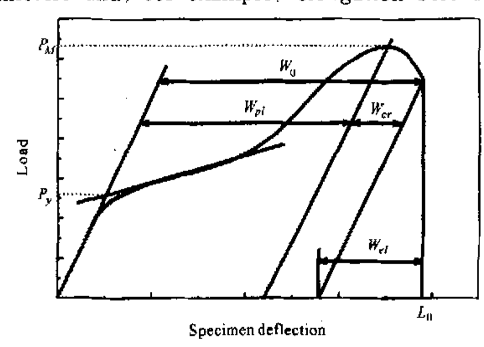

Fig. 1 Typical shape of MDBT loading curve for reasonable ductile metals and alloys P_M, Py—strength parameters; W — ductile parameters

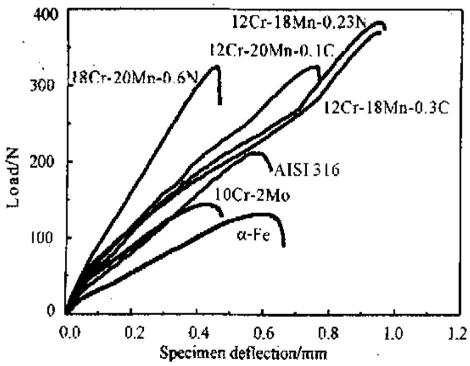

Fig. 2 Typical MDBT-curves for α-Fe and different steels in annealed condition

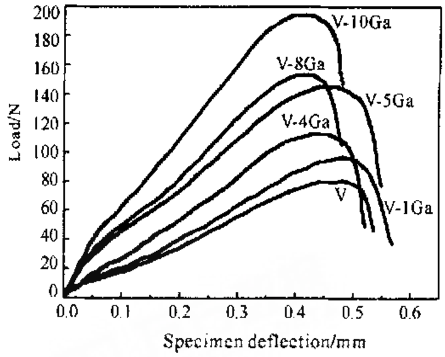

Fig. 3 Effect of Ga contents on MDBT-curves of V-Ga alloys

The most obvious and simultaneously complicated way of determination of mechanical properties of materials from the results of MDBT is calculation of the stress distribution in disc specimen under the loading. Knowledge of the actual stress and strain values in any moment of the test makes it possible to reconstruct a "load-deflection" curve to the true "stress-strain" one. As a consequence, the standard strength and ductility parameters of tested material can be obtained. Unfortunately, this problem can not be solved analytically. But it can be made numerically by finite element analysis at given law of the material deformation during the test. Such calculations provide a way for a physically clear qualitative explain of the main peculiarities of various parts of MDBT-curves[4], but in the literature there are not data on the use of such approach for the treatment of real MDBT-curves. However, it is worth noting that finite element analysis of MDBT were carried out recently for some practical important cases[19,26,27].

MDBT technique was developed and used in the first place for an estimation of the effect of radiation on the mechanical properties of metals and alloys for nuclear application[28−30]. And now with the help of this technique investigations of nanocrystalline, ceramic and polymer materials were carried out [18−20,31]. Besides, MDBT technique was used for evaluation of thermal aging embrittlement in stainless steel [32] and for study of steel dislocation deformation mechanisms[33].

As an illustration of MDBT method possibilities, we refer to the typical loading curves for the disk specimens of α-Fe and some stainless steels (Fig. 2). The loading curves for the steels even with similar composition are seen to be diverged considerably and these results show promise the MDBT technique as a method for rapid evaluation of changes of mechanical properties of materials.

MDBT technique was used in IMET RAS in the course of the work on development of candidate radiation-resistant V-based alloys. V-Ga and V-Ga-Cr systems were investigated. Effect of alloying with Ce on mechanical properties of these alloys has been studied, too. Increase of Ga content leads to improvement of the strength properties of V-Ga alloys without ductility loss, as indicated by Fig. 3. Comparison of dependencies of MDBT strength parameters P_M, P_y and tensile strength σ_B and yield stress $\sigma_{0.2}$ on Ga content indicates on a linear correlation between corresponding values (Fig. 4). As shown in Fig. 5, alloying of V-5% Ga (at. fraction) alloy with a small concentration of Ce makes the all mechanical properties worse, however additional alloying with Cr as well as increasing Ce concentration compensate a softening effect, but anyway ductility of complexly-alloying alloys is worse than for reference one. Data on the effect of electron irradiation (E = 2 MeV, fluence 7.5×10^{18} cm^{-2}, T = 300 ℃) on the properties of V-Ga-Cr-Ce alloy establishes that radiation strengthening takes place and simultaneously tendency to a radiation embrittlement occurs.

Hence, the results of our tests show a favorable effect of alloying V with Ga while an additional alloying with Cr and Ce is not promising from the point of view of mechanical properties of V-based alloys.

Such tests of wider circle of V-based alloys will make possibility to select the most promising compositions for careful investigations including the standard mechanical tests.

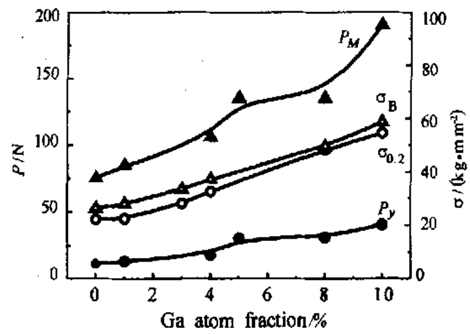

Fig. 4 Correlation between the strength MDBT-parameters P_M and Py and tensile strength 6_B and yield stress $6_{0.2}$ respectively for V-Ga alloys

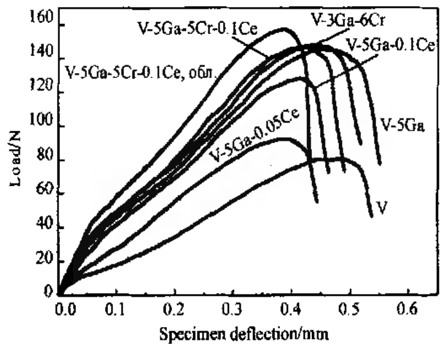

Fig. 5 Effect of alloying of V-5 % Ga(at. fraction) alloy with Cr and Ce on MDBT-curves

References

[1] The use of small-scale specimens for testing irradiated materials. ASTM STP 888. Eds. W. R. Corwin, G. E. Lucas. American Society for Testing and Materials, Philadelphia, 1986, 379 p.

[2] Miniaturized specimens for testing of irradiated materials. Proc. IEA Int. Symp. J lich, Germany, 22-23 Sept. 1994. Eds. P. Jung, H. Ullmaier. J lich: Forschungszentrum, 1995, p 226.

[3] Hamilton M. L., Hyang F. H. Use of the disk bend test to assess irradiation performance of structural alloys. In [1], p5-16.

[4] Manahan M. P., Browning A. E., Argon A. S., Harling O. K. Miniaturized disk bend test technique development and application. In [1], p17-49.

[5] Harling O. K., Lee M., Sohn D. S., Kohse G., Law C. W. The MIT miniaturized disk bend test. In [1], p50-65.

[6] Klueh R. L., Braski D. N. Disk-bend ductility tests for irradiated materials. In [1], p66-82

[7] Okada A., Yoshiie T, Kojima S., Abe K., Kiritani M. Correlation among a variety of miniaturized mechanical tests and their application to D-T neutron-irradiated metals. J. Nucl. Mater., 1985, v. 133/134, p321-325.

[8] Mao X., Takahashi H. Development of a further-miniaturized specimen of 3 mm diameter for TEM disk (φ3 mm) small punch tests. J. Nucl. Mater., 1987, v. 150, p42-45.

[9] Kullen P. S., Smith H. H., Michel D. J. The shear punch measurement of the mechanical properties of selected unirradiated and irradiated alloys. J. Nucl. Mater., 1988, v. 158, p57-63.

[10] Kameda J., Buck O. Evaluation of the ductile-to-brittle transition temperature shift due to temper embrittlement and neutron irradiation by means of a small-punch test. Mater. Sci. Eng., 1986, v. 83, p29-38.

[11]Bystrov L. N., Geminov V. N., Ivanov L. I., Kuzmin A. A., Tsepelev A. B. Determination of mechanical properties of irradiated stainless steel by the method of miniaturized disk bend test. In: Problems of nuclear science and technology: Physics of radiation damages and radiation materials science, 1990, issue 3(54) p. 89-95 (in Russian).

[12] Okada A., Hamilton M. L., Garner F. A. Microbulge testing applied to neutron irradiated materials. J. Nucl. Mater., 1991, v. 179/181, p. 445-448.

[13] Tsepelev A. B., Ivanov L. I., Poymenov I. L. Miniaturized disk bend tests of electron irradiated stainless steels. In [2], p. 59-78.

[14] Hamilton M. L., Toloczko M. B., Lucas G. E. Recent progress in shear punch testing. In [2], p. 46-58.

[15] Tsepelev A. B., Poymenov I. L. Application of miniaturized disk bend test technique for selection of optimum composition of candidate materials for fusion reactors. J. Nucl. Mater., 1992, v. 189, p. 222-225.

[16] Shinohara K., Lucas G. E., Odette G. R. Shear punch and ball microhardness measurements of 14 MeV neutron irradiation hardening in five metals. J. Nucl. Mater., 1985, v. 133/134, p. 326-331.

[17]Suzuki M., Eto M., Nishiyama Y., Fukaya K., Saito M., Misawa T. Small specimen test technique for the evaluation of toughness degradation. J. Nucl. Mater., 1992, v. 191/194, p. 1023-1027.

[18] Malow T. R., Koch C. C. Mechanical properties in tension of mechanically attrited nanocrystalline iron by the use of the miniaturized disk bend test. Acta mater., 1998, v. 46, No. 18, p. 6459-6473.

[19] Chen F. C., Ardell A. J. Fracture toughness of ceramics and semi—brittle alloys using a miniaturized disk—bend test. Mater. Res. Innovat., 2000, v. 3, p. 250—262.

[20]Zhang X., Wang H., Scattergood R. O., Narayan J., Koch C. C. Mechanical properties of cyromilled nanocrystalline Zn studied by the miniaturized disk bend test. Acta Mater., 2002, v. 50, p. 3527-35-33.

[21] Toloczko M. B., Hamilton M. L., Lucas G. E. Ductility correlations between shear punch and uniaxial tensile test data. J. Nucl. Mater., 2000, v. 283/287, p. 987-991.

[22]Bulloch J. H. The small punch toughness test: some detailed fractographic information. Int. J. Pressure Vessels and Piping, 1995, v. 63, issue 2, p. 177-194.

[23]Song S. —H., Faulkner R. G., Flewitt P. E. J., Smith R. F. Marmy P., Victoria M. Irradiation-induced embrittlement of a 2.25Cr1Mo steel. J. Nucl. Mater., 2000, v. 280, p. 160-168.

[24] Ishii T., Ohmi M., Saito J., Hoshiya T., Ooka N., Jitsukawa S., Eto M. Development of a small specimen test machine to evaluate irradiation embrittlement of fusion reactor materials. J. Nucl. Mater., 2000, v. 283/287, p. 1023-1027.

[25]Lee J. S., Kim I. S., Kasada R., Kimura A. Microstructural characteristics and embrittlement phenomena in neutron irradiated 309L stainless steel RPV clad. J. Nucl. Mater., 2004, v. 326, No. 1, p. 38-46.

[26] Toloczko M. B., Kurtz R. J., Hasegawa A., Abe K. Shear punch tests performed using a new low compliance test fixture. J. Nucl. Mater., 2002, v. 307/311, part 2, p. 1619-1623.

[27]Campitelli E. N., Spatig P., Bonade R., Hoffelner W., Victoria M. Assessment of the constitutive properties from small ball punch test: experiment and modeling. J. Nucl. Mater., 2004, v. 335, p. 366-378.

[28]Ulmaier H., Hishinuma A., Lucas G. E., Jung P. Recommendation of miniaturized techniques for mechanical testing of fusion materials in an intense neutron source. J. Nucl. Mater., 1996, v. 232, No. 2-3, p. 186-205.

[29]Gondi P., Donato A., Montanari R., Sili A. A miniaturized test method for the mechanical characterization of structural materials for fusion reactors. J. Nucl. Mater., 1996, v. 233/237, part 2, p. 1557-1560.

[30]Tsepelev A. B. Application of miniaturized disk bend test technique for evaluation of mechanical properties of irradiated ferrite steels. Physics and Chemistry of Materials Treatment, 2001, No. 1, p. 31-38 (in Russian).

[31]Kurtz S. M., Foulds J. R., Jewett C. W., Srivastav S., Edidin A. A. Validation of a small punch testing technique to characterize the mechanical behaviour of ultra—high—molecular—weight polyethylene. Biomaterials, 1997, v. 18, No. 24, p. 1659-1663.

[32]Jin Sik Cheon, In Sup Kim. Evaluation of thermal aging embrittlement in CF8 duplex stainless steel by small punch test. J. Nucl. Mater., 2000, v. 278, No. 1, p. 96-103.

[33]Lee E. H., Byun T. S., Hunn J. D., Hashimoto N., Farell K. A method to study deformation mechanisms for irradiated steels using a disk—bend test. J. Nucl. Mater., 2000, v. 281, No. 1, p. 65-70.