Defining the Fracture Toughness for Small-sized Samples of Materials with Submicrostructure

E.E. Deryugin, B.I. Suvorov

Institute of Strength Physics and Materials Science SB RAS, Tomsk, Russia

dee@ispms.tsc.ru

Keywords: ultrafine grain structure, strain localization, fracture, stress intensity factor

Abstract. A new method for defining material fracture toughness is described which was applied to small-sized chevron-notch test samples of ultrafine grain titanium alloy VT6.

1. Introduction

A standard testing procedure for fracture toughness is conducted as a rule for massive test samples having thickness ≤ 10 mm. In many instances, however, the test samples of choice are small-sized ones. In this case, there is no need for heavy-duty testing machines or large quantities of material. The mechanical properties of material are known to depend heavily on the sample shape and dimensions. Of particular interest is defining the fracture toughness for ultrafine grain and nanostructured materials, which often presents a considerable challenge since the fabrication of large billets involves certain technical problems. Therefore, small-sized chevron-notch samples are generally used for this purpose [1-5].

A new method was developed for defining the fracture toughness for ultrafine grain materials produced by severe plastic deformation (SPD). The investigations were carried on for chevron-notch samples. A series of computation problems involved were tackled successfully, i.e. (i) the Young modulus was calculated for the studied material by taking into account the geometric shape of the test sample and the experimental dependence ‘loading-displacement’ obtained for the initial loading stage and (ii) the specific surface energy was determined by the formation of free surface of the crack.

2. Material and Experimental Procedure

The investigations were carried on using test samples of ultrafine grain titanium alloy VT6 (Ti—6A1—4V) produced by SPD, using *abc* forging schedule to 50% reduction at 400ºC with subsequent annealing for 1 h at 300ºC.

The samples 18mm long were cut out from a square rod having section $6\times6mm^2$. Using electroerrosion method, a 0.25mm chevron notch was applied which divided the sample into two equal parts. The slot border is a broken line aligned along the sample axis, with the angle $\alpha = \pi/6$ (see Fig. 1). The chevron-notch samples were tested in tension at room temperature at the rate of moving clamp of the test machine v = 4.0 μm/s.

Photographic images were obtained every two seconds for the sample under loading with the aid of a mirror camera PENTAX K-5. Using these images, the change in the crack opening was measured for the points of load application and for the end of the chevron notch; the crack opening and crack length were also measured in the course of sample loading. The data obtained was used to calculate the fracture toughness criteria for the studied materials.

3. Results

3.1. *Defining the Young modulus for the chevron-notch samples tested*

The needed data on the Young modulus for ultrafine grain materials is practically missing. It is only known that the value E is affected significantly by the SPD schedule [6]. Therefore, the value E was determined for each chevron-notch sample tested. A chevron notch is a narrow slot having a broken border which has angle α and is aligned along the extension axis (Fig. 1). This configuration can be regarded as a double-cantilever construction.

Each cantilever may be thought of as a pile of elemental beams having infinitesimally small thickness dx, with the length of elemental beams increasing on going to the sample side. As is seen from Fig. 1, the elemental beam which is x distant from the sample axis has length

$$l(x) = l_0 + x \cdot \cot\frac{\alpha}{2} \ , \qquad (1)$$

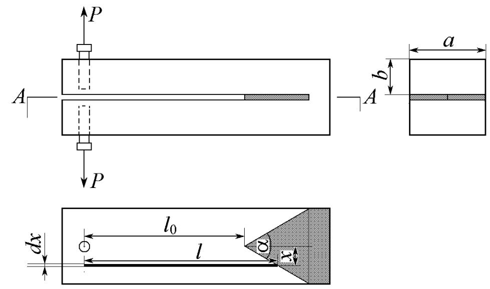

Fig. 1. A schematic of the chevron-notch sample

where l_0 is the distance between the point of load application and the end of chevron notch (Fig. 1). For each square-section beam the following well-known formula holds true:

$$E = \frac{4 \cdot dP(x)}{\lambda \cdot dx} \cdot \left(\frac{l(x)}{b} \right)^3 , \qquad (2)$$

where dP – elemental loading which causes elemental beam to take up sag λ and b – cantilever thickness.

Using the variable x from (2), the elemental load dP applied to the end of elemental beam is given as

$$dP(x) = \frac{E \cdot \lambda \cdot b^3}{4} \cdot \frac{dx}{l(x)^3} . \qquad (3)$$

The integration of all elementary forces from (3) gives the real loading P, which provides the deflection of the beam by an amount λ:

$$P = \frac{E \cdot \lambda \cdot b^3}{4} \int_{-\frac{a}{2}}^{\frac{a}{2}} \frac{dx}{\left(l_0 + x \cdot \cot\frac{\alpha}{2} \right)^3} = \frac{E \cdot \lambda \cdot a}{4} \left(\frac{b}{l_0} \right)^3 \frac{4 + \frac{a_0}{l_0} \cdot \cot\frac{\alpha}{2}}{\left[2 + \frac{a_0}{l_0} \cdot \cot\frac{\alpha}{2} \right]^2} , \qquad (4)$$

where a – sample width (Fig. 1).

Hence the Young modulus can be determined as

$$E = \frac{4 \cdot P}{\lambda \cdot a} \cdot \left(\frac{l_0}{b} \right)^3 \frac{\left[2 + \frac{a}{l_0} \cdot \cot\frac{\alpha}{2} \right]^2}{4 + \frac{a}{l_0} \cdot \cot\frac{\alpha}{2}} . \qquad (5)$$

The Young modulus was calculated from (5) for VT6 with ultrafine grains and for coarse grains. In the latter case, for a = 4.97 mm; b = 1.9 mm; l_0 = 11.6 mm; P = 637.7 N; $\alpha/2 = \pi/6$ and λ□ = 0.358 mm, we obtained the value E = 107 GPa, which agrees with the handbook data [7]. In the former case, the respective value E = 93 GPa. Such a low value of the Young modulus is supported by the experimental evidence [6] which suggests that the grain refinement due to SPD treatment is liable to impair the fracture toughness.

3.2. *Determination of the specific energy of free crack surface formation*

For a plane deformed state, a one-to-one correspondence exists between the specific energy of free crack surface formation, G, and the critical coefficient of stress intensity, K_{Ic} [7], i.e.

$$K_{Ic} = \sqrt{\frac{EG}{1-\nu^2}}, \tag{6}$$

where ν – the Poisson ratio.

In case a crack having length l propagates spontaneously to elemental distance dl over sample having width x, critical elastic energy released per unit of crack front length is given as

$$G_{cr} = 0.5 \cdot \frac{P_{max}^2}{x} \cdot \frac{\partial \eta}{\partial l}, \tag{7}$$

where η – sample compliance. P_{max}, by definition, is the maximal external load at which spontaneous crack propagation would occur.

Let us apply the above reasoning to the chevron-notch sample. The narrow slot might be regarded as crack having length l_0 (Fig. 1). Assume that in the course of loading material continuity violation occurs on plot Δl (Fig. 2). Let crack front be a straight line which has length x and is normal to the sample axis (рис. 2). Now let us single out from the sample a middle portion having width x. In accordance with [8, 9], loading causes beam having width x and length l to take up sag λ/2, i.e.

$$P = \frac{E \cdot \lambda \cdot x}{8} \cdot \left(\frac{b}{l}\right)^3. \tag{8}$$

The beam width $x = 2\Delta l \cdot \tan(\alpha/2)$ (here α is chevron notch angle).

The compliance of sample portion having width x is given by the following expression

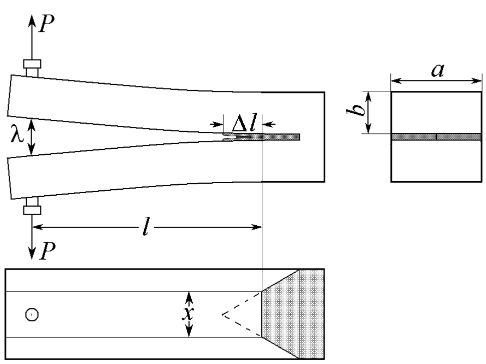

Fig. 2. On determination of specific energy G

$$\eta = \frac{\lambda}{P} = \frac{8}{E \cdot x} \cdot \left(\frac{l}{b}\right)^3 = \frac{4}{E \cdot \Delta l \cdot \tan\frac{\alpha}{2}} \cdot \left(\frac{l}{b}\right)^3. \tag{9}$$

As crack length increases by value dl, the compliance changes as follows

$$\frac{\partial \eta}{\partial l} = \frac{12 \cdot l^2}{E \cdot \Delta l \cdot \tan\frac{\alpha}{2} \cdot b^3}. \tag{10}$$

Substitution of the latter value and of expression (8) to equation (7) gives

$$G_{cr} = \frac{3E}{16} \cdot \frac{\lambda_{cr}^2 \cdot b^3}{l^4}. \qquad (11)$$

Thus using the P - λ diagrams obtained for the small-sized chevron-notch test samples of alloy VT6 (here P is loading and λ is notch edges displacement), one can determine the critical loading P_{cr} and the critical notch edges displacement λ and, consequently, the instant of time at which spontaneous crack propagation would begin. The values G_{cr} = 90.5 kJ/m^2 and K_{Ic} = 103 MPa/m$^{1/2}$ were calculated for the coarse grain counterpart from (11) and (6), respectively; these are found to agree with the corresponding values obtained for standard samples [10]. The respective values obtained for the ultrafine grain counterpart, i.e. G_{cr} = 30.9 kJ/m^2 and K_{Ic} = 56.4 MPa/m$^{1/2}$, are significantly lower relative to the coarse grain counterpart. It can thus be concluded that the SPD treatment (*abc*-schedule) would impairs significantly the fracture toughness.

4. Summary

A new method for defining material fracture toughness is described which was applied to small-sized chevron-notch test samples of ultrafine grain titanium alloy VT6.

A series of computation problems involved were tackled successfully. Analytical expressions have been derived which can be used to calculate the Young modulus in the course of testing and to determine specific surface energy by formation of free crack surface.

The calculated values of the Young modulus, E, and of the stress intensity coefficient, KIc, are found to agree with the data obtained for standard test samples.

Acknowledgments

This work was supported by the Russian Foundation of Basic Research. Project No 08-10-001182-a.

References

[1] L.M. Barker: Int. J. of Fracture Vol. 16 No. 6 (1979), p. 515.

[2] C.T. Wang, R.M. Pillar: J. Mater. Sci. No 24 (1989), p. 2391.

[3] T.J. Grant, L. Weber, A. Mortensen: Engineering Fracture Mechanics No. 67 (2000), p. 263.

[4] B.A. Drozdovsky, T.V. Polishchuk, V.P. Volkov: Zavodskaya laboratoriya No.6 (1987). p. 74.

[5] R.R. Rakhimkulov: Neftegazovoe delo Vol. 2 (2010), p. 1. Information on http://www.ogbus.ru/authors/Rakhimkulov/Rakhimkulov_1.pdf.

[6] G.A. Salischev, R.M. Galeev, S.P. Malicheva, S.B. Michailov, M.M. Mischljaev: Fizica Metallov i Metallovedenie Vol. 85 No 3 (1998) p. 178.

[7] R.W. Hernzberg: *Deformation and Fracture Mechanics of Engineering materials* / John Wiley and Sons, Toronto, NY (1983).

[8] Information on http://ums.physics.usu.ru/melab/Lab09.pdf

[9] GOST 16483.9-73. *Wood. Methods for calculation of elasticity modulus by static bending*.

[10] A.A. Il'in, B.A. Kolachov, I.S. Pol'kin: *Titanium alloys. The composition, structure and properties. Handbook* / VILS-MATI, Moscow, Russia (2009).