PROCEEDINGS OF THE INTERNATIONAL CONFERENCE
NANOMATERIALS: APPLICATIONS AND PROPERTIES
Vol. **2** No 1, 01PCSI06(4pp) (2013)

Fracture Mechanisms of Nano- and Submicrocrystalline Materials under Various Loading Conditions

V.E. Panin*

Institute of Strength Physics and Materials Science SB RAS,
2/4, Akademicheskii Ave., 634021 Tomsk, Russian Federation

(Received 17 May2013; published online 30 August 2013)

The paper provides a review of research results obtained by the author and colleagues in studying the fracture mechanisms of nano- and submicrocrystalline materials under various loading conditions. Fracture of material is considered in the context of Gibbs' principles of nonequilibrium thermodynamics and is treated as its local structural phase decay. Nucleation of cracks is associated with initiation of micropores in high-curvature zones and their development proceeds by nonlinear wave mechanisms of opening mode cracking, dynamic rotations, and sliding or tearing mode cracking.

Keywords: Nano- and submicrocrystalline materials, Fracture, Structural phase decay, Fatigue, Wave theory.

PACS numbers: 62.20.mm, 62.25.Mn

1. INTRODUCTION

Analysis of the $F(\upsilon)$ dependence between the Gibbs thermodynamic potential F and the molar volume υ (Fig. 1) shows that nanostructural states arise only in highly nonequilibrium media and are a pretransition stage to loss of their translation invariant crystalline state in the vicinity of zero $F(\upsilon)$ [1]. This means that fracture of nanostructured material occurs as its local structural phase decay at $F(\upsilon) > 0$. The fracture is preceded by the formation of micropores in high-curvature zones. A crack in fracture develops as coagulation of micropores in an inhomogeneous internal stress field. The paper provides a review of research results obtained by the author and colleagues in studying the fracture mechanisms of nano- and submicrocrystalline materials under various loading conditions.

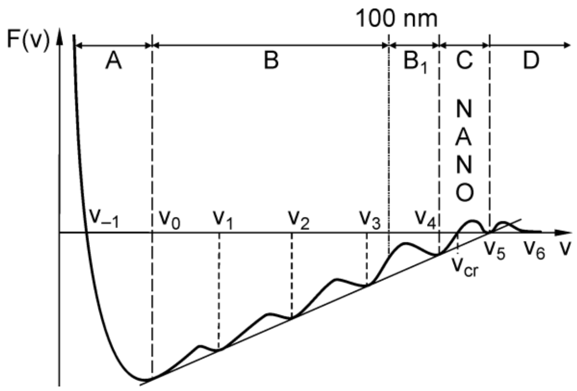

Fig. 1 – Dependence of the Gibbs thermodynamic potential on the molar volume, $F(v)$, accounting for local hydrostatic compression region A and hydrostatic tension regions at different scales where defect structures are generated: B is mesoscale substructures of different structural scales, B_1 is nanosized structures, C is nanostructural states, and D is ensuing porosity and fracture regions

2. UNIAXIAL TENSION

2.1 Fracture in the Neck

Fracture in the neck gives rise to two macrobands of localized deformation which follow a self-consistent cross pattern, Fig. 2 [2]. The fracture begins with the formation of a pore in the neck center at the intersection of the macrobands. The pore as a notch generates a crack developing in stages: as an opening mode crack in the transverse direction, then as a sliding mode crack, and finally as a tearing mode crack by shear, Fig. 3 [3].

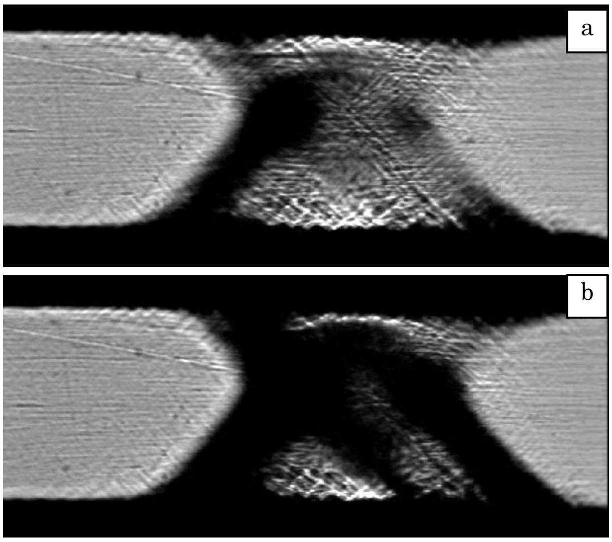

Fig. 2 – Macroscale localization of plastic deformation at the prefracture stage of submicrocrystalline armco iron; tension, $T = 293$ K, $\varepsilon = 3$ % (a) and 5 % (b). Observed areas are 5.7×2.2 mm^2

---

* paninve@ispms.tsc.ru

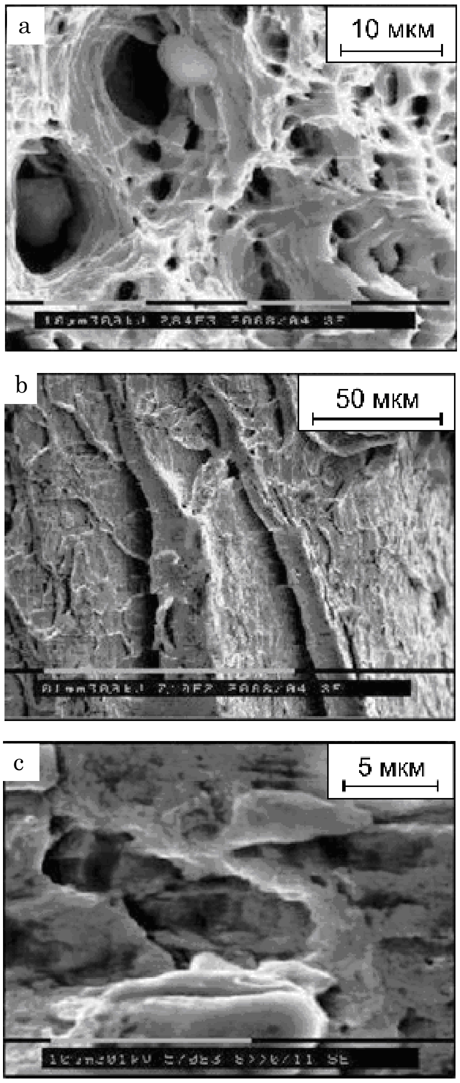

Fig. 3 – Microfracture elements in submicrocrystalline α-Fe: opening mode zone (a), sliding mode zone (b), tearing mode zone (c)

2.2 Shear Fracture

In shear fracture of material, only one macroband of localized deformation develops in which intensive work softening takes place. The stresses operating in the band are tangential stresses that realize shear and tensile normal stresses that increase the molar volume in the band and stimulate cold recrystallization of nanostructure. The process culminates in structural phase decay of the material in the macroband, showing up as a tearing mode crack.

3. CHEVRON NOTCHED SPECIMEN

3.1 Quasibrittle Fracture

In chevron notched specimens, quasibrittle fracture of high-strength nanostructured material develops as a nonlinear transverse wave in normal mode cracking. At the lateral boundaries of the transverse wave, fibrous material degraded by structural phase decay on the fracture surface is concentrated, Fig. 4 [4, 5].

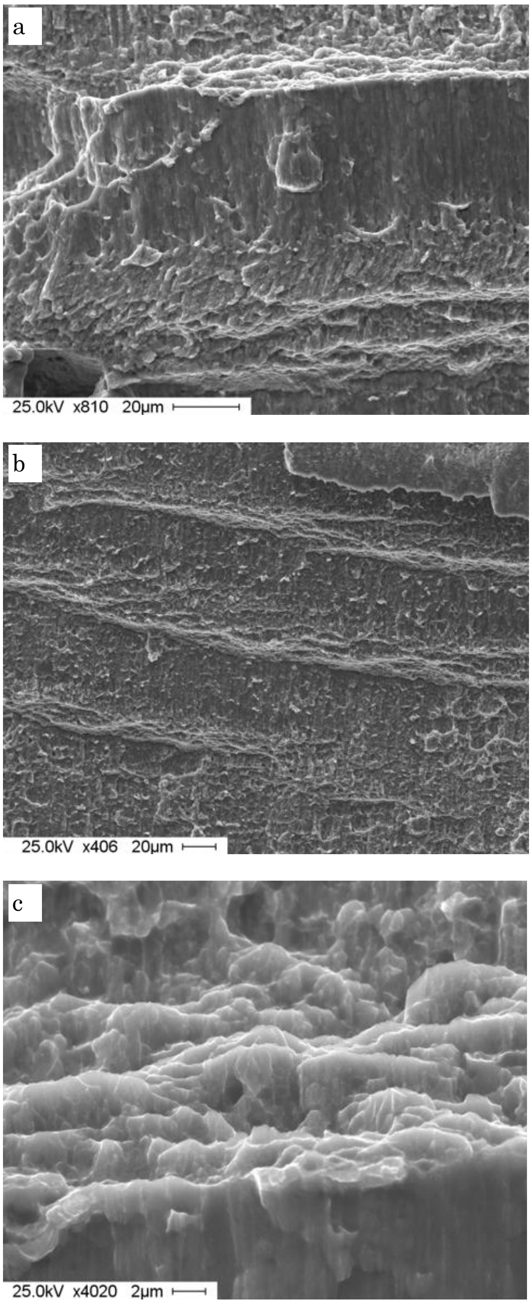

Fig. 4 – Fracture of submicrocrystalline VT1-0 titanium with a chevron notch (scanning electron microscopy): transverse cleavage step (a) and transverse mesofolds of fibrous material degraded by structural phase decay on fracture surface (b, c)

3.2 Ductile Fracture

In ductile fracture of nanostructured material, nonlinear waves of normal mode cracking are “dispersed” into dynamic rotations in which the fracture velocity is commensurable with the velocity of sound. Each dynamic rotation produces a crater on the fracture surface with a crater depth ranging to 15 μm and crater diameter on the fracture surface ranging to 40-60 μm, Fig. 5 [4]. At the bottom of the craters, one can detect a particle of compounded alloying elements or impurities resulting from vortex motion of the material in dynamic rotation zones with mass transfer of anomalously high rates. The entire fracture surface has a fibrous structure formed as structural phase decay of the nanostructured material in dynamic rotations. The high rate of structural phase transformations in dynamic rotations owes to the formation of bifurcation states in the rotated material with hierarchically developed curvature [5].

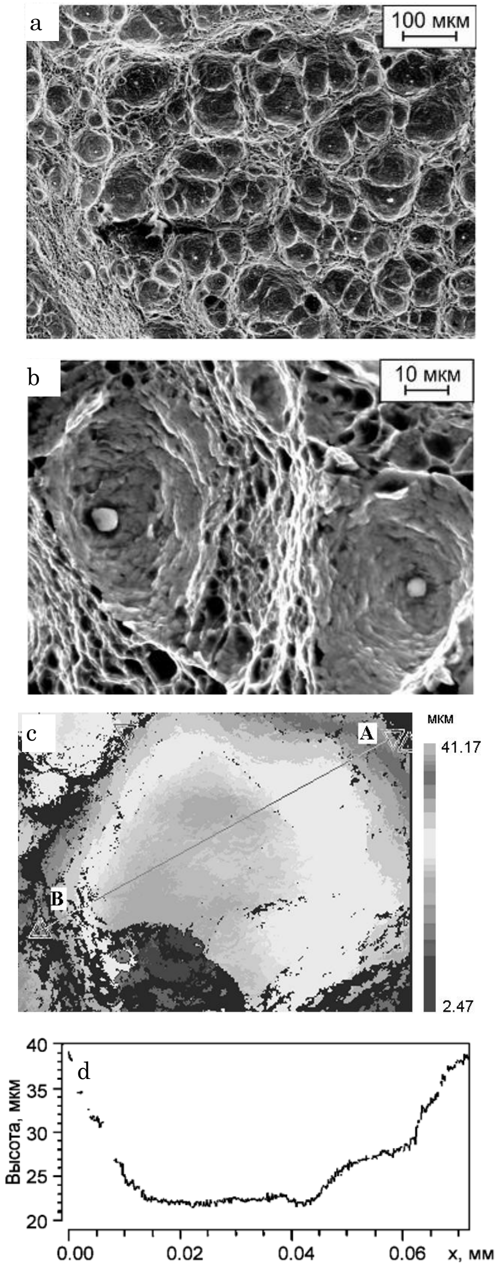

Fig. 5 – Fracture surface of chevron notched submicrocrystalline 12GBA pipe steel after tensile tests, scanning electron microscopy (a, b); crater region of structural phase decay (c); profile of the crater region over cross-section AB; interference optical microscopy (d)

The dependence of wear resistance of the multilayer coatings on the thickness of Si-Al-N and Zr-Y-O layers (providing constant total coating thickness) is characterized by the presence of an extremum. Increase of a number of bilayers in the coating and, therefore, appearance of additional interfaces prevents from expansion of strain deep into the specimen. Thus the rate of adhesive wear of the coatings consisting of 6 Si-Al-N / Zr-Y-O bilayers considerably decreases as compared with the one of the bilayer coating. However, increase in the number of bilayers providing constant total coating thickness leads to diminishing layer thickness. Therefore, tests of the coatings consisting of 17 bilayers showed increasing wear rate caused by quick tearing of bilayers due to debonding along the Zr-Y-O / Si-Al-N interfaces. It is clearly evident as stepped surface of the wear track (see Fig. 4c), with step height well agreeing with the bilayer thickness.

4. NONLINEAR WAVE THEORY OF FRACTURE

A nonlinear wave theory of fracture as local structural transformations was developed [4, 5]. Analysis of nonlinear wave equations for the density and flux of defects passed through structural transformations in fracture shows that the type of a main crack is defined by the type of stress-strain state at the crack tip. The constitutive parameters of the stress-strain state are principal normal stress and tangential stress intensity, plastic distortion gradient, nanostructural shear stability, and shear strain vorticity. Depending on the principal normal stress (tension or high-pressure torsion), a nanostructured material can either undergo brittle fracture or display superplasticity, forming anomalously high curvature of its internal structure and mobile nanostructured phase boundaries.

This dualism in the behavior of nanostructured material takes place because plasticity of a deformed solid is governed by competitive development of multiscale nonlinear waves of plastic flow and nucleation of discontinuities as local structural phase decay of the material in zones with a positive Gibbs thermodynamic potential [7]. Deformation in which the Gibbs thermodynamic potential remains negative $F(\upsilon) < 0$ determines superplasticity of nanostructured material. The possibility of the formation of zones with $F(\upsilon) > 0$ in a deformed nanostructure governs local structural phase decay of condensed state and development of brittle fracture (see Fig. 1).

5. EFFECT OF SURFACE LAYER NANOSTRUCTURING ON FATIGUE LIFE OF STRUCTURAL MATERIALS

Systematic research was performed to study the influence of surface layer nanostructuring on fatigue life of structural materials and their welds [8]. It is shown that surface layer nanostructuring of welds by ultrasonic shock treatment or ion implantation allows an increase in fatigue life by a factor of 2-10. Fig. 6 shows the fracture surface of a weld of high-strength Al alloy after cyclic loading. The fractograph of the initial weld reveals a great many micropores, Fig. 6a; fatigue fracture occurs after $N = 44700$ loading cycles. The surface layer nanostructuring of the weld governs the formation of a submicron fibrous fracture at $N = 69900$ loading cycles, Fig. 6b. The nonlinear wave theory of fracture substantiates the high damping capacity of the submicron fibrous structure presented in Fig. 6b.

The effect of increasing fatigue life of welds due to their surface layer nanostructuring depends on the type of structural material (see Table 1): on the proximity of its thermodynamic state to structural phase decay in fracture.

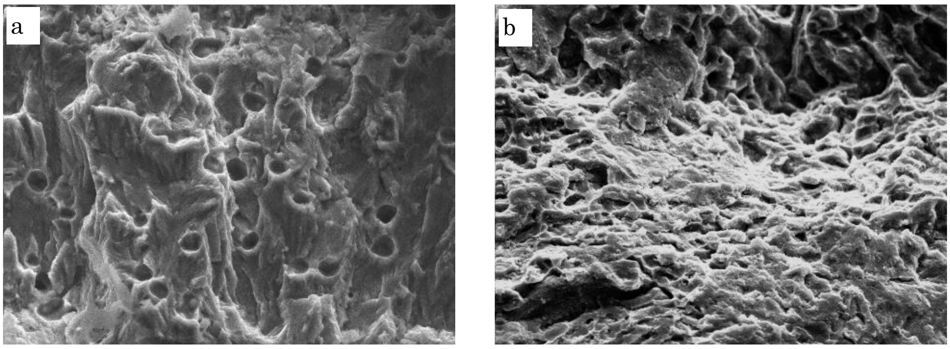

Fig. 6 – Fracture surface of Al 1370 alloy weld: with no nanostructuring, $N = 44700$ cycles, × 1000 (a); with surface layer nanostructuring, $N = 69900$ cycles, × 1000 (b)

Table 1 – Fatigue life of welds of aircraft structural materials before and after nanostructuring

Material, Stress	Number of cycles before fracture		
	Untreated	Subjected to ultrasonic shock treatment	Factor of increase
High Strength Steel VKS12 700 MPa	33000-38000	48500-68000	1.5-1.8
Super alloy VZh172 700 MPa	up to 12800	72000-84600	5.8-6.6
Al alloy V1461 170 MPa	20500-23500	> 300000	> 12.5
Al alloy V1693 160 MPa	20000-30000	> 300000	> 10
Ti alloy VT18U 400 MPa	16600-32350	> 150000	> 4.6

REFERENCES

1. V.E. Panin, V.E. Egorushkin, *Fiz. Met. Metalloved.* **110** No 5, 486 (2010).
2. V.E. Panin, Yu.V. Grinyaev, A.V. Panin, S.V. Panin, *Proc. 6th Int Conf. Mesomech.* (Patras. Greece: Univ. of Patras 2004).
3. L.S. Derevyagina, V.E. Panin, A.I. Gordienko, *Phys. Mesomech.* **10** No 4, 59 (2007).
4. V.E. Panin, V.E. Egorushkin, L.S. Derevyagina, E.E. Deryugin, *Phys. Mesomech.* **15** No 6, 5 (2012).
5. V.E. Panin, *Proc. Eur. Conf. Fracture 19,* (Kazan, Russia: Kazan Sci. Center RAS: 2012).
6. V.E. Panin, V.E. Egorushkin, *Phys. Mesomech.* **16** No3, 5 (2013).
7. V.E. Panin, V.E. Egorushkin, A.V. Panin, *Phys.-Usp.* **182** No. 12, 1351 (2012).
8. V.E. Panin, V.P. Sergeev, A.V. Panin, *Surface Layer Nanostructuring of Structural Materials and Deposition of Nanostructured Coatings* (Tomsk: Tomsk Polytechnic Univ.: 2009).