THE NATURE OF FRACTURE IN SOLIDS

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Various types of deformation of ionic single and polycrystalline samples revealed that the variation of fracture stress with stress rate temperature, impurity content and state scales with the variation of the parameters of precursor micro- and macroplastic flow.This strict correlation is universal for all published data on so-called "brittle" and "ductile" insulators, metals, superconductors and semiconductors, ceramics. It is explained by the universality of dislocation mechanisms like double cross-slip and climb in different crystal classes at all stages of plastic deformation.

INTRODUCTION

Although two principal types of fracture are generally distinguished as so-called "ductile" and "brittle", there is no consensus about the role of precursor plasticity in these processes (Schmid and Boas (1), Evans and Langdon (2), Stepanov (3)). Professor A. V. Stepanov was the first in 1934-1937 to suggest that in ionic crystals in the temperature range 77 to 673K every type of fracture was preceded by a finite extent of plasticity (3).

The purpose of this work is to draw attention to the remarkable and universal correlation between the initial stresses of stages of preceded plasticity and fracture in different classes of crystals under various tests and in widest ranges of temperature and stress-rate changes.

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EXPERIMENTAL AND RESULTS

This study deals with the effect of temperature, stress rate and impurity content on the flow stresses at the beginning of different stages of deformation (dislocation unpinning and multiplication, macrosopic yielding and fracture) in alkali halides: NaCl and KCl-KBr single (s) crystals and polycrystals (p) in a wide range of temperatures ($T \cong (4\times10^{-4}$ to $0.64)T_m$, T_m the melting point), stress rates (3×10^{-5} to 10^6 MPa/s) and stresses (10^{-2} to 10^2 MPa).

The specimens were deformed by compression, tension, bending or oscillation stresses.The principal finding is the scaling of the stresses: starting stress for dislocation motion-multiplication stress (Fig.1,curve I, points 1 to 6) and starting stress-fracture stress (Fig.1, curve II, points 1' to 6') which are compared with the literature data: shock loading — 10^8 MPa/s of NaCl (Savenko and Gering (4)); Si — 7,7', 10' (Kisel (5), Sylwestrovich (6)); Al_2O_3 (sapphire) — 8' (Roberts et. al.(7); CdS ($T \cong 2\times(10^{-3}$-$10^{-2})T_m$) (Negrii and Osipyan (8)), ceramics — 11' (Soldatov et al. (9)).

The same scaling of the yield stress - fracture stress in widest range of stresses confirms the universality of the mechanisms governing the plasticity and fracture of various crystalline structures under different tests (Fig.2, $T \cong 10^{-3}$ to 0.8 T_m): NaCl — points 1, KCl-KBr — 2, $NaCl_p$ —3, 5 (1, Stokes and Li (10, 11)); LiF, AgCl, $CaCl_2$, BaF_2 — 4 (1,2); Al — 6 (10); Cu — 7; W — 8; Ti alloys — 9 (10); Si — 10 (Castaing (6)); Ge — 11 (Suzuki and Kojima (11)); Mo — 12; Al_2O_3 (sapphire) — 13 (Bokstein et al., Farber et al. (12)); superconducting or normal states of Sn, Pb — 14 (Kirichenko (13)); MgO_p — 4' (2).

It is worth stressing that it is at low yield stresses only (range A, yield stresses < 3 MPa) the dislocations demonstrated a noticeable cross-slip, wavy slip and crystals fractured in so-called "ductile" mode irrespectively of test conditions (at $T \cong 4.2$ K in extra-soft NaCl or at $T \cong (0.6$-$0.95)T_m$ in hardened NaCl), while at much higher stresses (range B,yield stress > 3 MPa) the slip traces and bands were narrow and straight (the cross-slip heights were small and frequent) irrespectively of experimental conditions, the fracture mode was "brittle".

It is worth noting that it was the visible cross-slip of dislocations that caused the dislocation drag, full stop and only then their multiplication.When the multiplication was exhausted,the microcrack nucleation, growth and coagulation into macrocracks were developed.

In the case of invisible (in an optical microscope, for example) cross-slips the crucial role of stress-aided jogs in dislocation retardation (crystal work-hardening) was confirmed by the absolutely regular dislocation multiplications after their full stop, and by very different Widersich's parameters of the dislocation double cross-slips in various slip planes (Kisel et al. (14)).

DISCUSSION

Figs 1, 2 clearly demonstrate that the mechanisms of plasticity and fracture have the same origin. The scaling of various parameters of plastic flow and fracture just with the multiplication ones points to the crucial role of dislocation double cross-slip mechanism irrespectively of other experimental conditions.

It is the deformation stress which governs the dislocation unpinning, Orowan bowing and jogging either by cross-slip, intersections or climb (at high stresses) (5, 14, Kisel (15)).

Having covered the ultimate pathlengths determined by the parameters of crystals and tests (they were high in the range A — 'ductile', and very small (down to the lattice parameter (5)) in the range B — "brittle", Fig.2), the dislocations exposed to successive acts of multiplication thus forming the slip lines with a mean spacing of dislocations, cell walls and grain boundaries (15).

The latters are the standard sources of micro- and macrocrack nucleation (Smirnov et al. (16)).

It is evident that in the frames of this chain of physical events the cross-slip and climb mechanisms explain the structure of rupture surfaces, too.

It is worth noting that in several cases the precursor deformation effects (the generation of new dislocations, point defects and even microvoids, etc.) before fracture may be so considerable that they can noticeably change the characters of temperature and other dependences of fracture parameters like we can see in some cases for different levels of deformation stress.

CONCLUSIONS

This study gives the first reliable results on the universal scaling behavior of micro- and macroplasticity and macrofracture in principal crystal classes, single crystals and polycrystals. Close interconnection of these processes with the mechanism of multiplication shows the controlling role of the deforming stress through the dislocation cross-slip, bowing and climb in the strict chain of stages: dislocation unpinning, motion, drag and full stop, multiplication and retardation, grain boundaries and crack origin.

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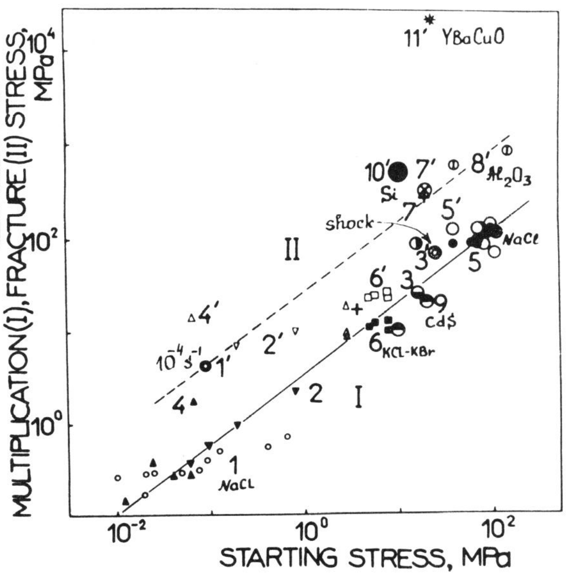

Figure 1. Variations of multiplication — I and fracture — II stresses versus starting stress for dislocation motion.

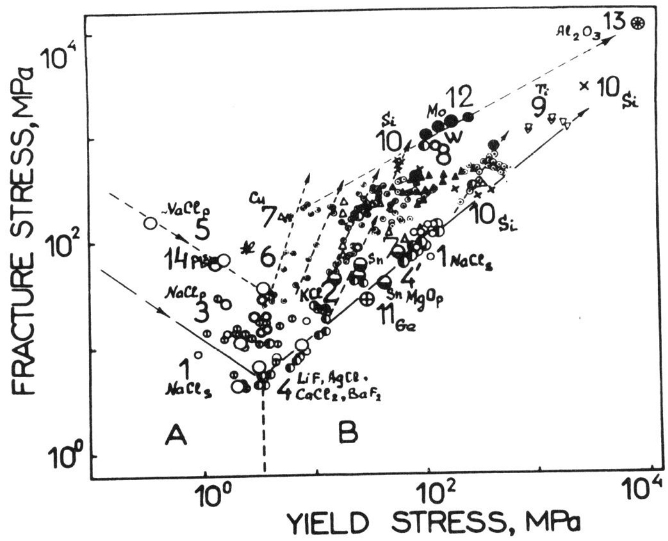

Figure 2. Variations of fracture stress versus yield stress in ionic, metal,semiconductor crystals, ceramics.