

FRACTURE TOUGHNESS OF MOLYBDENUM SHEET UNDER
BRITTLE-DUCTILE TRANSITION

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Temperature dependence of fracture toughness of sheet molybdenum was studied in the temperature range $-196^{\circ}\text{C} \dots 300^{\circ}\text{C}$. It was found that nonmonotonous behaviour of this dependence is due to the change in crack nucleation mechanism.

EXPERIMENTAL PROCEDURE

In the present study temperature dependence of fracture toughness of molybdenum sheet 2.25 mm wide of alloy CM-10 was investigated, samples were annealed at 2000°C for one hour. Grain size was obtained about 300-400 μm . Critical strength intensity factor was used as fracture toughness, K_{IC} or K_C were used as general yield has been arisen. Flat samples with two-edge notch with 0.05 mm radius have been subjected to tension at the rate 10^{-3} s^{-1} in the temperature range of $-196^{\circ}\text{C} \dots 300^{\circ}\text{C}$. Tensile tests at temperature higher than room temperature were performed in vacuum chamber with pressure of 0.1 Pa. Samples shape, size and method of fracture toughness calculation were chosen in accordance with Soviet standard (1). Initial cracks appeared at the tip of electrospark notch, their length being 20-50 μm .

RESULTS AND DISCUSSION

Temperature dependence of fracture toughness of annealed CM-10 alloy is shown in Figure 1 (curve 1). As may be seen from this fi

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ture, fracture toughness in this temperature range is nonmonotonous and exhibits maximum at room temperature. At subsequent temperature increase in fracture toughness is again observed in the range 100 °C...300 °C.

Analysis of mechanical tests shows that conditions of plane strain deformation are preserved in the temperature range up to 70 °C. This fact has attracted our interest to the investigation of fracture toughness since the transition from plane strain state to plane-stress one is usually accompanied with increase in fracture toughness according to Krasovsky (2).

Temperature dependence of fracture stress is similar to that of fracture toughness (Fig. 1, curve 2). Fracture stress exceeds yield strength when the temperature exceeds room temperature and plasticity becomes noticeable. These two facts together with the fractographic peculiarities which will be described later allows us in accordance with Ioffe-Orovan model (3) to determine room temperature as a lower temperature limit of brittle-ductile transition of notched samples.

Fractographic analysis shows that in the temperature range -196 °C...20 °C fracture by cleavage proceeds from electrospark cracks, blunted as the test temperature is increased. Therefore, at liquid nitrogen temperature these cracks are hardly visible (Fig. 2a). They are clearly seen at room temperature (Fig. 2b). In some cases cleavage cracks can also start from favourably orientated grain boundaries.

In the temperature range above room temperature samples are also fractured by cleavage. Pure cleavage is preceded now by cleavage cracks with relaxation (Fig. 2c). These ones are according to Friedel-Orlov mechanism (4, 5) and propagates from blunted electrospark cracks. Length of cleavage cracks with relaxation increases as the test temperature is increasing Fig. 1 (curve 5). Stereoscopic analysis shows that cleavage cracks with relaxation are much sharper than blunted electrospark ones. Growth of introduced cracks to their critical length leads to the change in net specimen cross-section which is to be taken into account in calculation of fracture toughness. At the temperature 300 °C ductile fracture elements, intergranular and transgranular delamination (Fig. 2d) are also observed at the fracture surface together with the cleavage and cleavage with relaxation.

Thus, the increase of fracture toughness below temperature T_{bd} results from blunting of electrospark cracks due to plastic processes at the crack tip. At T_{bd} temperature microplastic blunting of these cracks is so strong that cleavage is not be able to nucleate.

As can be seen from Fig. 1 (curve 5), length of crack with relaxation increases from 0.015 mm at T_{bd} to 0.052 mm at 100 °C.

This fact must lead to increase of K_{Ic} . However level of fracture stress resulting from already nucleated crack sharpness and from structural changes in deformed material at the crack tip, which are difficult to evaluate today, is reduced from 370 to 220 MPa in the temperature range under discussion.

Fracture toughness as it is known may be calculated as:

$$K_{Ic} = \sigma_F \sqrt{\pi C} \quad (1)$$

Analysis of the influence of changes both of crack length and fracture stress on fracture toughness of molybdenum sheet clearly shows that in the observed temperature range the main reason for decrease of fracture toughness is reduction of fracture stress but not increase of a crack length, according to the dependence between fracture stress and crack length (1). Further rise of temperature with continuous rise of fracture stress results in essential growth of the relaxation crack (Fig. 1, curves 2 and 5). This fact explains a new increasing of fracture toughness in the next temperature range. Increase of fracture toughness in the temperature range over 70 °C results also from the change in the specimen stress state - from plane strain state to plane-stress one. As follows from Fig. 1 (curve 4), plasticity before fracture increases at these temperatures. Size of the plastic zone is comparable to the specimen width. Therefore specimen becomes too "thin" for correct calculation of critical strength intensity factor K_{Ic} according to formulae (1). It is possible to estimate only its relative value K_c (Fig. 1, curve 1') and coefficient K_c taking into account crack growth (Fig. 1, curve 1'').

In some work, e.g., done by Vasilev et al (6), Lung and Gao (7) it has been shown that, using fractographic determination of fracture toughness of molybdenum, temperature dependence of fracture toughness of material failed by cleavage may be expressed by exponential relation:

$$K_{Ic} = K_0 \exp\left(-\frac{V_0}{kT}\right) \quad (2)$$

It is seen, that dependence (2) is monotonous and differs from dependence found in this work.

As follows from data showed above, the main reason of the non-monotony of temperature dependence of fracture toughness of molybdenum results from the change of fracture mechanisms and, more exactly, from the change of mechanisms of bearing of cleavage. Before temperature of the lower limit of brittle-ductile transition T_{bd} the cleavage cracks are originated on blunted electrospark cracks, after T_{bd} , the cleavage cracks are originated on cracks of cleavage with plastic relaxation. The sharpness of cracks of cleavage with relaxation is more high, than blunted electrospark ones.

Because the mechanism of full fracture in the both cases is the same, i. e. cleavage, it is possible to describe the found temperature dependence of fracture toughness of molybdenum by two exponents, activation energies of which are equal, but differing by some constants appropriate for different temperature intervals: before T_{bd} and after it.

Scheme of the temperature dependence of fracture toughness of molybdenum is represented by Figure 3. The transition from the first exponent to the second one happens when cleavage cracks are preceded by cracks of cleavage with relaxation.

REFERENCES

- (1) GOST RD 50-260-81, the same as ANSI/ASTM E 399-78.
- (2) Krasovsky, A.Ya., "Brittleness of Metals at Low Temperatures", Naukova Dumka, Kiev, U.S.S.R., 1980, in Russian.
- (3) Yoffe, A.F. "Selected works", Nauka, Leningrad, U.S.S.R., 1974, vol.1, in Russian.
- (4) Friedel, J., in: "Mechanism of Fracture", Metallurgizdat, Moscow, U.S.S.R, 1963, pp. 504-534, in Russian.
- (5) Orlov, A.N., Solid State Physics, 1961, vol.3, No 2, pp. 500-504, in Russian.
- (6) Vasilev, A.D., Firstov, S.A. and Trefilov, V.I. et al Phys. Chem. of Mater. Treat., 1981, No. 3, pp. 100-104, in Russian.
- (7) Lung, C.W. and Gao, H., Phys. Stat. Sol. (a), 1985, vol. 87, pp. 565-569.

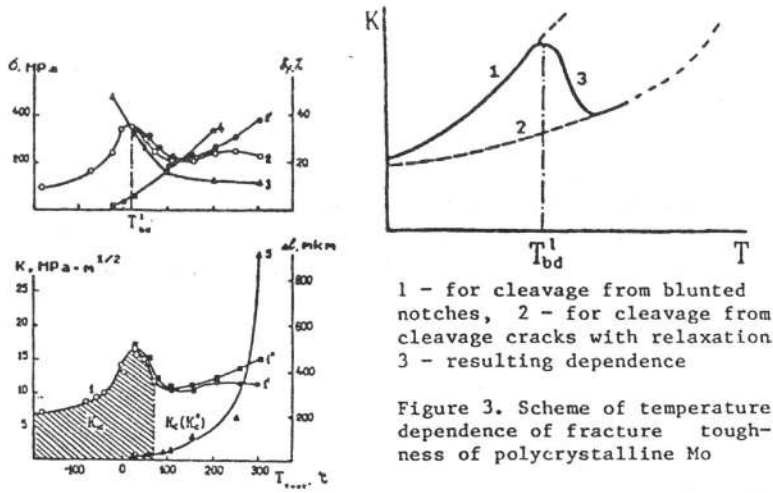
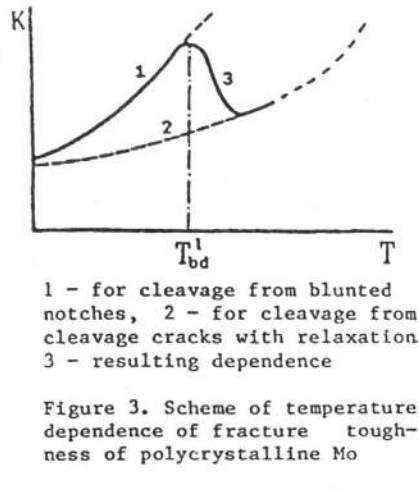


Figure 1. Temperature dependence of mechanical properties of polycrystalline Mo. (1, 1', 1'' - fracture toughness, 2, 2' - fracture strength, 4 - plasticity before fracture, 5 - length of cleavage crack with relaxation)



1 - for cleavage from blunted notches, 2 - for cleavage from cleavage cracks with relaxation, 3 - resulting dependence

Figure 3. Scheme of temperature dependence of fracture toughness of polycrystalline Mo

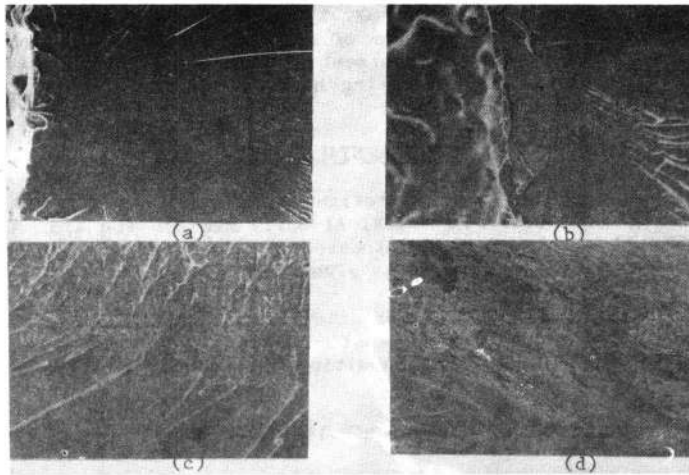


Figure 2. SEM view of the fracture of polycrystalline Mo at different temperatures