

FRACTURE MECHANISMS AND FRACTURE TOUGHNESS OF MOLYBDENUM

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ABSTRACT

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

KEYWORDS

Fracture toughness, fracture mechanisms, brittle-ductile transition, cleavage crack, cleavage with relaxation.

INTRODUCTION

Studies of fracture toughness of thin-sheet materials are of particular interest. These studies permit to use the results obtained in the evaluation of carrying capacity of different construction elements.

There are some difficulties in determination of critical stress intensity factor. They arise from demand to preserve plane strain condition which is not always possible due to the small width of samples used. In such cases other criteria are to used, e.g. critical stress intensity factor for a sample of given width under maximum stress named K_{c0} or its renormed value K_c and J-integral or crack-tip opening displacement δ_c .

In spite of the fact that previously mentioned criteria are in great extent nominal, co-analysis of mechanical tests and fractography data permitted us to fulfil sufficiently correct estimation of changes in fracture toughness of material depending on test condition, namely on temperature.

EXPERIMENTAL PROCEDURE

In present study temperature dependence of fracture toughness of molybdenum sheet 2.25 mm width of alloy CM-10 was investigated, samples were annealed at 2000°C for one hour. Grain size was obtained about 300-400 mkm. Critical stress intensity factor was used as fracture toughness, K_c or K_c^*

were used as general yield has been arisen. Flat samples with two-edge notch with 0.05 mm radius have been tested in tension with the strain rate 10^{-3} s^{-1} in the temperature range $-196 \text{ }^{\circ}\text{C} \dots 300 \text{ }^{\circ}\text{C}$. Tensile tests at the temperature higher than room temperature were performed in vacuum chamber with pressure 0.1 Pa. Samples shape, size and method of fracture toughness calculation were chosen in accordance with Soviet standard (1981). Initial cracks appeared at the tip of electrospark notch, their length being 20-50 mkm.

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 figure, 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 over $100 \text{ }^{\circ}\text{C} \dots 300 \text{ }^{\circ}\text{C}$.

Analysis of mechanical tests shows that conditions of plane strain deformation are preserved in the temperature range up to $70 \text{ }^{\circ}\text{C}$. 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 (1980).

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.

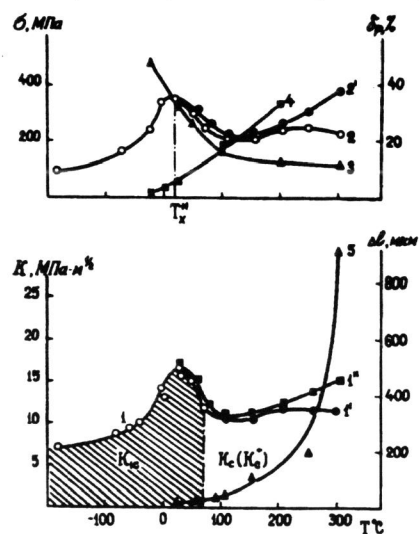


Figure 1. Temperature dependence of mechanical properties of polycrystalline Mo (1, 1', 1'' - fracture toughness, 2, 2' - fracture strength, 3 - yield strength, 4 - plasticity before fracture, 5 - length of cleavage crack with relaxation).

These two facts together with the fractographic peculiarities which will be described later allows us in accordance with Ioffe-Orovan model (1974) to determine room temperature as a lower temperature limit of brittle-ductile transition of notched samples.

Fractographic analysis shows that in the temperature range $-196 \text{ }^{\circ}\text{C} \dots 20 \text{ }^{\circ}\text{C}$ fracture by cleavage proceeds from electrospark cracks, blunted as the test temperature is increased. Therefore if 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

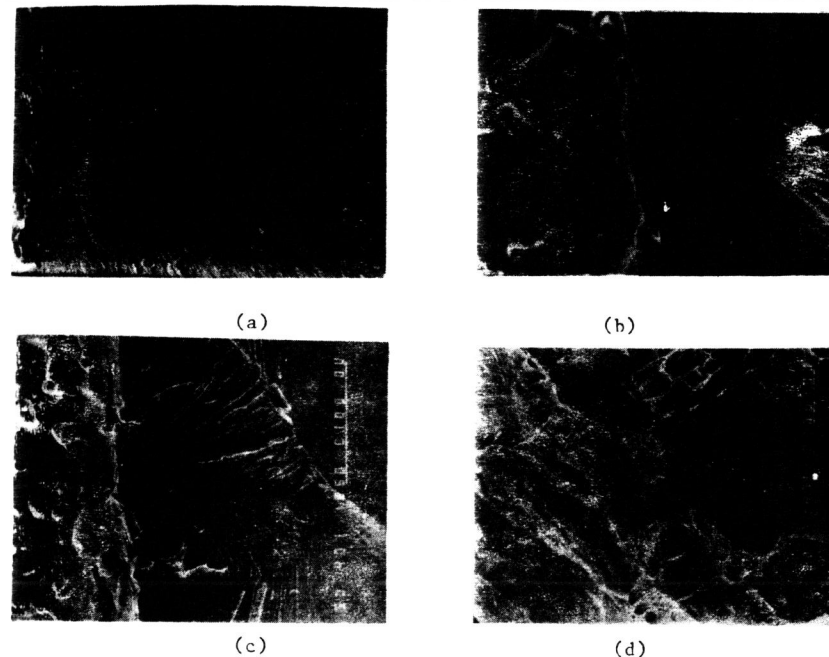


Figure 2. SEM view of the fracture of polycrystalline Mo at different temperatures

can also start from favourably orientated grain boundaries. In the temperature range over 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 (1963, 1961) 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 $300 \text{ }^{\circ}\text{C}$ together with the cleavage and cleavage with relaxation are also observed at the fracture surface ductile fracture elements, intergranular and transgranular delamination (Fig. 2d).

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 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:

$$K_{Ic} = \sigma_p \sqrt{\pi c} \quad (1)$$

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} after chosen formula (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 (1981), Lung and Gao (1985) 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:

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

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 nonmonotony 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 of the mechanism of full fracture in the both cases is the same, it is 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.

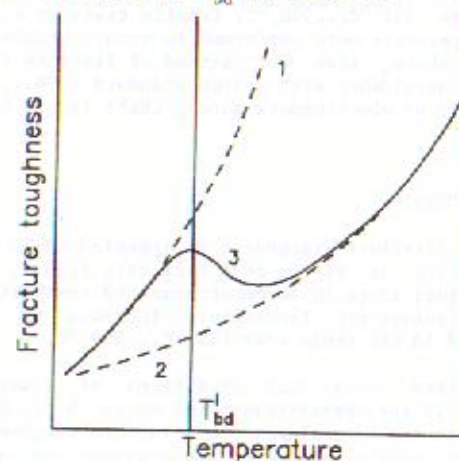


Figure 3. Scheme of temperature dependence of fracture toughness of polycrystalline Mo (1 - for cleavage from blunted notches, 2 - for cleavage from cleavage cracks with relaxation, 3 - resulting dependence).

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.

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