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 $^{\circ}$C...300 $^{\circ}$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 $^{\circ}$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 rangeof-196 $^{\circ}$C...300 $^{\circ}$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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gure, 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 relaxaton 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_{1c}. 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:

$$K_{1c} = \sigma_F \sqrt{\pi c} \tag{1}$$

Analysis of the influence of changes both of crack length and frac-
ture stress on fracture toughness of molybdenum sheet clearly shows
that in the observed temperature range the main reason for decrease
fracture toughness is reduction of fracture stress but not inc-
rease of a crack length, according to the dependence between frac-
ture stress and crack length (1). Further rise of temperature with
continuos 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 temperatu-
res. 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_{1c} according to formulae (1).
It is possible to estimate only its relative value K_c (Fig. 1, cur-
ve 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 frac-
ture toughness of molybdenum, temperature dependence of fracture
toughness of material failured by cleavage may be expressed by
exponential relation:

$$K_{1c} = K_0 \exp\left(-\frac{V_0}{kT}\right) \tag{2}$$

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 molyb-
denum results from the change of fracture mechanisms and, more
exactly, from the change of mechanisms of bearing of cleavage. Be-
fore 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 clea-
vage 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.

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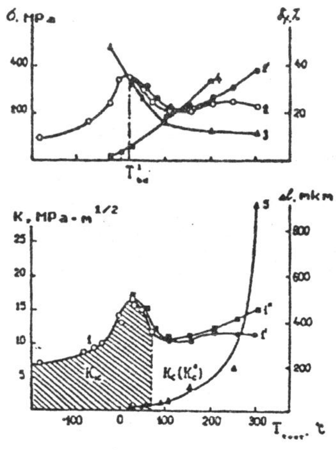

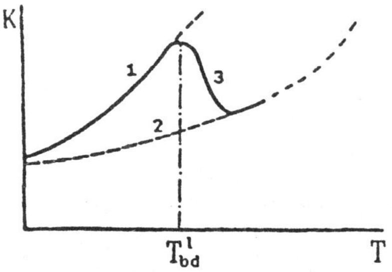

1 - for cleavage from blunted notches, 2 - for cleavage from cleavage cracks with relaxation 3 - resulting dependence

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

Figure 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)

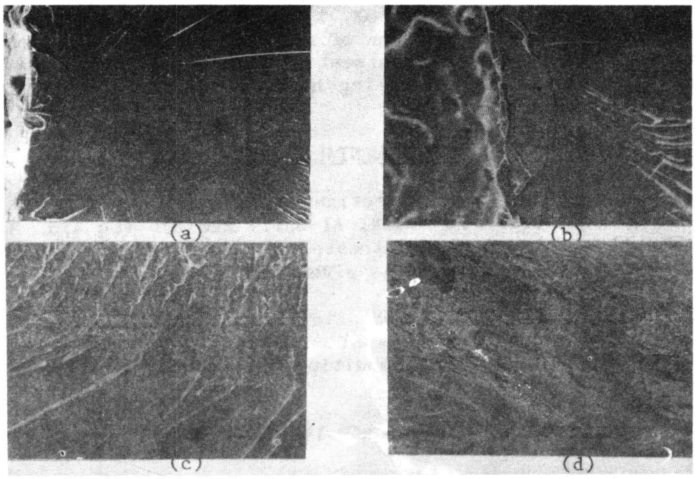

Figure 2. SEM view of the fracture of polycrystalline Mo at different temperatures