THE INFLUENCE OF PLASTIC DEFORMATION ON FRACTURE TOUGHNESS OF MOLYBDENUM

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The influence of structure formed by plastic deformation on fracture toughness of molybdenum by cleavage was studied. It was found that dependence of fracture toughness on degree of deformation is nonmonotonous,what results from structural changes of mobybdenum under deformation. The increase of deformation wighin a single structural state results in the decrease of fracture toughness. Formation of cellular structure results in the growth of fracture toughness due to blunting of cracks by delaminating inter-cellular cracks. That results from the increase of carbon and oxygen concentration on cell boundaries.

INTRODUCTION

Plastic deformation is a way to produce materials with different structures, that allows to study the influence of dislocation structure on failure mechanisms, fracture toughness and other mechanical properties. Along with a considerable strengthening it was found by Trefilov et al (1) that plastic deformation decreases the lower limit of brittle-ductile transition down to -120 °C if the ultrafine-grain structure based on disoriented dislocation cells are ensured. Decreasing of temperature of deformation below 1000 °C leads to drastical growth of mechanical properties anisotropy of deformed metal due to the development of structural anisotropy and the growth of inner stresses on boundaries of cells and grains.

The main purpose of this work was to study the effect of the structure formed by deformation on structure toughness of metal.

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MATERIALS AND METHODS

Molybdenum alloy Mo-0,5Ti was used. Metal was deformed by rolling under temperature 600 and 900 °C.

Fine structure of deformed molybdenum was observed by transmission electron microscope JEM100-CXII (JEOL), chemical composition of boundaries of grains and cells was analysed by Auger electron microanalyser JAMP-10S (JEOL) with fracturing device and working vacuum about $7 \cdot 10^{-8}$ Pa.

Fracture toughness was measured under three-point bending of specimens with electrospark cracks. To measure fracture toughness in rolling plane special techniques was used.

Failure mechanisms were investigated by scanning electron microscope Superprobe-733 (JEOL).

RESULTS

A number of structural changes occurs in material in the course of plastic deformation. On dependance on the degree of deformation we may distinguish three structural states: under small degrees (0 - 15 %) of plastic deformation single dislocations and pile-ups are observed; in region 15 - 60 % the slightly disoriented cellular structure is observed and when exceeding 60 % of deformation misoriented cellular structure may be recognized. With growth of the deformation degree the initially equiaxial cells are drawn in the direction of rolling. Misorientation of cells is increased continuously in the course of deformation, and at its high degree large misorientations prevail.

As is shown in Fig. 1, there are typical bending outlines on boundaries of grains and cells justifying to the presence of elastic deformations. Analysis of the latter's dependence on the distance to boundary, obtained by Zubec et al (2), shows that internal stresses, associated with deformation, diminish in reverse proportion to the distance. In other words, internal stresses have dislocation nature and result from random arrangement of dislocations in boundaries.

However, separate boundaries between cells are free from internal stresses. Increasing degree and decreasing temperature of deformation enhance the named effect.

As was proved by structural analysis of deformed molybdenum, there exist at least three types of boundaries: boundaries of initial grains; relatively small-angle boundaries of cells with high level of stresses; large-angle boundaries of cells that are free from internal stresses.

With growing deformation, the content of impurities on the grain boundaries changes (Fig. 2). We were not able to obtain any information about the impurity content on cell boundaries since in all studied states only grain boundaries revealed themselves under failure tests.

Only 92 % of deformation sometimes helped to observe the cell boundaries, but they cannot be reliably analyzed by methods presently existing. According to fractographic analysis, the grain boundaries in deformed to 92 % molybdenum are the weakest structural element. Apparently the strength of cell boundaries of 92 % deformed molybdenum approaches to the strength of grain boundaries and the former becomes as weak as latter.

In spite of great spread of data (Fig. 2), we would like to emphasize that with growing deformation the content of carbon on grain boundaries decreases. A certain increase in the content of carbon and oxygen on grain boundaries in the specimens deformed by 75 % is the result of intermediate heating after 50 % deformation.

Fractographic analysis of specimens, rolled down to the small degree of deformation (40 %), did not reveal any features in interaction between cleavage crack with structure elements (discrete dislocations, slightly misoriented cells). With growing plastic deformation the change of failure mechanisms from cleavage to ductile fracture and delamination along boundaries of structural elements occurs (Fig. 3). Ductile fracture happens when deformation was increased to 92 %.

The dependence of fracture toughness of molybdenum on the degree of deformation is shown in Fig. 4. It seen that the region of small deformation with single dislocations and pileup is characterized by decreasing fracture toughness, while the appearance of slightly misoriented cellular structure is accompanied with rather sharp increasing K_{1C}. Further growth of deformation leads to misoriented cellular structures, resulting in decreasing fracture toughness in rolling plane and increasing its in perpendicular one.

DISCUSSION

As it is possible to see in the above mentioned data , the change in structural state of material caused by deformation changes the value of the fracture toughness. The fracture toughness decrease at initial stages of deformation results from the yield stress rise and the decrease of fracture stress caused by increasing dislocation density and spot defects as was shown by Korniushin et al (2). Formation of internal interfaces similar to cell boundaries results in a sharp increase of shear stress, therefore, fracture toughness also sharply increases as well as a rise of yield stress.

The further growth of plastic deformation, results in reducing the fracture toughness that is associated with texture changes in material. Fractographic analysis shown that all deformed states of Mo have fractured by cleavage but slightly deformed states were characterized by more smooth fracture surface. At deformations exceeding 40 %, cleavage cracks run practically in one direction. At large deformations (over 75 %), the presence of highly misoriented cells favors intercellular fracture that leads to further decrease of fracture toughness in rolling plane. As far as perpedicular plane is concerned, cleavage is still mainly responsible for failure. The boundaries of highly misoriented cells, being effective barriers for cleavage crack, stimulate the fracture toughness enhancement in this plane.

The most characteristic feature of the interface is the tendency to fail along the boundaries being manifested in the form of delamination. With growing deformation, along with intergranular delamination at 50 % of deformation, there also occurs and increases intercellular delamination which prevails at 92 % deformation (Fig. 4). Delamination is a specific mechanism of failure resulting from the presence of tensile stresses which are lateral and longitudinal with respect to the main crack. When the crack interact with interface, such stresses are able to delaminate structural elements if the bond strength is rather low. In the main crack tip the cross delaminating cracks are arisen that blunts the crack tip and promotes raising the fracture toughness.

As was mentioned above, the effects associated with inner stresses are not found on large-angle boundaries, and this tendency enhanced with the deformation growth. Fine structure investigations demonstrate that in highly deformed metal there already exist the delaminating cracks on some large-angle boundaries which results in disappearance of internal stresses on these boundaries. A partial delamination has taken place on certain cell boundaries. Internal stresses are distinctly visible on intact parts of boundaries while they are absent on delaminated ones (Fig. 1). This happens since the stresses relaxed here due to formation of free surface. On the other hand, no cracks were found on a number of large-angle boundaries without internal stresses. Apparently, these boundaries are free from the stresses due to the return of their structure as Vasilev et al (4) have shown. Perhaps also that they are boundaries between texture components.

Thus, in molybdenum intertnal stresses resulting from deformation are removed either due to the return of structure of the inner interfaces or due to intercellular and intergranular delaminations.

Comparison of the results of analysis the structure, chemical heterogeneity and failure mechanisms gives grounds to conclude that low concentration of carbon and insufficiently high stresses is the main reason for the absence of intercellular delamination at the

50 % deformation. Stresses and segregations complement each other and only their combined action can result in delamination.

CONCLUSIONS

1. The change of structural state pedetermines the variation of fracture toughness. The deformation degree increase within a single structural state (with single failure mechanism) results in the decrease of crack resistance.

2. Introducing in material the new delaminating interfaces results in increasing fracture toughness due to blunting cracks. High fracture toughness in the plane perpendicular to the direction of rolling is caused by formation of laminated structure in the form of drawn cells with rather weak boundaries. Fracture toghness in the plane of rolling is minimal.

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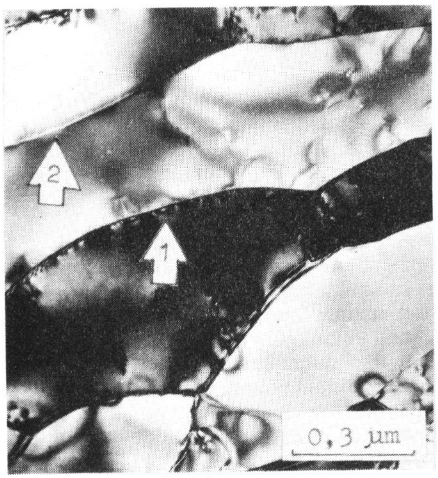


1 - the inner stresses,
2 - the crack.

Figure 1. Fine structure of deformed (75 %) molybdenum

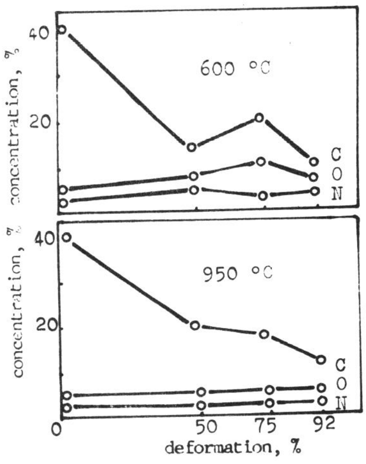


Figure 2. Content of impurities on grain boundaries vs degree of deformation

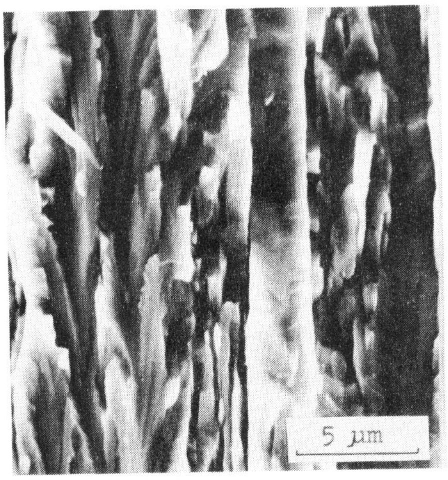
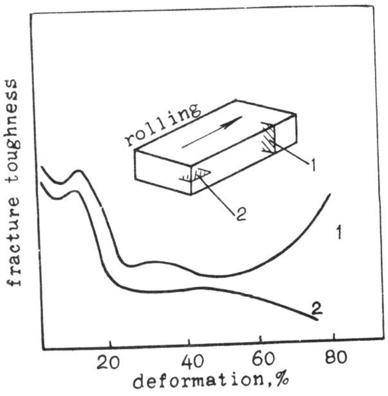


Figure 3. SEM view of fracture of deformed (92%) molybdenum



1 - across plane,
2 - rolling plane

Figure 4. Fracture toughness of molybdenum vs degree of deformation