FRACTURE MECHANISMS AND FRACTURE TOUGHNESS OF CHROMIUM

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ABSTRACT

Fracture toughness, fracture mechanisms and fractographic features of polycrystalline chromium alloys have been studied at temperature range from 77K to 1073 K. The fracrographic analysis shows that brittle fracture of chromium occurs by the cleavage. Using the scanning electron microscopy stereoscopic technique it has been found that chromium is characterized by the cleavage crack branching. The shape of the crack front at the moment of branching is about square and it does not depend on the shape of specimen. The stress state determines both the temperature range of the brittle-ductile transition and mechanisms of fracture. The least square method is used for the approximation of temperature dependence of fracture toughness. An activation energy obtained from the dependence is 0,068 eV.

KEY WORDS

Fracture, fractography, fracture machanism, fracture toughness, brittle materials, clevage, crack branching, crack shape at the moment of branching.

INTRODUCTION

The essential fractographic difference of chromium from other body-centered cubic metals, as has been noted by Vasilev et al (1985), consists in a practically complete absence of intergranular fracture and delamination. Cleavage with periodic relaxation is seldom observed in it. A division of deformed chromium specimen during fracture into three parts with a formation of a biconcave muff in a middle part of a specimen is also rather unusual, as was shown by Bullen et al (1970), Brodnikovsky et al (1992) and others.

An assumption has been made by Bullen et al (1970) that the above fracture feature is resulted from crack branching. Yoffe (1951) attempted to explain the branching of cracks from an analysis of the problem of a moving crack. From this solution she found that the naximum stress acted normal to lines that make an angle of 60° with the direction of crack propagation when the crack velocity exceeded 60% of the shear wave speed. She suggested that this fact might cause the crack to branch. Congleton and Petch (1967) developed a theory in which branching occurs when critical stress intensity factor, K_B, is achived. A crack is subjected to branching when a stress intensity factor at a crack tip exeeds a fracture toughness, K_{IC}, Anthony and Congleton (1968).

This research deals with the fracture toughness, crack branching, and mechanisms of fracture within the temperature range of the brittle-ductile transition and brittle fracture in chromium.

MATERIALS AND TECHNIQUES

The alloy examined was chromium containing 0,3 La, 0,3 Ta, 0,3 V, 0,02 C, 0,01 O and 0,015 N (in wt. %). Active elements (La, Ta, V) were introduced to increase the plasticity by purification of solid solution from C, N and O. The rods deformed by the extruding had grain size 5-10 microns. Some of them were recrystallized in vacuum at 1273 K for 1 hour. This procedure resulted in an increase of average grain diameter up to 30 microns. The fracture toughness of materials was tested by a tension of round spesimens with circular notch. To make a sub-critical crack in chromium is rather difficult task. A sharp crack created easily spreads through cross section of specimen (Sally, 1971). Therefore fatigue crack was not grown. Uniaxial tension of round samples was carried out under the temperature range 77 K - 1073 K at the deformation rate about $10^{-3}s^{-1}$. Fracture mechanisms were studied with scanning electron microscopes JSM-T20 and "Superprobe-733" (JEOL).

EXPERIMENTAL PROCEDURES

Fracture Toughness. The dependence of the fracture toughness of the alloy on the test temperature is presented in Fig. 1. These data were obtained for small specimens (diameter 3 mm) at temperatures from 77 K and 293 K to large specimens (diameter 10 mm) at higher temperatures. The increase of the spesimen size allows to keep the plane deformation condition at high temperature.

The least square line of the best fit gives the folowing correlation between the fracture toughness and test temperature:

$$K_{IC} = A\exp(BT) \qquad (1)$$

where A and B are constants. For deformed material A is 2,17 $MPa.m^{1/2}$ (the fracture toughness for T = 0 K) and B is $3,6x10^{-3}$ K^{-1}. The dependence corresponds to a one obtained by Lung and Gao (1985).

Crack Branching. The fractographic analysis shows that the brittle fracture of the deformed and recrystallized chromium occurs by cleavage (Fig. 2, Fig. 3,a).

By the stereoscopic technique using the scanning electron microscopy it has been found that chromium is characterized by the cleavage crack branching. The crack arising in the perpendicular direction to the extention axis branches into two cracks going further under the angle about 35° to the starting direction and forming a square shape aperture in a muff (Fig. 2,a). As a result of this the specimen may be divided into three parts with formation of a beconcave muff.
The specimen is separated into three parts when the branching cracks reach its side surface. In some cases (the low testing temperature or the big size of grains) one of the cracks may not reach the side surface and the specimen is separated into two parts but the place of the branching is clearly seen (Fig. 2,b).

The crack shape at the moment of branching is about a square and it does not depend on the shape of specimen. When the rectangular cross-section specimens are tested, the crack front sides at the moment of branching are oriented at the angle approximately 45° to the side surfaces of the specimen (Sameljuk at al, 1990). The crack front shape is preserved during the crack propagation after the branching and is also almost a square at the moment of the second branching.

Mechanisms of Fracture. The ductile fracture by pores coalescence (Fig. 3,b) arose at 473 K for small notching specimens deformed and annealed chromium and at 873 K for large notching specimens in deformed state. The pores were formed at the second phase particles. The small specimens of the annealed chromium are fractured in this manner at temperature range from 473 K to 873 K. At higher temperatures (up to 1073 K) pores were formed at grains boundaries. The fracture is caused by the delamination at grain boundaries and the stretch of grains to a knife (Fig. 3,c).

The ductile fracture was not observed in large specimens of the recrystallized chromium. The brittle intergranular fracture (Fig. 3,d) was formed at the notch tip at 823 K and higher temperatures. The area of the brittle intergranular fracture connecting with the propagation of the intergranular crack increased with test temperature.

The transcrystalline brittle cleavage was observed in the case of the behind-critical crack propagation. Due to the formation of the sharp intergranular crack the brittle cleavage was kept until higher temperatures. The signs of the dimple fracture was revealed only at 1073 K.

DISCUSSION

The change of the plane stress state to the plane deformation one at the crack tip increases the brittle-ductile transition temperature. In addition sub-critical brittle intergranular crack arises at the notch tip. The appearance of a sharp crack at the notch tip permits to keep the plane deformation state in the specimens up to high temperature.

Crack branching is known as the phenomenon in brittle materials (glasses and ceramics) where it is widely used to estimate the fracture toughness (Mecholsky and Freiman, 1979). Anthony and Congleton (1968) pointed out that branching occurs only over a small range of values of the ratio K_B/K_{IC}. Branching is not common in metals, because of the absorption of energy by mobile dislocations and by tearing at grain boundaries in polycrystals. That is why for metals the crack branching is practically unknown.

The above fractographic data (Fig. 2.) show that the crack branching is inherent in chromium. The chromium has a low fracture energy compared with other BCC metals: molybdenum (Vasilev at al, 1981) and iron (Romaniv, 1979). It enables to reach a critical stress intensity of branching in chromium.

The yield stress of material being investigated is described by the equation (Milmam at al, 1983)

$$\sigma_y = \sigma_0 \exp(U_0/3KT) \qquad (2)$$

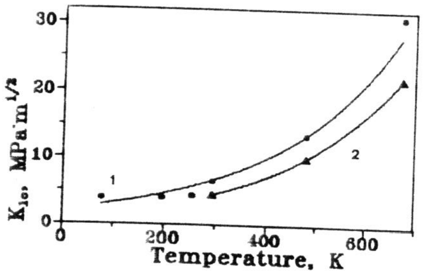
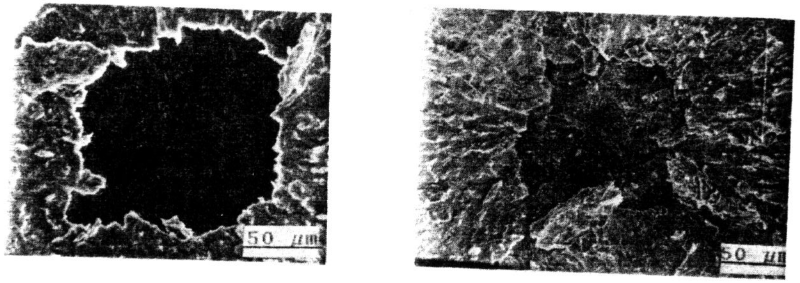
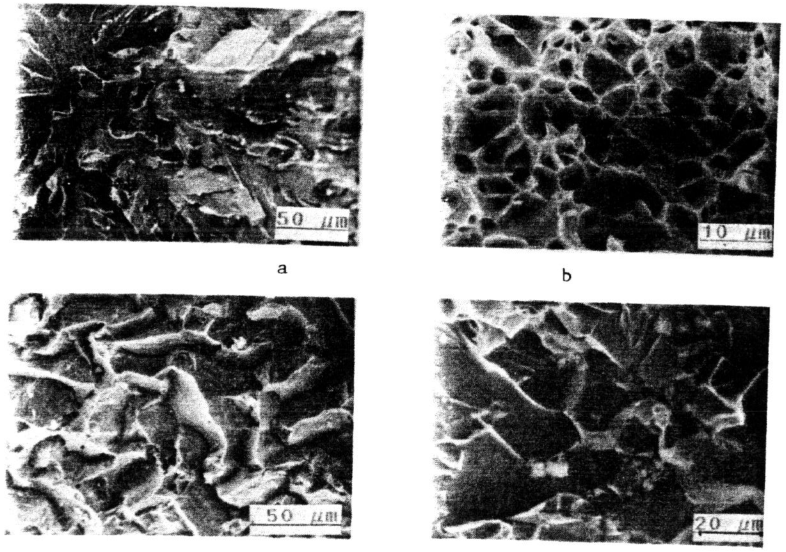


Fig. 1. The variation of fracture toughness of deformed (1) and annealed (2) chromium with test temperature.



a b

Fig. 2. The shape of the crack front at the moment of branching when the muff was removed (a) and not (b).



a b c d

Fig. 3. SEM microphotographs chromium fracture surface in deformed (a - T = 293 K, b - T = 823 K, c - 973 K) and recrystallized (d - T = 923 K) states.

where K is Boltzmann's constant, U_o is an activation energy of plastic deformation, σ_o is an constant. The activation energy obtained from these data is about 0.07 eV.

Lung (1985) and Vasilev et al (1981) found that the same process controls the temperature dependences of yield stress and fracture toughness. Therefore B is $3K/U_o$ in equation (1). The activation energy obtained from the temperature dependence of the fracture toghness is about 0.068 eV.

CONCLUSIONS

1. The plane deformation state in the tensile specimen may result in the brittle intergranular fracture which is not typical for chromium.

2. The manner of chromium fracture is caused by the cleavage crack branching. The phenomenon is accounted for by low fracture energy.

3. The temperature dependece of fracture toughness of chromium can be described by the equation

$$K_{IC} = K_o\exp(3KT/U_o) \qquad (3)$$

where K_o is a fracture toughness for T = 0 K and U_o is an activation energy. For the deformed chromium K_o is 2,17 MPa.m$^{1/2}$ and U_o is 0,068 eV. Activation energies obtaned from temperature dependences of fracture toughness and yield sress coincide.

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