Effect of Pressure on the Temperature of Brittle-Ductile Transition in BBC Crystals

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Abstract. The change in plasticity of polycrystalline molybdenum and tungstem under pressure is studied for different temperatures (180–673 K for molybdenum, and 423–873 K for tungsten). Samples were deformed by tension to fracture at atmospheric and different hydrostatic pressures to 1150 MПa. It is shown that effect of pressure in increase of plasticity depends on the relaton between deformation temperature T_d and the temperature of brittle-ductile transition T_{bd}. For $T_d > T_{bd}$ increase of plasticity of molybdenum takes place without critical pressure and for $T_d < T_{bd}$ the plateau of zero plasticity appears on the curve $\lambda_p = \lambda$ (p). It is estblished that the relationship between λ_p and pressure is discribed by the equation $\lambda_p = \lambda_o^T + k_1(p - p_{crit.})^n$. Pressure dependence of T_{bd} is described by the equation $T^0_{bd} - T^P_{bd} = k_2 p^m$, where $m < 1$. The physical explanation of the nature of critical pressure is given.

Introduction

The study of the effect of different factors on the temperature of brittle-ductile transition is necessary for understanding of the physical nature of BCC metal brittleness. It is well known that the brittle-ductile transition of metals is controlled by a number of factors, such as temperature, strain rate, structure parameters, and pressure. However, little quantitative experimental data relating to study of influence of pressure on the temperature of brittle-ductile transition of BCC metal are available [1-4]. At deformation under normal pressure the ductile of these metals is small. Pressure raises the ductile properties of these metals, thus broadening the range of attainable degrees of deformation. It allows defining more precisely the relationship between the temperature of brittle-ductile transition and pressure.

The purpose of the present investigation was to study the temperature of brittle-ductile transition of polycrystalline molybdenum and tungsten as a function of pressure in order to obtain a complete picture of deformation behavior of these materials. Molybdenum and tungsten were selected because they have strongly different temperatures of the brittle-ductile transition.

Experimental procedure

The study was carried out on rods of commercially “pure” polycrystalline molybdenum (MCh) and tungsten (BA), which underwent rotational forging and annealing in vacuum at the high temperature. Tensile specimens having a gauge length of about 20 mm and a diameter of about 2 mm were prepared from such rods. The specimens were tested in tension at various temperatures and pressures in a high-pressure device at a nominal strain rate of 4.2^{-2} per second. The change of plasticity of molybdenum and of tungsten under pressure was studied for various temperatures (180–673 K for molybdenum and 423–873 K for tungsten). The maximum hydrostatic pressure in the experiment ran up to 1150 MPa. A scanning electron microscope microscope was used to analyze the fracture surface. In this investigation, we took the deformation temperature at which specimens were broken brittle as the temperature of the brittle-ductile transition T_{bd}. Plasticity as limiting degree of deformation before fracture is given by

$$\lambda = 2\sqrt{3}\ln(d_0/d_P) \qquad (1)$$

where d_0 is initial diameter and d_P is diameter of specimen in the place of break.

Results

Fig. 1 shows the curves of the plasticity λ_T at atmospheric pressure, obtained by formula (1), for molybdenum in the interval of temperatures 180–673 K and for tungsten in the interval of temperatures 423–873 K. These $\lambda^{Mo} = \lambda(T)$ and $\lambda^{W} = \lambda(T)$ curves show the maximum deformation of specimens before fracture at various temperatures. At deformation temperature $T_d \leq T_{bd}$ specimens of molybdenum and tungsten are broken without plastic deformation. At deformation temperature above T_{bd} the material receives some plasticity which continually increases with the growth of temperature. The temperature for brittle-ductile transition of molybdenum is 273 ± 3 K, and for tungsten – 558 ± 4 K.

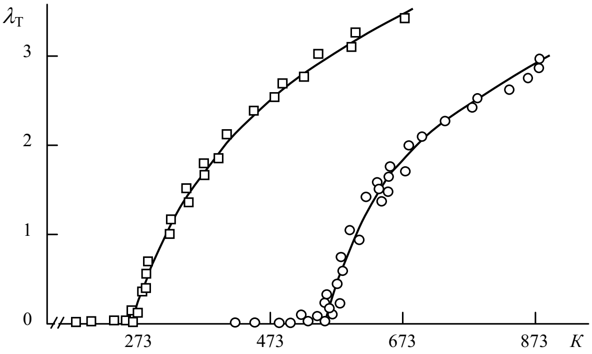

Fig .1. Dependence of the maximum deformation of molybdenum and tungsten before fracture versus temperature at atmospheric pressure: □ – molybdenum; ○ – tungsten.

The change of plasticity in polycrystalline molybdenum and tungsten depending on pressure for various deformation temperatures is shown on Fig. 2 and 3. From the obtained curves $\lambda_p^{Mo} = \lambda$ (p) we can see that at every T_d (except 180 K) the small increase in pressure immediately leads to an increase in initial plasticity. The shape of the $\lambda_p^{Mo} = \lambda$ (p) curve obtained at deformation temperature 180 K is different from that of others curves. This curve at pressures less than 200 MPa shows no increase in plasticity. The rise of plasticity takes place only beginning from some pressure which can be called the critical pressure of brittle-ductile transition ($p_{crit.}$). The obtained curves $\lambda_p^{W} = \lambda$ (p) also show that at temperatures of deformation below T_{bd} occurrence of plasticity and its growth with increase in pressure occurs only after achievement of some critical pressure for corresponding temperatures [4]. The shape of $\lambda_p = \lambda$ (p) curves does not vary with increasing deformation temperature, however all these curves are displaced toward greater pressures with changing pressure.

The plasticity of molybdenum and tungsten at deformation temperatures below than T_{bd} increases only beginning with the pressure $p > p_{crit.}$. The appearance of the plateau of zero plasticity is connected with the complete exhaustion of plasticity at deformation temperatures below T_{bd}, because the level of stresses required for plastic deformation becomes more the fracture stress. Therefore, in this case the effect of pressure is shown not at once, but only after elimination of "negative plasticity" of a material by means of critical pressure.

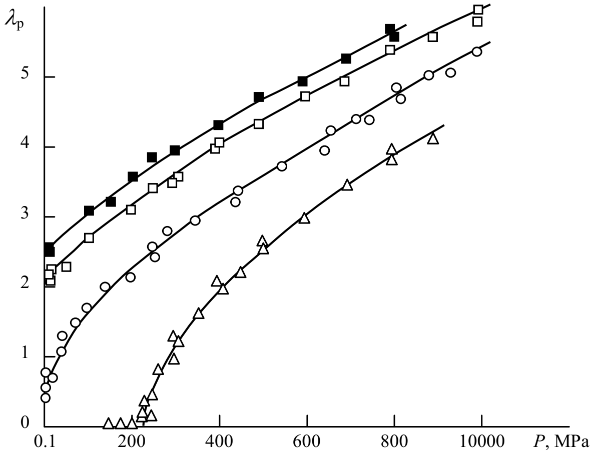

Fig. 2. Dependence of plasticity of molybdenum on pressure at different temperatures:
Δ – 180 K; o – 290 K; □ – 408 K; ■ – 463 K.

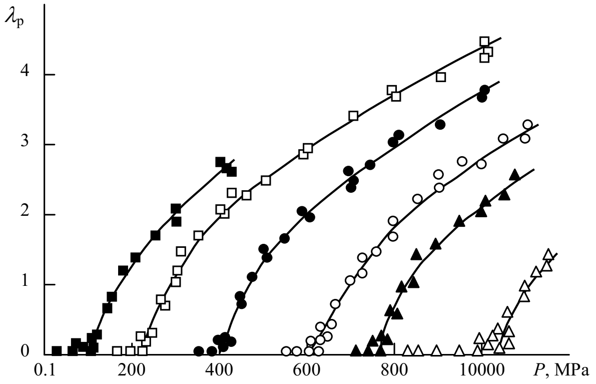

Fig. 3. Dependence of plasticity of tungsten on pressure at different temperatures:
Δ – 290 K; ▲ – 338 K; o – 363 K; ● – 408 K; □ – 463 K; ■ – 508 K.

The appearance of zero plasticity plateau can be explained as follows. At deformation temperature $T_d \leq T_{bd}$ the shear stress σ_s is is less or equally fracture stress σ_f. In order to make the material ductile at deformation temperatures $T_d \leq T_{bd}$, it is necessary to increase σ_f or to decrease σ_s. Pressure influences the shear stress σ_s for BCC metals is relatively slight. It can be considered practically constant at pressures used in this study. However, pressure hinders the formation and development of cracks. Therefore pressure influences essentially the fracture stress σ_f, increasing it with growth of pressure. At a certain pressure $p_{crit.}$, the level of fracture stress becomes higher than the shear stress σ_s, as a result of which the stress relaxation in the material during deformation will once again be achieved by dislocation motion.

The shape of all curves in Fig. 2 and 3, at used pressures, does not vary at transition through the temperature of ductile-brittle transition. Therefore if we will consider that pressure influences only the origin and the growth of the cracks, these curves can be described by the identical equation. In fact, if the pressure dependence of $\lambda_p = \lambda$ (p) will be plottted on a logarithmic plot; it is linear over a wide range of pressures. From this follows, that the dependence $\lambda_p = \lambda$ (p) can be expressed by the equation

$$\lambda_p = \lambda_0^T + k_1 (p - p_c)^n \qquad (2)$$

where λ_0 is the initial plasticity of molybdenum or tungsten for the test deformation temperature at atmospheric pressure, λ_p is the plasticity of metal for this temperature at pressure p; k_1 is the coefficient of proportionality ($k_1 = 0.84$); $n = 0.6 \pm 0.01$.

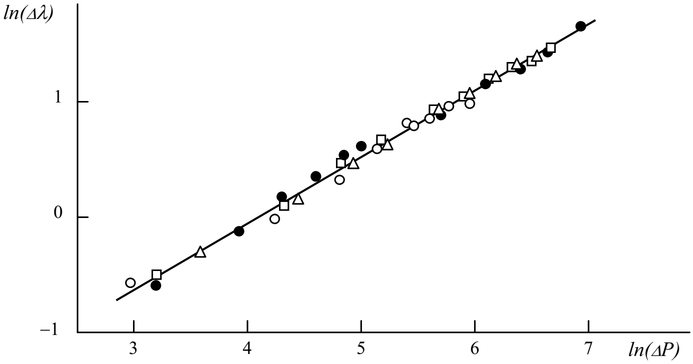

Fig. 4. ln(Δλ) of as a function of ln (ΔP) for molybdenum (Δ – 180 K; o – 290 K) and tungsten (● – 363 K; □ – 463 K).

Fig. 5 shows the pressure dependences of the temperature of brittle-ductile transition for molybdenum and tungsten. As seen in Fig. 5, the temperature of brittle-ductile transition with increase in pressure changes on the concave curves. The total drop of the temperature of brittle-ductile transition is 93 K per 225 MPa for molybdenum, and is 268 K per 1050 MPa for tungsten. Experimental dependence between the temperature of brittle-ductile transition and pressure is described by equation

$$T_{bd}^{0} - T_{bd}^{P} = k_2 p^m \qquad (3)$$

where T_{bd}^{0} is the temperature of brittle-ductile transition at atmospheric pressure; T_{bd}^{P} is the temperature of brittle-ductile transition at pressure p; k_2 is the coefficient of proportionality; m = 0.71.

Conclusions

1. The pressure dependence of λ_p of molybdenum and tungsten is discribed by the equation $\lambda_p = \lambda_o^T + k_1 (p - p_c)^n$.
2. The pressure dependence of T_{bd}^{P} is discribed by the equation $T_{bd}^{O} - T_{bd}^{P} = k_2 p^m$.

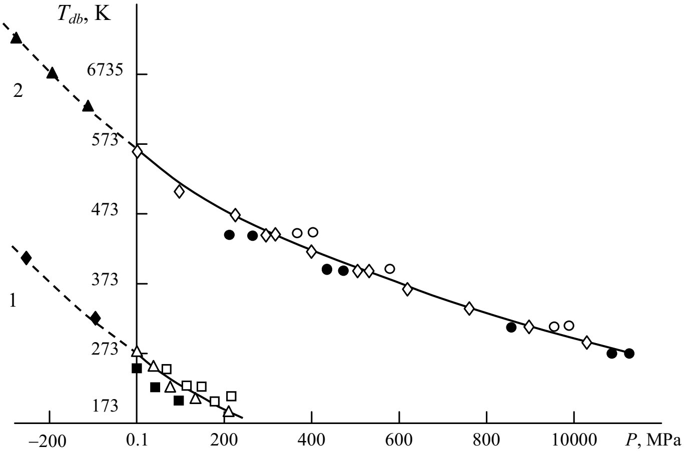

Fig. 5. Effect of hydrostatic pressure on the temperature of brittle-ductile transition of molybdenum (1) and tungsten (2): ●, ■ – brittle fracture; ▲, ♦ – the numerically calculated values by Eq. (3).

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