HIGH-TEMPERATURE FRACTURE TOUGHNESS OF TUNGSTEN AND TUNGSTEN-BASED ALLOYS

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The methodological aspects are considered for studies on fracture toughness of refractory materials. The results are presented for fracture toughness tests of different structural tungsten-based alloys over a wide temperature range of 293 to 2273 K. For each alloy the specific features, as well as for all the materials tested the general regularities of the fracture toughness variation with temperature are established which are described by the $K_{Ic} - T$ curves with the maximum at the brittle-to-ductile transition temperature and a decrease of fracture toughness at higher temperatures. The correlation is found between K_{Ic} and $\sigma_u, \sigma_{0.2}$.

INTRODUCTION

The progress in modern engineering is essentially determined by the level of service temperatures. Accordingly, refractory metals, in particular tungsten and tungsten-based alloys, find more extensive application as structural materials. Technological and structural defects contributing to the initiation of micro- and macrocracks in service are inherent in this type of materials obtained by the powder metallurgy method. In addition, these materials are brittle at ambient temperatures and tend to high-temperature embrittlement which reduces their grain-boundary strength. Therefore, when making choice of a structural refractory material, along with such conventional characteristics of mechanical properties as the ultimate strength σ_u , the offset yield stress $\sigma_{0.2}$, etc.,one must know the fracture toughness characteristics of materials over a wide temperature range.

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At the same time, the problems associated with the investigation into high-temperature fracture toughness of refractory materials have not been sufficiently reported in literature and remain topical and important.

MATERIALS AND EXPERIMENTAL PROCEDURE

Studies were conducted on different structural refractory tungsten-based alloys obtained by the powder metallurgy method which involve sintered hot-deformed commercially pure tungsten, the precipitation hardened tungsten alloy, the tungsten-molibdenum composition and the tungsten-copper pseudoalloy.

Fracture toughness tests were conducted with small scale compact tension specimens of $(32.5x31.2x6.5)x10^{-3}$m in statics, vacuum of about $1.3x10^{-2}$ Pa over the temperature range of 293 to 2273 K, with the cross-head speed of about 0.3 m/h and the load-displacement diagram recording making use of the testing machine VURT-1 designed at the Institute for Problems of Strength of the Ukrainian Academy of Sciences and described by Babak and Uskov in (1). The rate of heating was $2 \cdot 10^2$ degrees per minute, exposure at a given temperature constitutes 0.5 hour.

Since the adopted techniques for crack initiation prove to be unadequate for tungsten, to this effect the original procedures were employed based on the method of static wedging with controlled lateral compression which is reported by Babak and Uskov in (2).

For refractory materials, the critical stress intensity factor K_{Ic} was chosen to be the fracture toughness parameter which is given by the known expression of linear fracture mechanics (LFM) reported in (3)

$$K_Q = \frac{P_Q Y}{t \sqrt{b}}$$

where P_Q is the calculated load at the initial crack onset; Y is the specimen shape coefficient, t is the specimen thickness and b is the specimen width.

The calculated load was assumed to be either the maximum load or the load determined by the rule of the 5 % secant reported in (3).

The validity of the LFM approaches for evaluation of fracture toughness of refractory alloys is confirmed by the results of investigation into the dependence of the parameter K_{Ic} on the size effect and crack initiation conditions involving the type of loading and temperature, as well as studies on specimen behaviour in fracture. It was shown by Troshchenko et al (4) that the parameter K_{Ic} is invarient to the specimen thickness variation within the range of $5 \cdot 10^{-3}$ and $25 \cdot 10^{-3}$ m, as well as the initial and current crack length over the whole temperature range; fracture of the specimens was predominantly brittle.

Basing on the results obtained, thickness of the compact tension specimens for the fracture toughness tests should satisfy the following size requirements which are reported in Babak and Uskov (5)

$$t;\ \ell;\ b-\ell \geqslant 0.15\,(K_{Ic}^{T}/\sigma_{0.2}^{T})^{2}$$

where K_{Ic}^{T} and $\sigma_{0.2}^{T}$ are, respectively, the fracture toughness parameter and the offset yield stress at corresponding values of T ; ℓ is the initial crack length. The accelerated testing technique for refractory alloys is suggested basing on the data which show that the value of the parameter K_{Ic} at higher temperatures is independent on specimen pre-tension, as well as crack initiation at lower temperatures. The fracture toughness testing technique involves the recurrent usage of a single specimen at different temperatures which exceed the brittle-to-ductile transition temperature T_{tr} for the given material when considering the region of the stable crack growth. The single specimen technique makes it possible to obtain the temperature dependence on the factor K_{Ic} . Here the factor is given by the formula from Babak and Uskov (5)

$$K_{Ic}^{T} = \frac{P_{a}^{T} \cdot Y}{t\sqrt{b}}\,(1+\beta)$$

where P_{a}^{T} is the calculated load at crack onset with temperature T ; β is the correction factor which takes into account the initial crack length, averaged crack extension in one testing and the consecutive number of the test.

The fracture toughness dependences on temperature for the refractory alloys studied which were obtained in 10 to 12 specimen testing (with 2 to 3 specimens tested at each temperature level) practically coincide with those observed for a single specimen accelerated technique.

TEST RESULTS AND DISCUSSION

Figure 1 shows the regularities of the fracture toughness variation for the different structural refractory tungsten-based alloys over the temperature range of 293-2273 K.

In Figure 1a curve I describes commercially pure tungsten characterized by the presence of the maximum in the fracture toughness-temperature dependence at the temperature T_{tr} which corresponds to the brittle-to-ductile state transition temperature, the exponential nature of the parameter K_{Ic} growth close to the above temperature, which is accounted for the diffusion grain-boundary processes, and the irreversible reduction in the material fracture toughness at higher temperatures due to the high-temperature embrittlement. The latter is confirmed by curve 2 in figure 1a where the material annealed at 2473 K for one hour shows rather low fracture toughness, the values of which remain almost invariable over the whole temperature range studied (293 to 2273 K).

Commercially pure tungsten hardening by precipitation refractory oxides improves its fracture toughness at temperatures over 1073 K (Figure 1b) but this is accompanied by temperature range broadening in which the unstable crack growth is observed (in Figure 1 the above ranges are shown in section lining) while the brittle-to-ductile transition temperature region shifts to higher temperatures. All these factors should be taken into account for precipitation hardened tungsten-based alloys when used as structural materials.

The tungsten-molybdenum composition in the as-delivered (curve 1) and annealed state (curve 2), which are shown in Figure 1c, is characterized by the same regularities in fracture as commercially pure tungsten but the materials of the given class show more pronounced workability, their brittle-to-ductile transition temperature T_{tr} is lower compared to other tungsten-based alloys, for the temperatures over T_{tr} their fracture toughness is rather high making the above materials effective among structural materials.

The fracture toughness-temperature dependence of the tungsten-copper pseudoalloy (shown in Figure 1d by curve 1) is characterized by several extreme points which are accounted for both the brittle-to-ductile transition state and the physical state variation of copper upon its fusion T_f^{Cu} through its complete subsequent evaporation $T_{c.ev.}^{Cu}$. Copper fusion causes the significant reduction in fracture toughness and stipulates the unstable crack growth at temperatures exceeding T_f^{Cu} . Copper dealloyed materials through high-temperature annealing at 2073 K for one hour did not show fracture behaviour typical for the tungsten-copper pseudoalloy in the as-delivered state and the fracture toughness-temperature dependence for this material (Figure 1d, curve 2) is identical to that of commercially pure tungsten heat-treated according to the above conditions.

Making the analysis of the data presented in Figure 1 it is possible to single out the specific features not only of each material but also the general regularities of the fracture toughness variation for the alloys studied which involve the presence of the maximum in the brittle-to-ductile transition temperature region T_{tr} , the exponential nature of the parameter K_{Ic} growth close to the above temperatures, the irreversible reduction of fracture toughness at higher temperatures.

With the account taken of the above general regularities for the refractory alloys studied in high-temperature loading and to improve their fracture toughness, the original conditions of heat-treatment were worked out at the brittle-to-ductile transition temperatures which are considered in (6). Figure 2 shows the results for the effect of the above treatment on fracture toughness of commercially pure tungsten (Figure 2a), the precipitation hardened tungsten alloy (Figure 2b), the tungsten-molybdenum composition (Figure 2c) and the tungsten-copper pseudoalloy (Figure 2d). The dash lines show the material behaviour in the initial state, the solid lines describe the material behaviour after heat-treatment (open symbols refer to thermal cycling, solid symbols stand for quenching). As is seen, heat-treatment of the tungsten-based alloys studied makes it possible to improve fracture toughness at high temperatures.

Figure 3 shows the temperature dependences on the short-term strength (σ_u , $\sigma_{0.2}$) and fracture toughness (K_{Ic}) for commercially pure tungsten in absolute (open symbols) and relative (solid symbols) units, the latter are the percentage ratio of the values of the above characteristics at different temperatures to their maximum values -(in Figure 3, the latter are observed at a temperature of 873 K). The coincidence of the above dependences expressed in the relative units testifies to the correlation between the fracture toughness and short-term strength characteristics. For tungsten the following numerical relations are established: $K_{Ic} = 0.127\ m^{1/2} \cdot \sigma_u = 0.183\ m^{1/2} \cdot \sigma_{0.2}$. They make it possible to evaluate fracture toughness of tungsten with a high degree of confidence basing on the short-term strength characteristics over the temperature range studied.

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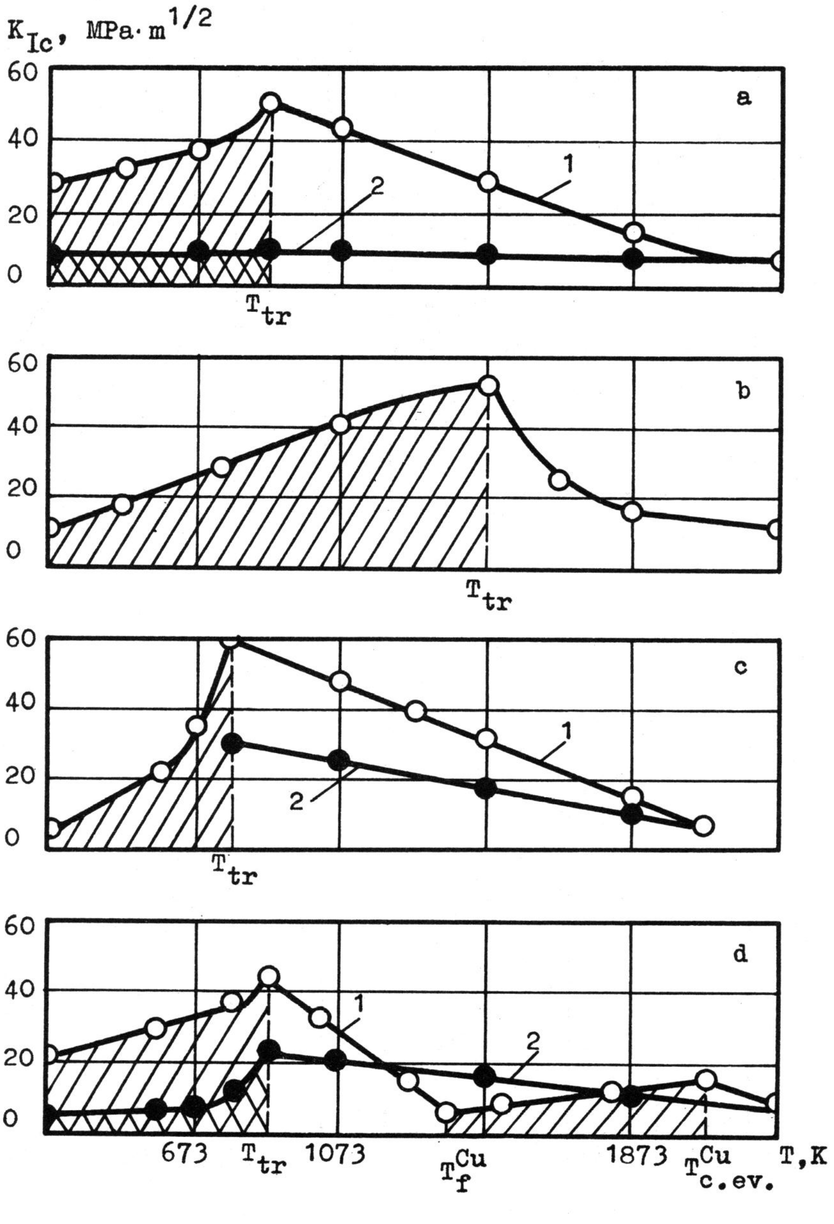

Figure 1 Fracture toughness - temperature dependence for structural tungsten alloys

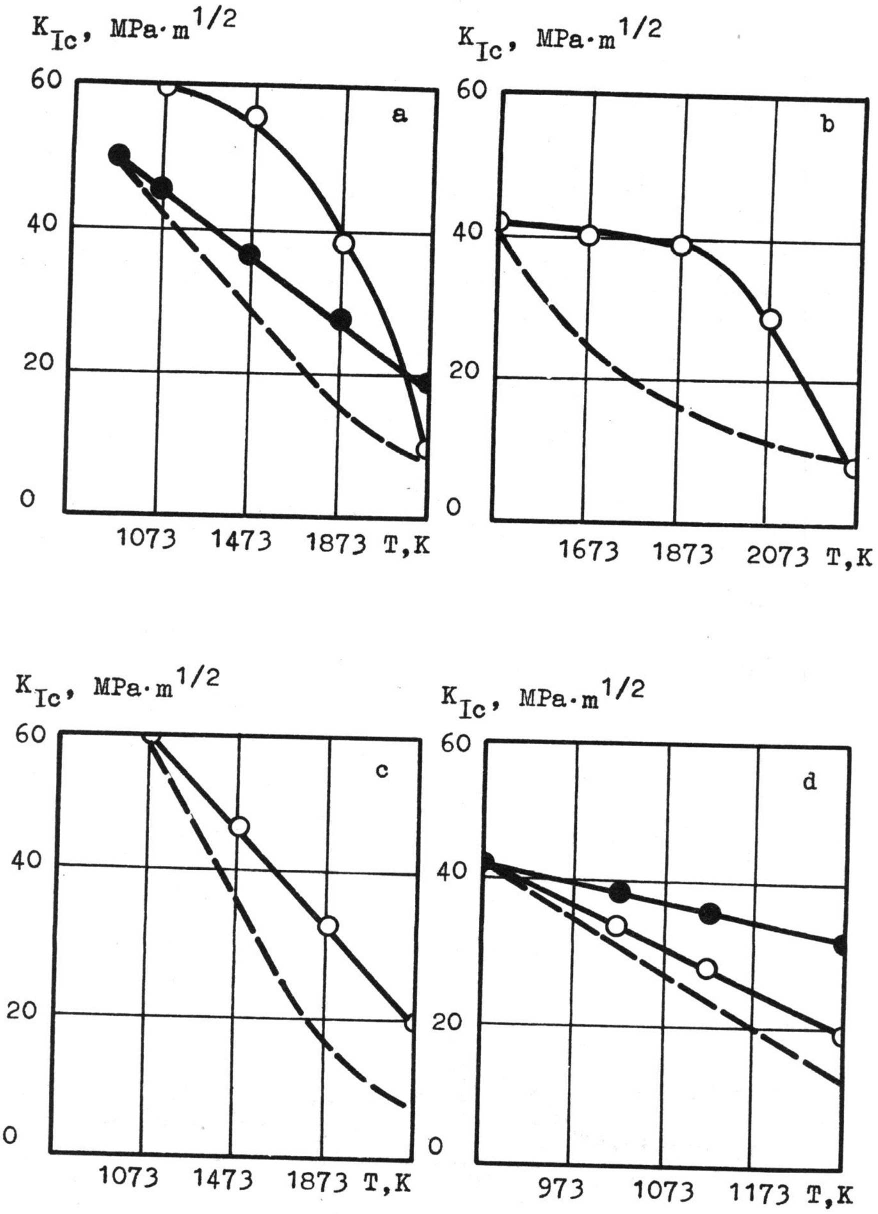

Figure 2 The effect of heat-treatment on fracture toughness of tungsten alloys

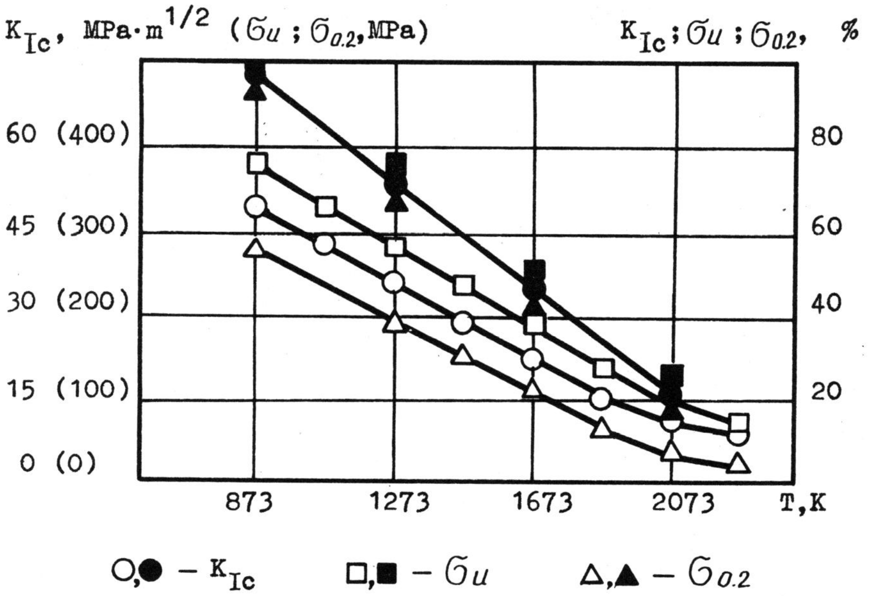

Figure 3 Relation between the fracture toughness and short-term strength characteristics at high temperature