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ARTICLE

Experimental and Simulation Analysis of Thermal Shock with Rapid Heating Followed by Water Quenching for CuW70 Alloys

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Abstract: By means of the rapid heating followed by water quenching, thermal shock experiments were conducted for CuW70 alloys to study the variations of mechanical behaviour. On the other hand, the simulation with finite element method was implemented to analyze the variations and the distributions of the temperature and the thermal stresses of CuW70 specimens during thermal shock process. The results show that the strength of CuW70 alloys degenerates and the ductility is improved after repeated thermal shock, and the maximum thermal stress appears at the beginning of heating and quenching period. The alternated thermal stresses which vary between tensile and compression stress will be applied on the internal and the external of CuW70 alloys during repeated thermal shock.

Key words: CuW70 alloys; thermal shock; finite element method; thermal stress

Because of the excellent thermal conductivity, thermal resistance and high strength, CuW alloys are used widely in high temperature environments sustaining thermal shock load. A common thermal shock (TS) configuration is for a component at an initially uniform temperature suddenly to be exposed to the medium at different temperatures. Therefore, rapid mutative temperature gradient induces thermal stress among the materials.

In past years, experimental and simulation investigations on thermal shock behaviour of refractory materials were reported extensively in literatures[1-4]. The thermal shock test by water quenching in a bath of water at room temperature is a very popular one because of its simplicity[5-7]. Generally, a thermal shock study is considered with two points of view, e.g. thermal and mechanical aspects. Thermal shock stresses have specific mechanical characteristics compared to the steady-state ones. It means that for thermal shock study both the temperature gradient and the corresponding thermal stresses in materials vary suddenly according to the necessary time to attain the thermal equilibrium state. Moreover, the mechanical properties of materials under high thermal loading rates are changed due to the damage and plastic deformation of materials[7].

The main objective of this paper is to bridge the thermal shock experiment and the mechanical behaviour of CuW alloys. Furthermore, finite element method is applied to study the internal thermal stress of CuW alloys under thermal shock loads according to thermal-elastic effect.

1 Experiment and Simulation Model

The materials used in this study were fabricated by infiltrating copper into sintered tungsten skeleton. The tungsten powder with 4-6 μm particle size was used. The CuW alloys were annealed. The nominal mass fractions of tungsten and copper were 70% and 30%, respectively, and the alloys is denoted as CuW70.

For the thermal shock experiment, the CuW70 alloys were machined into tensile test specimens, as shown in Fig.1. During thermal shock period, the specimens were firstly placed into a resistance furnace to hold at 900 °C for 2 min, and then

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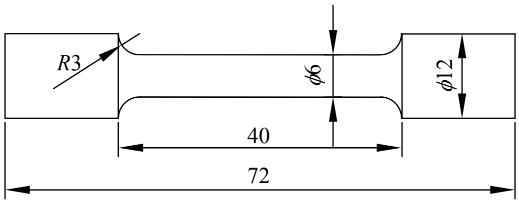

Fig.1 Tensile specimen of CuW70 alloys

taken out and rapidly quenched in water at 20 °C for about 1 min. After thermal shock cycling with 25 and 50 times, the tensile experiments were conducted by HT-2402-100KN Computer Servo Control material testing machine.

In order to analyze the internal temperature and the thermal stress, an axisymmetric model was employed for finite element analysis using Ansys Multiphysics Version 12.1, as shown in Fig.4a. Two-steps-load was applied on this model. Firstly, the initial temperature was set to 20 °C, and the boundary condition with the convection and the radiation at 900 °C was applied on specimens. Secondly, the initial temperature was set to 900 °C, and the boundary condition with convection only at ambient temperature of 20 °C was applied as well.

The thermo-mechanical properties of CuW70 are: coefficient of convection h_{air}=15 W/m^2·°C, h_{water}=1000 W/m^2·°C, Stefan-Boltzman constant σ=5.67×10^{-8} W/m^2·K^4, Emissivity ε=1, Young's modulus E=186 GPa, Poisson's ratio ν=0.3, mass density d=14.3 g/cm^3, thermal conductivity k=260 W·(m·K)$^{-1}$, heat capacity c=207 J/kg·K, coefficient of thermal expansion α=11×10^{-6} K^{-1}.

2 Results and Discussions

2.1 Mechanical properties analysis

The stress-strain curves of CuW70 alloys are shown in Fig.2. As seen in Fig.2, there are no obvious yield stages during deformation process and the alloys remain brittle fracture behaviour, while their little plastic deformation appears after the thermal shock test. After the 50 times thermal shock, the yield strength and ultimate strength decrease from 408 and 619 MPa to 355 and 544 MPa, respectively. While the elongation rate of the alloys increases from 3.1% to 5.0%.

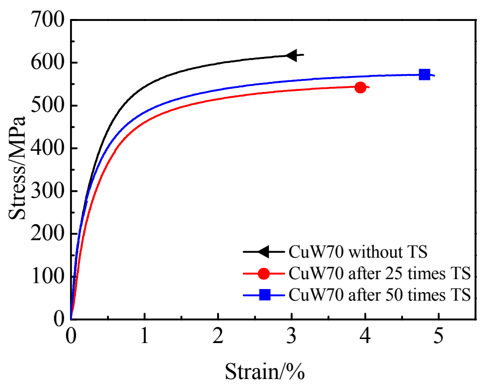

Fig.2 Stress-strain curves of CuW70 alloys under tensile load

The fracture surfaces of CuW70 alloys are shown in Fig.3. Four characteristics are exhibited in the fracture surfaces as mentioned in Ref.[8,9]: W grains boundary separation, W/Cu interface separation, tungsten grain cleavage and copper rupture. Generally, as shown in Fig.3a, most area of fracture surface presents the intercrystalline fracture of tungsten grains and the ductile tearing of copper phase. After 50 times thermal shock, as shown in Fig.3b, the dimples become deeper and more uniform than that appearing in Fig.3a, and the number of dimples increase significantly. It means that the ductile and plastic deformation increases after thermal shock.

2.2 Analysis of thermal stress

The distributions and variations of internal stress for CuW70 specimens are presented in Fig.4 and Fig.5. As shown in Fig.5, the temperatures of location A and location B are approximately same as the ambient temperature at the end of heating and quenching period, which means that the specimens have been balanced to thermal equilibrium state with outer medium. While the stresses are approximate zero value at the same time. During thermal shock, the maximum thermal stresses appear at the beginning of heating and quenching process, and the 1st principal stress distributions at 1s are presented in Fig.4b and 4c. As shown in Fig.4, the 1st principal stress of location A is much larger than that at location B, and the thermal stresses found during quenching period are higher than that appearing during heating period as well.

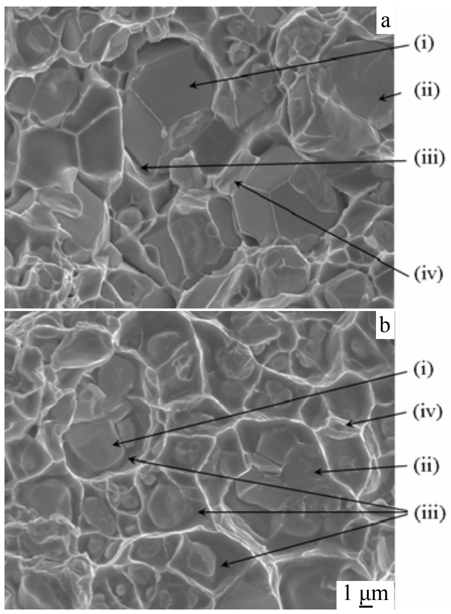

Fig.3 Fracture surface of CuW70 alloys under tensile load: (a) fracture surface morphology without thermal shock, (b) fracture surface morphology after 50 times thermal shock; (i) intercrystalline fracture, (ii) transgranular cleavage, (iii) dimple, (iv) tearing