Vol. 9 №. 1 **Trans. Nonferrous Met. Soc. China** Mar. 1999

COMPUTER NUMERICAL SIMULATION OF MECHANICAL PROPERTIES OF TUNGSTEN HEAVY ALLOYS①

Huang Jihua, Cao Zhiwei and Zhou Guo′an
Department of Materials Science and Engineering,
University of Science and Technology Beijing, Beijing 100083, P. R. China
Chen Hao
Wuhan Jiaotong University of Science and Technology, Wuhan 430063, P. R. China

ABSTRACT A microstructure model of tungsten heavy alloys has been developed. On the basis of the model and several assumptions, the macro-mechanical properties of 90 W heavy alloy under quasi-static tensile deformation and the effects of microstructural parameters (mechanical properties of the matrix phase and tungsten content) on them have been analyzed by computer numerical simulation. The mechanical properties of the alloy have been found to be dependent on the mechanical parameters of the matrix phase. As the elastic modulus and yield strength of the matrix phase increase, the tensile strength of the alloy increases, while the elongation decreases. If the mechanical parameters except the tensile strength of the matrix phase are constant, both the tensile strength and the elongation of the alloy increase linearly with the increase of tensile strength of the matrix phase. The properties of the alloy are very sensitive to the hardening modulus of the matrix phase. As the hardening modulus increases, both the tensile strength and the elongation of the alloy exponentially decrease. The elongation of the alloys monotonically decreases with the increase of tungsten content, while the decrease of tensile strength is not monotonic. When the tungsten content < 85 %, the strength of tungsten heavy alloys increases with the increase of tungsten content, while decreases when the tungsten content > 85 %. The maximum of tensile strength of the alloys appears at the tungsten content of 85 %. The results showed that the binder phase with a higher strength and a lower hardening modulus is advantageous to obtaining an optimum combination of mechanical properties of tungsten heavy alloys.

Key words tungsten heavy alloy mechanical property computer numerical simulation

1 INTRODUCTION

Tungsten heavy alloys are dual phase composites produced by liquid phase sintering of a mixture of 80 % ~ 97 % tungsten and a small amount of transition metal (as the binder phase) such as Ni, Fe powders, which have a unique combination of mechanical and thermal properties, high density, high strength, moderate ductility, good machineability and outstanding thermal conductivity. These properties allow the tungsten heavy alloys can be used for many applications as radiation shields, counterbalances, kinetic energy penetrators, etc. The application of tungsten heavy alloys in kinetic energy penetrators indicates that the penetrating power goes up with the increase of density and slenderness ratio of the penetrators, while the slenderness ratio in turn is governed by the strength and ductility of the material used for penetrators. Recently, strong attention has been focused on strengthening and toughening tungsten heavy alloys under the condition of not reducing the density of the alloys.

A great many means, including process optimizing, work strengthening, strain age hardening, alloying additions and various pre-sintering or post-sintering treatment, have been employed to obtain high-strength tungsten heavy alloys[1-14]. These technological or metallurgical

① Project 59471036 supported by the National Natural Science Foundation of China
Received Feb.4, 1998; accepted May 29, 1998

means can give the alloys in present compositions the optimum properties. However, the still higher properties need a new design for compositions of the alloys.

Generally, the tungsten grains in heavy alloys are little short of being pure, therefore, under definite technological conditions and given tungsten content, the properties of tungsten heavy alloys are governed by binder phase. There are two effects of binder phase on the properties of the alloys: (1) the mechanical properties of the binder phase determine the deformation and fracture behavior of the alloys; (2) the thermodynamic properties of the binder phase influence the structure of tungsten-matrix interface and the growth behavior of the tungsten grains in the course of sintering, as a result, also on the micro-mechanical behavior and the fracture behavior of the alloys. Accordingly, it is considered to be possible that tungsten heavy alloys are optimized by the optimum property matching between the matrix and tungsten, which can be obtained by analyzing the micro-mechanical behavior and its effect on the mechanical properties of the alloys. This paper reports a study of computer numerical simulation for the macromechanical properties of tungsten heavy alloys and effects of microstructural factors on them.

2 MODEL AND CONDITIONS

The typical microstructure of tungsten heavy alloys consists of tungsten grains and a small amount of binder phase. Because of the regulating effect of interfacial energy between tungsten(solid) and binder phase(liquid) on the dissolution and separation of tungsten, the tungsten grains in heavy alloys are similar to sphere, and well distributed in the binder phase with a similar structure to closed-packed hexagonal system. Fig.1 shows the microstructure model of tungsten heavy alloys. In the model, the tungsten grains are assumed to be spherical, in same size, and well distributed in matrix with the structure of closed-packed hexagonal system. The relation between the model parameters and the composition of the alloy can be expressed as

$$\rho_v = \pi r^2/(2ab) \tag{1}$$

$$r/a = (2\sqrt{3}/\pi)^{1/2}\rho_v^{1/2} \tag{2}$$

where, ρ_v is the volume fraction of tungsten grains in alloys, r is the radius of tungsten grains, a, b are the side length of the rectangle $ABCD$.

There are two typical directions to be loaded for the model, $AD(z)$ and $AB(y)$. Whichever direction is loaded, the rectangle $ABCD$ in Fig.1 can characterize the structure of the model, and the four sides of the rectangle remain straight in the course of deformation. Accordingly, a finite element model shown as Fig.2 has been established for computer numerical simulation. For whichever direction to be loaded, the boundary conditions can be expressed as

$$\left.\begin{aligned} & v_{AB} = 0,\ (\tau_{zy})_{AB} = 0 \\ & \frac{\partial u_{BC}}{\partial z} = 0,\ (\tau_{yz})_{BC} = 0 \\ & \frac{\partial v_{CD}}{\partial y} = 0,\ (\tau_{zy})_{CD} = 0 \\ & u_{AD} = 0,\ (\tau_{yz})_{AD} = 0 \end{aligned}\right\} \tag{3}$$

where u and v are the displacement component in y and z direction, respectively.

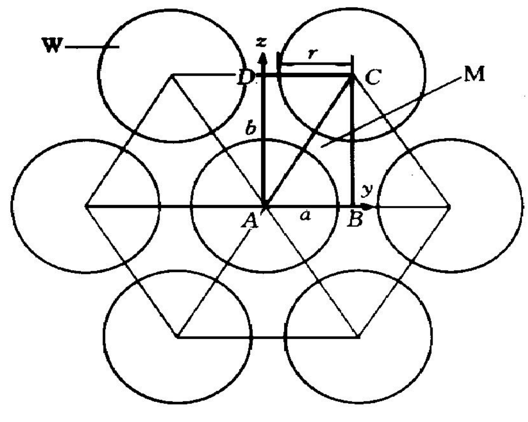

Fig.1 Microstructure model of tungsten heavy alloys
W—Tungsten grain; M—Matrix phase

By checking whether the stresses in tungsten grains and/or matrix phase satisfy the fracture criteria or not, the macromechanical properties of the tungsten heavy alloys under tensile deformation can be calculated. Furthermore, by calculating the properties with different values of

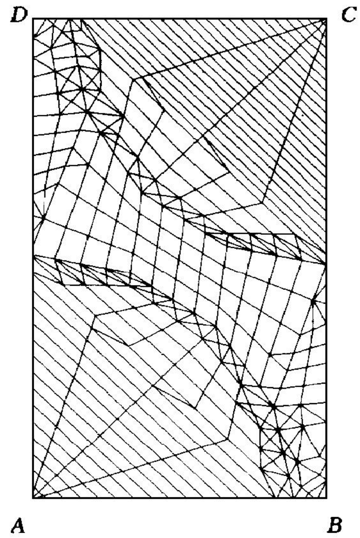

Fig.2 Finite element model for calculation

a microstructural parameter, we can obtain the relations between the properties and every microstructural parameter (such as properties of the matrix phase, tungsten content, etc.). In these analyses, the interface of the tungsten-matrix phase is assumed to be firm, i.e. no crack appears in the interface during tensile deformation, and the alloy before deformation is assumed to be undamaged and have no defect. The same yield criterion, Mises criterion, is employed for the tungsten and matrix phase, that is

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_s \quad (4)$$

where σ_1, σ_2, σ_3 are the principal stresses, σ_s is the critical stress for plastic flow. In consideration of different fracture modes between the tungsten grains and matrix phase, two different fracture criteria are adopted for the tungsten grains and matrix phase. For the cleavage fracture of tungsten grains, the fracture criterion is expressed as:

$$\sigma_1 \geqslant [\sigma] \quad (5)$$

where σ_1 is the major principal stress, $[\sigma]$ is the critical stress to fracture. For ductile fracture of the matrix phase, however, the following fracture criterion is adopted, that is

$$\sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \geqslant [\sigma] \quad (6)$$

where σ_1, σ_2, σ_3 are the principal stresses. In the course of calculation, the alloy is considered to be fractured, when one of the fracture criteria is satisfied at a certain point of tungsten grains or matrix phase. The mechanical parameters for calculation are listed in Table 1.

Table 1 Mechanical parameters for calculation[15,16]

	Elastic modulus / 10^2 GPa	Poisson ratio	Yield strength / 10^2 MPa	Tensile strength 10^2 MPa	Modulus of hardening / 10^2 MPa
Tungsten	4.1	0.27	8.0	11.0	3.0
Matrix phase*	2.0	0.31	5.0	9.1	1.5

* When a parameter of matrix phase is looked on as an influence factor to be analyzed, its value is varying

3 RESULTS AND DISCUSSION

Under the above conditions, the macro-mechanical properties of 90 W heavy alloy under quasi-static tensile deformation and the effects of micro-structural parameters (the mechanical properties of the matrix phase and the tungsten content) on them have been analyzed by computer numerical simulation. Figs.3 ~ 6 show the influences of the mechanical parameters (elastic

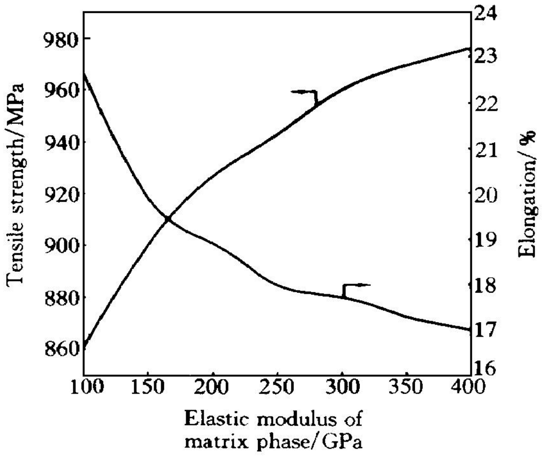

Fig.3 Mechanical properties of 90 W alloy vs elastic modulus of matrix phase

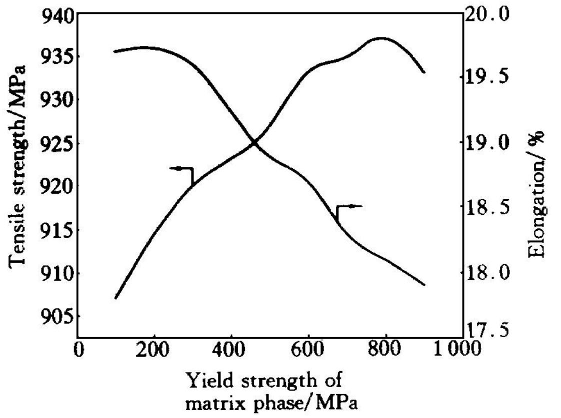

Fig.4 Mechanical properties of 90 W alloy vs yield strength of matrix phase

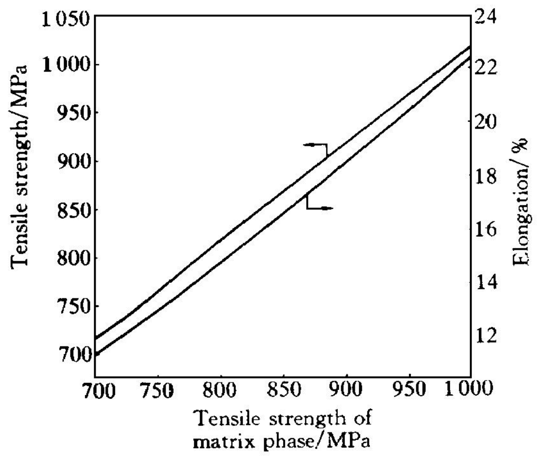

Fig.5 Mechanical properties of 90 W alloy vs tensile strength of matrix phase

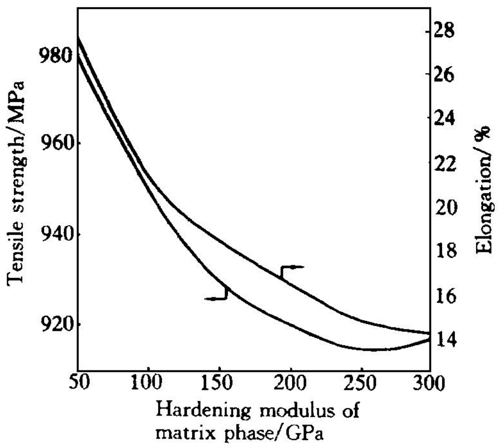

Fig.6 Mechanical properties of 90 W alloy vs hardening modulus of matrix phase

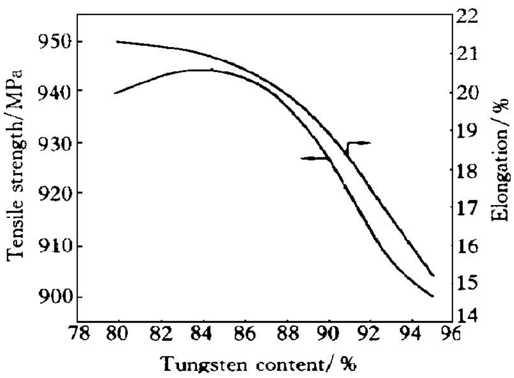

Fig.7 Mechanical properties of tungsten heavy alloys vs tungsten content

modulus, yield strength, tensile strength, modulus of hardening) of the matrix phase on the macro-mechanical properties (tensile strength and elongation) of the alloy. Fig.7 is the relation curves between the macro-mechanical properties and the tungsten content. The tensile strength of the alloy increases with the increase of elastic modulus of the matrix phase, while the elongation decreases. As the yield strength of the matrix phase increases, the elongation of the alloy decreases linearly, however, the tensile strength varies with a complicated pattern. The tensile strength of the alloy has a maximum at the yield strength of the matrix phase 800 MPa. When the yield strength of the matrix phase < 800 MPa, the tensile strength of the alloy goes up with its increase, but an opposite variation occurs when the yield strength of the matrix phase >800 MPa. Both the tensile strength and the elongation of 90 W alloy are found to increase linearly with the increase of tensile strength of the matrix phase, as shown in Fig.5. It is generally believed that an increase in strength signifies a decrease in ductility for common materials. However, both the tensile strength and elongation in Fig.5 increase with the increase of tensile strength of the matrix phase. Because under the conditions of definite yield strength, elastic modulus and modulus of hardening, the ductility of the matrix increases with the increase of tensile strength. In Fig.6, the tensile strength and elongation of 90 W alloy are found to be sensitive about the hardening modulus of the matrix phase. When the hardening modulus of the matrix phase < 150 MPa, the tensile strength of the alloy notably decreases with the increase of hardening modulus, and the first fracture appears in tungsten grains; when the hardening modulus of the matrix phase > 150 MPa, the tensile strength of the alloy decreases slowly, and the first fracture appears in the matrix phase in this case. As the hardening modulus of the matrix phase increases, the elongation of the alloy exponentially decreases. In this case, the ductility of the matrix phase decreases with the increase of hardening modulus. The dependences of tensile strength and elongation of the tungsten heavy alloys on the tungsten content are shown in Fig.7. The elongation of the alloys monotonically decreases with the increase of tungsten content, while the decrease of tensile strength is not monotonic. When the tungsten content < 85 %, the strength of tungsten heavy alloys increases with the increase of tungsten content, while decreases when the tungsten content > 85 %. The maximum of tensile strength of the alloys appears at the tungsten content of 85 %. The above results show that the binder phase with a higher strength and a lower hardening modulus is advantageous toobtaining an optimum combination of mechanical properties of tungsten heavy alloys.

4 CONCLUSIONS

(1) As the elastic modulus and yield strength of the matrix phase increase, the tensile strength of the alloy increases, while the elongation decreases.

(2) Under the conditions of fixed mechanical parameters except the tensile strength of matrix phase, both the tensile strength and elongation of the alloy increase linearly with the increase of tensile strength of the matrix phase.

(3) The mechanical properties of the alloy have a great sensitivity to the hardening modulus of the matrix phase. As the hardening modulus increases, both the tensile strength and elongation of the alloy exponentially decrease.

(4) When tungsten content > 85 %, the tensile strength of tungsten heavy alloys decreases obviously with the increase of the tungsten content, while increases when tungsten content < 85 %. The tensile strength of the alloys has a maximum at a tungsten content 85 %. The elongation of the alloys monotonically decreases with the increase of tungsten content.

(5) The binder phase with a higher strength and a lower hardening modulus is advantageous to obtaining an optimum combination of mechanical properties of tungsten heavy alloys.

REFERENCES

1 Hofmann H and Petzow G. Mod Dev Powder Metall, 1985, 17: 17.

2 German R M, Hanafee J E and Digiallonardo S L. Metall Trans, 1984, A15: 121.

3 Bourguignon L L and German R M. Intern J Powder Metall, 1988, 24: 11.

4 Bose A, Sime D and German R M. Metall Trans, 1988, A19: 487.

5 German R M and Churn K S. Metall Trans, 1984, A15: 747.

6 Posthill J B and Edmonds D V. Mater Res Soc Symp Proc, 1984, 21: 811.

7 Caldwell S G. Progr Powder Metall, 1987, 43: 123.

8 Bose A, Sime D M and German R M. Progr Powder Metall, 1987, 43: 79.

9 Bose A and German R M. Metall Trans, 1988, A19: 3100.

10 Bose A and German R M. Metall Trans, 1990, A21: 1325.

11 Bose A, Jerman G and German R M. Powder Metall Intern, 1989, 21: 9.

12 Cheynet M C. R&HM, 1986, 3: 55.

13 Kaneko T and Amano Y. Powder & Powder Metall, (in Japanese), 1988, 35: 92.

14 Huang J H, Zhou G A, Zhu C Q *et al*. Materials Letters, 1995, 23: 47.

15 Rabin B H and German R M. Metall Trans, 1988, A19: 1523.

16 Woodward R L, Medonald I G and Gunner A. J of Mat Sci Letters, 1986, 5: 413.

(Edited by Yuan Saiqian)