Effect of oxide dispersoids addition on mechanical properties of tungsten heavy alloy fabricated by mechanical alloying process

Kyong H. Lee, Seung I. Cha, Ho J. Ryu, Soon H. Hong

Abstract

The microstructures and mechanical properties of mechanically alloyed oxide dispersion strengthened tungsten heavy alloys were investigated. Elemental powders of tungsten (W), nickel (Ni), iron (Fe) and partially stabilized zirconia (PSZ) were mechanically alloyed by a planetary mill. Mechanically alloyed powders were consolidated by liquid phase sintering at temperature ranged 1465–1485°C for 1 h in hydrogen atmosphere to obtain full densification. The W grain size decreases with increasing PSZ content. The oxide dispersoids were dispersed both within W grains and W/W and W/matrix interfaces. The yield strength of oxide dispersion strengthened tungsten heavy alloy was not dependent on PSZ content but dependent on microstructural factor, while the elongation decreases with increasing PSZ content. However, the high temperature yield strength increases with increasing content of PSZ dispersoid and the PSZ dispersoids act as the strengthening agent at high temperature deformation.

Keywords: Oxide dispersion strengthened; Tungsten heavy alloy; Mechanical alloying; Sintering; Microstructure; Mechanical properties

1. Introduction

Tungsten heavy alloys, consisting of 88–97 wt.% of bcc structured W particles and fcc structured W–Ni–Fe alloy matrix, are widely used as kinetic energy penetrators, counter weight balances, radiation shields and vibration damping devices due to their high density, excellent strength and good ductility [1,2]. During decades, research to improve the penetration performance of tungsten heavy alloy has been carried out for replacement of depleted uranium, which has superior penetration performance with radioactive contamination problems [3–15].

In order to enhance the penetration performance of tungsten heavy alloy, several methods are proposed including W grain size control [10], alloying with Mo and Re [13], solid state sintering of mechanically alloyed powder [10,11], surface carburization [14], cyclic heat treatment [15] and oxide dispersion strengthening [11,12]. Among those methods, the oxide dispersion strengthening shows a change of dynamic fracture mode from adiabatic shear band to brittle fracture and it is considered as improvement mechanism in penetration performance of tungsten heavy alloy [12].

However, the researches on static mechanical properties of oxide dispersion strengthened tungsten heavy alloy are not analyzed yet. In this study, the mechanical properties of tungsten heavy alloy with oxide dispersoids at room temperature and high temperature are investigated. Especially, the strengthening mechanism of oxide dispersoids within tungsten heavy alloy during the deformation is investigated by analyzing the relationship between microstructural factors and mechanical properties of oxide dispersion strengthened tungsten heavy alloy at room and elevated temperatures.

2. Experimental procedures

The elemental powders of W (3 μm), Ni (6 μm), Fe (3 μm) and partially stabilized zirconia (PSZ) by 3 wt.% Y2O3 (60 μm) were weighted based on the designed composition. The composition of tungsten heavy alloy was designed as 94W–(6 – x)(Ni,Fe)–xPSZ with Ni/Fe weight ratio of 4:1 and 0–0.5 wt.% PSZ. The mechanical alloying of oxide dispersion strengthened tungsten heavy alloy was carried out by planetary
The mechanically alloyed powders were sieved with #360 and #400 sieves, and were cold compacted under a pressure of 300 MPa. The mechanically alloyed oxide dispersion strengthened tungsten heavy alloy powders were consolidated by liquid phase sintering in hydrogen atmosphere for 1 h at various sintering temperature from 1465 to 1485 °C. The sintered oxide dispersion strengthened tungsten heavy alloy was heat treated at 1150 °C for 1 h in N₂ atmosphere and followed by water quenching. The variation of microstructural parameters such as average grain size, volume fraction and contiguity was measured using optical and scanning electron microscopy. The tensile specimens with a gauge length of 25 mm, a width of 4.5 mm and a thickness of 5.0 mm were tensile tested at a strain rate of 6.67 × 10⁻⁴ s⁻¹ by using Instron 5583 machine. High temperature compression test was carried out using hot working simulator (Thermecmaster-Z) at 800 °C under strain rate of 10 s⁻¹.

3. Results and discussion

3.1. Microstructure of oxide dispersion strengthened tungsten heavy alloy

Microstructure of sintered oxide dispersion strengthened tungsten heavy alloy was dependent on the sintering temperature and oxide weight fraction. In Fig. 2, the microstructure...
of 94W–4.4Ni–1.1Fe–0.5PSZ oxide dispersion strengthened tungsten heavy alloy was shown according to sintering temperature. The W grain increases, W/W contiguity decreases and matrix volume fraction increases with increasing the sintering temperature. One remarkable thing is that the matrix cannot be rearranged when the sintering temperature is low as 1465 °C. However, the relative density is over 99% regardless of the sintering temperature. It is mainly due to the origin of the powder. When the powders were prepared by mechanical alloying process, the densification occurs at lower temperature than that of conventional mixed powder and it can be sintered without liquid matrix phase [8–11].

One remarkable thing is the PSZ particles were located within W grains as well as W/W interface and W/matrix interfaces as shown in Fig. 2. About 17 vol.% of total dispersed oxides were located within W grains in 94W–4.56Ni–1.14Fe–0.3PSZ oxide dispersion strengthened tungsten heavy alloy. In Fig. 3, the microstructure of oxide dispersion strengthened tungsten heavy alloy sintered at 1485 °C for 1 h was shown according to PSZ content. The tungsten grain size decreases with increasing the PSZ content as shown in Table 1.

Table 1
The microstructural parameters of tungsten heavy alloy sintered at 1485 °C for 1 h

<table>
<thead>
<tr>
<th>Compositions</th>
<th>W grain size (µm)</th>
<th>Oxide volume fraction (%)</th>
<th>Matrix volume fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>94W–4.8Ni–1.2Fe</td>
<td>27.8</td>
<td>–</td>
<td>12.8</td>
</tr>
<tr>
<td>94W–4.72Ni–1.18Fe–0.1PSZ</td>
<td>25.1</td>
<td>0.4</td>
<td>12.5</td>
</tr>
<tr>
<td>94W–4.56Ni–1.14Fe–0.3PSZ</td>
<td>22.7</td>
<td>1.2</td>
<td>11.5</td>
</tr>
<tr>
<td>94W–4.4Ni–1.1Fe–0.5PSZ</td>
<td>22.0</td>
<td>2.0</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Fig. 2. SEM micrographs of sintered 94W–4.4Ni–1.1Fe–0.5PSZ with varying the sintering temperature. Sintered at: (a) 1465 °C, (b) 1475 °C and (c) 1485 °C for 1 h. The tungsten heavy alloys were sintered from the powders mechanically alloyed under mechanical alloying speed of 200 rpm, mechanical alloying time of 6 h and ball-to-powder ratio of 10.

3.2. Mechanical properties of oxide dispersion strengthened tungsten heavy alloy

The tensile properties of oxide dispersion strengthened tungsten heavy alloy at room temperature were dependent on their sintering temperature and content of oxide dispersoids. In Fig. 4, the tensile properties of 94W–4.8Ni–1.2Fe tungsten heavy alloys prepared by mechanical alloying and following liquid phase sintering were shown. The elongation of oxide dispersion strengthened tungsten heavy alloys increases with increasing the sintering temperature, while the yield strength and tensile strength show little changes.

In Fig. 5, the tensile properties of 94W–(6−x)(Ni,Fe)–xPSZ oxide dispersion strengthened tungsten heavy alloy were shown according to PSZ content. The yield strength and ultimate tensile strength of oxide dispersion strengthened tungsten heavy alloys show little variation according to PSZ content. The yield strength of tungsten heavy alloy can be affected by microstructural factor [10,11]. Therefore, the variation of yield strength in Fig. 5 contains effects of microstructural factor, which is modified by addition of oxide dispersoids, and additional strengthening effect of oxide dispersoids. Ryu et al. [10,11] have been investigated the effect of microstructural factors on yield strength of tungsten heavy alloy under assumption that yielding of tungsten heavy alloy begins by deformation of Ni–Fe–W matrix. In this case, the yield strength of tungsten heavy alloy can be expressed as follows,

$$\sigma_y = \sigma_0 + K \left( \frac{C(1-V_m)}{d_W V_m} \right)^{1/2}$$  (1)
where $\sigma_y$ is the yield strength of tungsten heavy alloy, $\sigma_0$ and $K$ are constants, $C$ is the W/W contiguity, $d_w$ is the tungsten grain size and $V_m$ is the volume fraction of matrix. In order to analyze the effect of microstructural factor on yield strength of oxide dispersion strengthened tungsten heavy alloy, the yield strengths are plotted according to microstructural factor suggested in Eq. (1) as shown in Fig. 6. In this plot, the yield strengths of oxide dispersion strengthened tungsten heavy alloy are laid on one line regardless of their oxide dispersoid content. It means that the effect of oxide dispersion on yield strength at room temperature is caused by microstructural modification and there are no additional strengthening effects.

The elongation of oxide dispersion strengthened tungsten heavy alloy was severely decreased with increasing the PSZ content. The decreases in elongation are mainly due to the location of oxide dispersoids. In current study, about 17% of oxides were dispersed within W grains and others are dispersed in matrix and interface of W grains and matrix. The oxide at the W/W and W/matrix interfaces severely promotes fracture and, as a result, elongation was degrades. It is supported by the fractography of tensile specimens of oxide dispersion strengthened tungsten heavy alloy as shown in Fig. 7. Fracture occurs mainly at the oxide dispersoid dispersed at W/W and W/matrix interface in case of oxide dispersion strengthened tungsten heavy alloy. Therefore, it is expected that larger values of elongation can be obtained when more oxides were dispersed within W grains.

Even though, there is no additional strengthening effect of oxide dispersoids in room temperature yield strength, it shows considerable strengthening effect in high temperature deformation at 800 °C as shown in Fig. 8. The effect of oxide dispersoids can be analyzed by considering Orowan looping mechanism as follows [16],

$$
\sigma_y = \sigma_0 + \frac{Gb}{\pi(1-\nu)^{1/2}} \frac{1}{d} \left( \sqrt{\frac{\pi}{4V_p}} - 1 \right)^{-1} \ln \left( \frac{d}{b} \right)
$$

(2)
where $\sigma_y$ is the yield strength of tungsten heavy alloy at high temperature, $\sigma_0$ is a constant, $G$ is the shear modulus of tungsten heavy alloy, $\nu$ is the Poisson’s ratio of tungsten heavy alloy, $d$ is the mean particle size of PSZ dispersoids and $V_p$ is the volume fraction of PSZ dispersoids. As shown in Fig. 9, the high temperature yield strengths of oxide dispersion strengthened tungsten heavy alloy obey Eq. (2). It means that the main obstacle in movement in oxide dispersion strengthened tungsten heavy alloy changes from tungsten grains to oxide dispersoids by increasing the deformation temperature. This change is considered as the softening of W grain at high temperature deformation and cannot act as dislocation obstacles at high temperature deformation. Therefore, the stable oxide dispersoids act as mainly strengthening media at high temperature deformation.

4. Summary

Oxide dispersion strengthened tungsten heavy alloys were fabricated by the mechanical alloying and liquid phase sintering process. The microstructure of sintered oxide dispersion strengthened tungsten heavy alloy can be controlled by controlling the process parameters such as sintering temperature and oxide content. The yield strength of oxide dispersion strengthened tungsten heavy alloy was not affected by oxide dispersoid content but only dependent on microstructural factor, which means the main strengthening phase is W grains at room temperature. However, the high temperature yield strength increases with increasing content of PSZ dispersoid and the PSZ dispersoids act as the strengthening agent at high temperature deformation.
Fig. 8. (a) The stress–strain curves and (b) the compressive yield strength of oxide dispersion strengthened tungsten heavy alloy at 800 °C under strain rate of 10 s⁻¹ according to PSZ content.

Fig. 9. The relationship between high temperature compressive yield strength of oxide dispersion strengthened tungsten heavy alloy at 800 °C under strain rate of 10 s⁻¹ and microstructural factor derived from Orowan looping [16].

Acknowledgement

This work was supported from AOARD and AFOSR through Contract No. 034032.

References