Influence of Mo content on the γ-phase stability and properties of U-Mo alloy

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Abstract. U-Mo alloys have been considered as the potential new advanced nuclear fuel, due to its favourable irradiation stability associated with the presence of the metastable γ-phase in the microstructure. Thus its γ-phase stability and performance are of great importance. In this work, three kinds of U-Mo alloys with the content of 6, 8 and 10 wt.% Mo were prepared by non consumable arc melting technology, the homogenization annealing and heat treatment of isothermal decomposition. Through metallographic microscope, scanning electron microscope (SEM), X-ray diffraction, Brinell hardness tester, the microstructure and mechanical properties of U-Mo alloys were investigated. The results indicate that the stability of γ-phase in the U-Mo alloy is directly related to the content of Mo. With the increase of Mo, the stability of γ-phase is enhanced and the decomposition of γ-phase is delayed during the isothermal decomposition at 565℃. In addition, the mechanical properties of this alloy are closely associated with its phase rather than directly related to the content of Mo.

Keywords: U-Mo alloy, γ-phase, stability, properties

1. Introduction
In order to achieve the conversion of research reactors from high enriched uranium (HEU) fuel to low enriched uranium (LEU), high density uranium compounds or alloys are widely used [1-6]. For pure metallic uranium, the corrosion resistance and irradiation stability are very poor, which is related to the presence of α-phase at room temperature. Compared to the α-phase, the γ-phase of metallic uranium has a better radiation resistance and appears to possess the isotropic thermal expansion property, which makes it more suitable for the nuclear fuel [7]. Unfortunately, the γ-phase of metal uranium is not stabilized at the lower temperature range, and thus makes it a significant technical barrier for uranium using as the fuel. One solution to this problem is to stabilize the γ-phase at room temperature by the addition of Mo. While γ-phase is not thermodynamically stable, but a metastable phase. The high-temperature γ-phase will decompose into the α-phase and U₂Mo during the cooling process theoretically [8]. Since the diffusion velocity of molybdenum atoms is slow, the eutectoid reaction maintains sufficient thermal activation energy and soaking time, which keeps the γ-phase exist at room temperature at the normal cooling rate in the U-Mo alloy with the high content of Mo. Meanwhile, in the U-Mo alloys with low content of Mo, the γ-phase can also be maintained at room temperature by rapid cooling [9-11]. And the research shows that the phase structure has an important effect on the mechanical properties of the alloy [12].

In this paper, U-Mo alloy was prepared by non-consumable arc melting. The microstructure and phase composition of the U-Mo alloy were analyzed. Meanwhile, the mechanical properties of the alloys were studied, which provides the guidance for the research of U-Mo alloy fuels.
2. Materials and Experimental

2.1. Materials
The raw material was depleted uranium ingots (the content of carbon is less than 100μg/g) and molybdenum particles. In order to avoid the introduction of excessive inclusions, the depleted uranium ingots were refined and purified, and the chemical composition is shown in table 1. The metallographic photograph of the collected pure uranium is shown in figure 1. The size of molybdenum particle is Φ3mm×(5~10) mm. And the chemical composition is shown in table 2.

Table 1. Chemical composition of depleted uranium.

| Items (μg/g) | Fe  | C   | N   | O   | Ni  | Cu  | Mn  | Al  | Ca  | Si  | P   | S   | H  |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|----|
|             | 34  | 86  | 51  | 90  | <20 | <20 | <20 | <20 | <20 | <20 | <10 | <10 | 1.2|

Figure 1. Microstructure of the depleted uranium ingots.

Table 2. The chemical composition of Mo.

| Items (μg/g) | C   | O   | Fe  | Ni  | Si  | Al  | Mg  | Sn  | Ca  |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|             | 70  | 30  | 20  | 20  | 20  | 20  | 20  | 5   | 20  |

From metallographic photograph of the pure uranium ingot, it can be seen that the refining and purification effect of ingot is good, and there is no obvious impurity and reunion phenomenon of inclusions.

2.2. Preparation of Molybdenum Uranium Alloy
U-6wt. % Mo, U-8wt. % Mo, U-10wt. % Mo alloy (hereafter called U-6Mo, U-8Mo, U-10Mo) were prepared by non-consumable arc melting technology. The melting output current was 500A; stirring current was 8A. In order to accomplish homogenization, the sample were turned over and melted 6 times.

2.3. Heat Treatment of U-Mo Alloys
The homogenization annealing heat treatment of U-Mo alloys was carried out at the temperature of 1000 °C with the cooling holding time of 24 hours in furnace. And the isothermal decomposition heat treatment of the alloys was conducted at 565 °C for 20 hours.

2.4. Metallographic examination
The metallographic examination of polished and corroded states of U-Mo alloys under different heat treatments was carried out. The sample is observed by universal research-level automatic metallographic microscope (Axio Observer Z1m). At the same time, the alloy composition was analyzed by scanning electron microscopy (SEM, VEGA 3XMU).

The phase composition of U-Mo alloy was analyzed by X-ray diffract meter (D8 DAVINCI). The scanning mode is 2θ mode. The scanning range is 10°~90°. The step is 0.02°, and the acquisition time is 0.02s. The source of radiation was standard Cu K\(\alpha\) with a wavelength of 0.154 nm. The operating voltage of the X-ray tube was 40 kV and the current was 40 mA.

The hardness test of U-Mo alloy prepared with different heat treatment was carried out by using electronic hardness tester. The model was HBE-3000A, and the standard hardness block was HB2.5/187.5.

3. Results and Discussion

3.1. Microstructure Analysis of U-Mo Alloy

The metallographic polishing state and corrosive state photos of U-Mo alloy are shown in figure 2 and figure 3. The scanning test results are shown in figure 4 and figure 5.

Figure 2. Metallographic photos of as-polished. (a) U-6Mo, (b) U-8Mo, (c) U-10Mo.

From figure 2, it can be seen that the prepared sample contains little inclusions and no obvious impurity agglomeration. Figure 3 shows that there are different contrasts caused by corrosion between the crystals and the adjacent crystal boundaries, which indicates that the presence of composition segregation within the crystals [13-14]. From the results of the scanning detection in figure 3 and figure 4, the matrix element is uranium and molybdenum, and there is no un-melted molybdenum with the inclusions mainly constituting of carbides or nitrides of uranium.
Figure 3. Metallographic photos after corrosion. (a) U-6Mo, (b) U-8Mo, (c) U-10Mo.

Figure 4. SEM images of inclusions.
Brinell hardness test of three kinds of alloys were carried out, and the test results are shown in table 3. The results show that the hardness of U-Mo alloy enhances with the increase of Mo.

**Table 3.** Hardness of U-Mo alloy prepared by non consumable arc melting.

| Samples | U-6Mo | U-8Mo | U-10Mo |
|---------|-------|-------|--------|
| 1       | 217   | 242   | 252    |
| 2       | 218   | 249   | 258    |
| 3       | 212   | 245   | 253    |
| Average | 216   | 245   | 254    |

3.2. *Phase Structure and Property Analysis of U-Mo Alloy after Homogenization Heat Treatment*

![SEM images of matrix](image)

**Figure 5.** SEM images of matrix.

![Photos after heat treatment of homogenization](image)

**Figure 6.** Photos after heat treatment of homogenization (a) U-6Mo, (b) U-8Mo, (c) U-10Mo.
Figure 6 shows the metallographic as-polished photos of the alloy after the homogenization. It can be seen that the homogenization reduces the agglomeration of the inclusions, and the composition segregation of the samples is obviously improved compared with that before the heat treatment, with sufficient alloying and uniform components.

Phase analysis of the samples showed that the U-6Mo alloy contains a small amount of α phase, mainly due to the low content of Mo. And the metastable γ-phase has changed during the cooling process in the furnace [9]. γ-phase is the main phase in the U-8Mo and U-10Mo. When the content of Mo is around 8%, it can be enough to guarantee the high temperature phase of uranium, that is, the γ-phase is stable at room temperature and does not decompose in the process of cooling in the furnace. (figure 7)

![Figure 7. XRD pattern after heat treatment of homogenization.](a) U-6Mo, (b) U-8Mo, (c) U-10Mo.]

Table 4. Hardness of U-Mo alloy after heat treatment of homogenization.

| Samples | U-6Mo | U-8Mo | U-10Mo |
|---------|-------|-------|--------|
| 1       | 223   | 245   | 253    |
| 2       | 228   | 247   | 256    |
| 3       | 225   | 245   | 251    |
| Average | 225   | 246   | 253    |

Brinell hardness testing of three kinds of alloys is carried out. The test results are shown in table 4. It was found that the hardness value of U-6Mo alloy after homogenization is higher than that of before, which may be related to the phase transformation and the change of the structure of U-6Mo alloy. This
is consistent with the XRD test results. Compared with the hardness of as-cast, U-8Mo and U-10Mo alloy have no obvious change, as is shown in table 3. The hardness of U-Mo alloy increases with the increase of Mo at as-cast condition, which mainly due to the fact that γ-phase is stable at room temperature under rapid cooling [10]. Compared with the U-6Mo, U-8Mo and U-10Mo alloys, the increase of Mo content leads to the increase of hardness.

3.3. Phase Structure and Property Analysis of U-Mo Alloy after Heat Treatment of Isothermal Decomposition.

Figure 8 is the metallographic photograph of the U-Mo alloy after homogenization annealing and heat treatment of isothermal decomposition. As it can be seen that for the (a) U-6Mo, γ-phase decomposition takes place at the crystal boundary and in the inner part of the crystal [15]. For the (b) U-8Mo sample, there is a significant phase transition (black region) at the crystal boundary. The contrast exhibited by corrosion shows the shape of crystal boundary, which is smaller than that of U-6Mo. (c) There is no obvious phase transition at the crystal boundary of U-10Mo samples, which may be related to the high content of Mo and the good stability of γ phase [10-11].

![Figure 8](image)

XRD shows that (as shown in figure 9) in addition to the peak of the γ phase uranium molybdenum alloy, the α-phase U peak of (a) U-6Mo and (b) the U-8Mo also appeared, which indicates that γ→α phase transformation occurred during the heat treatment of isothermal decomposition. The results of U-10Mo show that the phase structure of alloy is still γ-phase, indicating that U-10Mo does not undergo the phase transition during the isothermal decomposition. This is in accordance with the metallographic results. The Brinell hardness test of three kinds of alloys were carried out and the results are shown in table 5.

It can be seen from table 5 that the hardness values of U-6Mo and U-8Mo alloy are higher than that after homogenization heat treatment, which may be closely related to its structure phase decomposition. And the decomposition leads to Mo enrichment in the γ-phase [10], resulting to the hardness increase. While the U-10Mo alloy with γ-phase hardly changes its hardness value before and after isothermal decomposition.
Table 5. Hardness of U-Mo alloy after treatment of isothermal decomposition.

| Samples | U-6Mo | U-8Mo | U-10Mo |
|---------|-------|-------|--------|
| 1       | 232   | 265   | 258    |
| 2       | 239   | 262   | 263    |
| 3       | 237   | 269   | 254    |
| Average | 236   | 265   | 258    |

4. Conclusions
The U-6Mo, U-8Mo and U-10Mo alloys prepared by non-consumable arc melting lead to the retention of the γ-phase at room temperature and there hardness increase with the increase of Mo content.

The stability of γ-phase of U-Mo alloy is directly related to the content of Mo. And the increasing addition of Mo causes a delay in the γ-phase decomposition during isothermal heat treatment.

The hardness of U-Mo alloys after the isothermal heat treatment is measured, it is found that the hardness of U-Mo alloys are closely associated with its phase rather than directly related to the content of Mo.

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