Materials Research Express

PAPER

Microstructures and properties of 90W-4Ni-6Mn alloy prepared by vacuum sintering

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Keywords: W–Ni–Mn alloy, vacuum sintering, microstructure, mechanical properties

Abstract

Tungsten-nickel-manganese alloy is an excellent potential replacement of depleted uranium alloy for kinetic energy penetrator (KEP) due to its high self-sharpening effect. In this work, the 90W–4Ni–6Mn alloy was prepared by vacuum sintering, and the effects of the sintering temperature and oxygen content on its microstructure and properties were discussed. Sintering temperature had a great influence on the properties of tungsten heavy alloy. The optimal properties of 90W–4Ni–6Mn with the relative density of 99.43%, the W grain size of 3.80 μm, and the compressive strength of 2790 MPa were obtained at the sintering temperature of 1125 °C for 60 min under a vacuum of 10⁻²–10⁻³ Pa. With the increase of oxygen content, the densification of powders became more difficult, and the microstructure homogeneity and mechanical properties of sintered samples decreased accordingly. The results provide a new effective way to prepare W–Ni–Mn alloy with high performance.

1. Introduction

Tungsten heavy alloys (WHAs) are a class of tungsten matrix composites with additions of Ni and other elements such as Fe, Cu, Co, Mn, etc. They have been widely used in the field of national defense, aerospace, electronic information, and nuclear industries, especially in the military industry as kinetic energy penetrator (KEP), due to the excellent comprehensive properties such as high density, high strength, good corrosion and oxidation resistance [1–4]. However, the conventional tungsten heavy alloys system (W–Ni–Fe) have poor adiabatic shear sensitivity, which will lead to the manufactured penetrator becoming blunt by forming a ‘mushroom head’ during ballistic penetration and decreasing the penetration depth [5]. It has been found that the main factors to improve the adiabatic shear performance are low thermal conductivity, high hardness, and relatively small grains size of W in the matrix [6, 7]. Bose et al [6, 8, 9] and A Belhadjhamida et al [10] demonstrated that an adiabatic shear band can be maximized by adding manganese (Mn) with the low thermal conductivity instead of the iron (Fe) and copper (Cu) contained in conventional W–Ni–Fe and W–Ni–Cu heavy alloys. The presence of Mn in W–Ni–Mn alloy is helpful to the refinement of W grains for the insolubility of tungsten in Mn and the lower sintering temperature based on the Ni–Mn binary alloy phase diagram [11], which will cause the improvement of properties of the heavy alloys [12, 13]. Besides, it was also reported that the W–Ni–Mn alloy can produce intense shear bands at high strain rates [7–9]. Thus, compared to conventional W–Ni–Fe and W–Ni–Cu heavy alloys, the W–Ni–Mn alloy seems to be a better candidate for KEP.

However, W–Ni–Mn alloy with the high performance is difficult to be obtained, because Mn is easy to oxidize and the formed MnO hinders the densification of powders. To resolve this problem, the atmospheric controlling sintering process was proposed to prepare 90W–6Ni–4Mn (wt%) alloy [14, 15]. The sintering process consisted of heating to reduction temperatures (1150 °C ∼ 1200 °C) and holding for 4h under the high purity N₂, subsequently, changing N₂ into dry H₂ and heating to the sintering temperature of 1260 °C for 1h. Using this method, although the W–Ni–Mn alloy with near full density was prepared, its mechanical properties were not satisfactory owing to the coarse grain size caused by high sintering temperature. Moreover, the complexity of
this process also restricted its further development. Furthermore, some scholars thought that this method was not suitable for sintering W–Ni–Mn alloy with higher Mn/Ni than 4/6 [16]. Recently, Pan et al. [17–20] tried to use spark plasma sintering (SPS) technology to prepare high-performance W–Ni–Mn alloy with fine grain microstructure and made good progress. However, SPS is difficult to be used in mass production and requires expensive equipment. Therefore, it is urgent to develop a new effective method or technology to prepare W–Ni–Mn alloy. The vacuum sintering is a prospective sintering technique. Because it is not only easy to operate, but also can avoid the harmful influence of oxygen [21].

The purpose of this paper is to prepare a full dense 90W-4Ni-6Mn alloy with fine W grains by vacuum sintering and study the effects of sintering temperature on its microstructures and properties. Meanwhile, the influence of impurity oxygen on the microstructures of the 90W-4Ni-6Mn alloy is also discussed, which it has not been reported in relevant literature so far.

### 2. Experimental

#### 2.1. Materials

The raw materials were reduced tungsten powder, carbonyl nickel powder, and electrolytic manganese powder, which were supplied by Xiamen Tungsten Co. Ltd, Chengdu Nuclear 857 New Materials Co. Ltd, and Shanghai Aladdin Biochemical Technology Co. Ltd, respectively. The characteristics of the powders are shown in table 1 and their morphology is shown in figure 1.

#### 2.2. Experimental method

Elemental W, Ni, and Mn powders weighed according to the composition design of 90W-4Ni-6Mn (wt%) were placed in the cylindrical stainless steel jar and mixed at 150 rpm for 20 h under the protection of Ar atmosphere in the planetary high-energy ball mill (QM–3SP4, Nanjing University Instrument Factory, China). The mass ratio of ball to powder was 6:1. The SEM micrographs and the elemental mapping of the mixed powders are shown in figure 2. Obviously, Mn and Ni powder are relatively homogeneously distributed around W powder. To investigate the effect of oxygen content on the microstructure and properties of tungsten heavy alloys, two kinds of mixed powders with the average oxygen content of 0.07% and 0.15% were obtained by controlling the ball milling process. The effects of the sintering temperature on microstructure and properties of the 90W-4Ni-6Mn alloy were investigated using the milled powder with the oxygen content of 0.07%.

Subsequently, the as-milled powders were uniaxially pressed at a pressure of 200 MPa for 60 s into cylinders of 10 mm in both diameter and height.

Sintering was conducted in a vacuum sintering furnace (ZHJ-90-16W, produced by Jinzhou Transformer Electric Furnace Co., Ltd, China). The vacuum pressure was controlled in the order of $10^{-2} \sim 10^{-3}$ Pa and the sintering temperature varied between 1050 °C and 1200 °C to obtain the optimum condition. The samples were
sintered at a designed sintering temperature for 60 min followed by naturally cooling down to room temperature within the furnace.

2.3. Characterization
The oxygen content of as-milled powders and sintered specimens were measured by an oxygen/nitrogen/hydrogen elemental analyzer (TCH600, produced by LECO Corporation, America). With the methods of ICP AES (Agilent 725, produced by Agilent Technology Co., Ltd, America), the contents of W, Ni, and Mn in the as-milled powders have been determined. After ultrasonic cleaning, the phase of the entire upper surface of the sintered samples was analyzed through x-ray diffraction (XRD, D/Max2500, produced by Rigaku, Japan). The density of the specimens was measured by a high precision densitometer (DE-120M, produced by Hangzhou Jinmai Instrument Co., Ltd, China) based on the Archimedes’ principle. The compression strength of sintered specimens was measured by an electronic universal testing machine (DDL300, produced by Sinotest Equipment Co., Ltd, China). The hardness of all as-sintered specimens was measured by a digital microhardness tester (HVS-1000, produced by Shanghai Lianer Experimental Equipment Co., Ltd, China). The plane of the sintered specimen was divided into nine square areas, and the hardness measurement points were located in the center of each area. The tests repeated three times for each measuring point to reduce the error. Based on the standard deviation of the hardness values, the homogeneity coefficient HI of the sintered specimens can be calculated according to the following formulas to suggest the microstructure uniformity [22]:

$$S^2 = \frac{1}{n-1} \sum_{i=1}^{n} (H_i - \bar{H})^2$$

$$HI = \frac{S}{\bar{H}} \times 100$$

where $S$ is the standard deviation of the hardness value; $H_i$ and $\bar{H}$ represent the hardness measurement value and the average hardness value respectively; $n$ is the number of measurements.

The morphology and element distribution of sintered specimens were characterized by scanning electron microscope (SEM, Quanta 200, produced by FEI, Holland). The software Nano Measurer 1.2 and Image-Pro Plus were used to calculate the average W grain size, the distribution of W grain size, the matrix volume fraction, and the W-W contiguity $(C_{WW})$ in the SEM images. The W-W contiguity was calculated using the following formula [23]:

$$C_{WW} = \frac{2N_{WW}}{N_{WM} + 2N_{WW}}$$

Where $N_{WW}$ is the length of W-W interfaces and $N_{WM}$ is the length of W-matrix interfaces on the SEM images.

3. Results and discussion

3.1. Effect of sintering temperature on the microstructure and density
Figure 3 shows the microstructures and its distribution of W grain size of 90W-4Ni-6Mn alloy sintered at a different temperature. The W grains are of light silvery and the matrix is of lighter shade of gray.
As the sintering temperature increased, the residual pores of the alloy gradually decreased, and the W grain sizes increased gradually with its shape sphericized slowly. In addition, the distribution of grain size continuously changed during the growth of the W grains. It was obvious that the small particles gradually shrink and disappear, and the large W grains grew even more, simultaneously. Densification of W–Ni–Mn alloy is a typical liquid phase sintering process. The liquid phase sintering process can be roughly divided into three stages where the boundaries are not very obvious: (1) formation of liquid phase and rearrangement of particles, (2) dissolution-reprecipitation of the solid phase and (3) formation of the solid-phase skeleton [24, 25]. When the sintering temperature was at 1050 °C, 20 °C higher than the liquidus [11], the amount of liquid phase formed was small, densification was difficult to continue and many pores were retained (see figure 3(a)). It suggests that the densification procedure just stayed at the first stage. As shown in figure 3(b) and (c), when the sintering temperature increased, because small W grains and the edges of the W grain surface preferentially dissolved into

![Figure 3. The microstructures and distribution of grain size of samples sintered at different temperatures: (a) 1050 °C, (b) 1100 °C, (c) 1125 °C, (d) 1150 °C, (e) 1200 °C.](image-url)
the matrix phase, the typical solid-phase dissolution-precipitation stage, in which coarsening of the microstructure is observed. From the W grain distribution diagrams, it can be seen that small W grains tend to shrink and disappear, and large W grains grow further. And more liquid phase is formed. Seen in figure 3(d), as small W grains disappeared, other W grains coalesced and grew. The continuous W skeleton, mainly caused by the further close contact, bonding, and adhesion of the W grains (the yellow circle) at the higher sintering temperature, is presented obviously in figure 3(e).

Figure 4 exhibits the variation of average W grain size with sintering temperature. The average W grain size constantly increases from 1050 °C to 1200 °C, which is consistent with the microstructure shown in figure 3. It is worth noticing that when sintered at 1125 °C, a full density 90W-4Ni-6Mn alloy was obtained with average W grain sizes of 3.8 μm, which is much smaller than that of conventional WHA (20 ~ 60 μm) [2], 90W-6Ni-4Mn alloy (10 ~ 15 μm) [26] and 90W-4Ni-6Mn alloy obtained under an atmospheric controlling cycle (around 10 μm) [16]. This is because as the Mn / Ni ratio increases, the solubility of W in the Ni-Mn matrix decreases, which helps refine the tungsten grains [13]. However, the solubility of W in the Ni-Fe matrix is much larger, which causes the tungsten grains to be coarse [27].

Figure 5 illustrates the variation trend of the W-W contiguity and the matrix volume fraction of the 90W-4Ni-6Mn alloy sintered at different temperatures.

With the sintering temperature increasing from 1050 °C to 1150 °C, the matrix volume fraction increases from 8.13% to 14.27%, while the W-W contiguity decreases from 0.4587 to 0.298. As the temperature increases,
the amount of liquid phase increases. The sufficient liquid phase penetrates the bonded boundary among the W particles, thus leading to a decrease of the W-W contiguity. With the further increase of the sintering temperature to 1200 °C, the liquid content decreases with the reprecipitation of the solid phase and the growth of W grains. On the contrary, the formation of W skeleton makes the W-W contiguity rising. Since the elongation of WHAs is closely related to the W-W contiguity, excessive high W-W contiguity deteriorates the mechanical properties of the alloy [16, 20, 26, 28].

Figure 6 shows the variation of the density and mass loss of the 90W-4Ni-6Mn alloy with sintering temperature. It can be seen that the density of sintered samples goes up with the increase of sintering temperature. A full dense 90W-4Ni-6Mn alloy (99.43% of the relative density) is obtained at 1125 °C, which is lower than the previous report [17–20]. It indicates that the vacuum sintering is beneficial to the densification of W–Ni–Mn alloy. However, it is necessary to note that the density obtained exceeds the theoretical density of the 90W-4Ni-6Mn alloy when the temperature rises above 1150 °C. The mass loss curve suddenly in figure 6 becomes sharply steep from an unchanged state when the temperature exceeds 1150 °C, which suggests the volatilization of some substance under vacuum.

Figure 7(a) presents the SEM micrographs of the surface layer of the sintered 90W-4Ni-6Mn alloy at different temperatures. It is obvious that the liquid phase overflows the surface at 1150 °C and above. It increases the evaporation area, which results in faster mass loss. The XRD spectra for the surface layer (as shown in figure 4(b)) reveals that the MnNi3 phase with the rich Ni is formed. It indicates that the abnormal increase of the density of sintered samples comes from the change of composition of alloys caused by the volatilization of Mn [29, 30].

3.2. Effect of sintering temperature on mechanical properties

Figure 8 describes the effect of the sintering temperatures on the hardness and compressive strength of the 90W-4Ni-6Mn alloys.

As the sintering temperature rises from 1050 °C to 1125 °C, the compression strength increases from 580 MPa to 2790 MPa, and the hardness increases from 67.9 HRA to 70.0 HRA correspondingly. However, with the further increase in temperature, the hardness and compression strength decline. The mechanical properties of 90W-4Ni-6Mn alloy are related to its relative density and microstructure, especially pores, W grain size, and W-W contiguity [16–20, 26, 28]. When the temperature is lower than 1125 °C, the compressive strength and hardness increase with the increase of temperature. It is ascribed to the increasing density, decreasing residual porosity and pore size. When sintered at the 1125 °C, the 90W-4Ni-6Mn alloy acquires near full density, homogenous microstructure with the fine grain size of 3.80 μm (seen as figure 3(c)), and relatively low W-W contiguity (seen as figure 5), thus the maximum mechanical properties obtained. When sintering temperature is above 1125 °C, the increase in density is due to the evaporation of the matrix phase rather than the disappearance of residual pores, however, the W grain size and W-W contiguity grow rapidly, thus deteriorating the mechanical properties.
3.3. Fracture morphology of 90W-4Ni-6Mn alloy

Figure 9 shows the fracture morphology of 90W-4Ni-6Mn alloy sintered at different temperatures. Generally, there are four possible fracture modes in W alloys, namely tungsten cleavage (W), matrix rupture (M), W-W grain boundary separation (W-W), and W-matrix interface separation (W-M) [20].

Seen in figure 9(a), many residual pores acting as crack sources are observed on the fracture surface of the 90W-4Ni-6Mn alloy. The binding force at the pores is the lowest. As a consequence, the 90W-4Ni-6Mn alloy sintered at 1050 °C is prone to fracture and its mechanical properties are the poorest. When the temperature reaches 1100 °C, the density of the alloy further increases, and the number and size of pores decreases rapidly, resulting in an improvement of the mechanical properties. Obviously, the fracture mode is dominated by the W-W grain boundary separation as a result of the high W-W contiguity (seen as figure 9(b)). From figure 9(c), it can be seen that the main fracture modes of the 90W-4Ni-6Mn alloy sintered at 1125 °C comprise the W-matrix interface separation (W-M), W-W grain boundary separation (W-W) and the matrix rupture (M), which is related with the high mechanical properties caused by the full densification and fine grain strengthening. When the temperature rises to 1150 °C and above, the main fracture modes are W-W grain boundary separation (W-W), the W–matrix interface separation (W-M) and the matrix rupture (M) (seen as figures 9(d) and (e)). However, due to the volume fraction of the matrix phase and the W-W contiguity start to decrease and increase,
respectively. Thus, the proportion of the W-W grain boundary separation (W-W) begins to increase obviously, and a few tungsten cleavages (W) are also observed. It may be attributed to the low mechanical properties due to the growth of W grains.

Table 2. The characteristics of 90W-4Ni-6Mn alloy with different oxygen content.

| Specimen | Oxygen content (wt %) | Relative density (%) | Average W grain size (μm) | W-W continuity (%) | Compressive strength (MPa) | Hardness (HRA) | HI |
|----------|----------------------|----------------------|---------------------------|--------------------|---------------------------|---------------|----|
| 1#       | 0.19                 | 99.43                | 3.80                      | 34.02              | 2790                      | 70.0          | 5.07|
| 2#       | 0.22                 | 98.88                | 3.94                      | 32.72              | 2520                      | 69.1          | 14.99|

Figure 9. Fracture morphology of W–4Ni–6Mn alloy sintered at different temperatures. (a) 1050 °C, (b) 1100 °C, (c) 1125 °C, (d) 1150 °C and (e) 1200 °C.

Figure 10. Microstructure of the specimen 1 # and the EDS mapping results of O, Mn and the overlay of O and Mn.
3.4. Effect of impurity oxygen on microstructure of 90W-4Ni-6Mn alloy

It was believed that the presence of oxygen intensified the formation of MnO during the sintering process, which hindered the liquid phase sintering and densification \[9, 14, 15\]. But the more specific impact of oxygen content has not been explored. Table 2 shows the characteristics of 90W-4Ni-6Mn alloy with different oxygen content sintered at 1125 °C for 60 min.

Using the mixed powders with the oxygen content of 0.07% and 0.15%, the sintered 90W-4Ni-6Mn alloys with the oxygen content of 0.19% and 0.22% were prepared, respectively. Higher oxygen content results in lower relative density because the manganese oxide impurity phase formed during sintering hinders the densification of powders. The homogeneity coefficient HI is used to characterize the microstructure uniformity of alloys. From table 2, it can be seen that the HI value of specimen 2# is up to 14.99, which is much higher than that of specimen 1#. It indicates that the more oxygen, the less homogeneous the microstructure of 90W-4Ni-6Mn alloys is. Both the lower density and inhomogeneous microstructure lead to the deterioration of the mechanical properties.

Figures 10 and 11 show the microstructure and the EDS mapping results of O, Mn and the overlay of O and Mn of the specimen 2# and 1#, respectively. The density of the specimen 1# and 2# are 16.83 g cm\(^{-3}\) and 16.71 g cm\(^{-3}\), respectively. It is observed that more manganese oxides impurity phase are accumulated in the manganese-rich phase in sample 2# than that in sample 1#, resulting in the uneven microstructure. It was also observed in other sintered samples other than sample 1# and 2#. However, the microstructure and element distribution of W alloys obtained by vacuum sintering seem to be more uniform than those of spark plasma sintering generally \[20\].

4. Conclusion

A vacuum sintering process that can make a 90W-4Ni-6Mn alloy with full density has been developed. The sintering temperature has a significant effect on microstructure, density, and mechanical properties. When sintered at 1125 °C for 60 min, the 90W-4Ni-6Mn alloy exhibits a fine W grain size of 3.80 μm, relative densities about 99.43%, the maximum compression strength of 2790 MPa and hardness of 70.0 HRA. Compared with the previous report, the 90W-4Ni-6Mn alloy prepared by vacuum sintering has higher relative density, finer W grain size, and more homogeneous microstructure due to the lower sintering temperature. In addition, impurity oxygen intensified the heterogeneity of microstructure and element distribution, accelerated the accumulation and increase of manganese oxide phase, and hindered the further densification of powder, which deteriorated the mechanical properties of the 90W-4Ni-6Mn alloy.
Acknowledgments

This work was financially supported by the National Key R&D Program of China (2017YFB0305601), Hunan Provincial Innovation Foundation for Postgraduate (150110005), the Innovation Foundation for Undergraduate (202321020) and the Open Sharing Fund for the Large-scale Instruments and Equipments of Central South University.

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References

[1] Ekbohm L B 1991 Tungsten heavy metals Scand. J. Metall. 20 190–7
[2] Schubert W D 1992 Aspects of research and development in tungsten and tungsten alloys Int. J. Refract. Met. Hard Mater 11 151–7
[3] Khalid F A and Bhattacharya A 1999 Microstructure and properties of sintered tungsten heavy alloys J. Mater. Eng. Perform. 8 46–50
[4] Bose A, Sadjadi R and German R M 2012 A review on alloying in tungsten heavy alloys Supplemental Proc.: Materials Processing and Interfaces 1, 435–65
[5] Magness I S Jr 1994 High strain rate deformation behaviors of kinetic energy penetrator materials during ballistic impact Mech. Mater. 17 147–54
[6] Bose A 1992 Shear localization in tungsten heavy alloys Met. Powder Rep. 47 53
[7] Kim D K, Lee S and Baek W H 1998 Microstructural study of adiabatic shear bands formed by high-speed impact in a tungsten heavy alloy penetrator Mater. Sci. Eng. A 249 197–205
[8] Bose A, Coque H R and Langford J Jr 1992 Development and properties of new tungsten-based composites for penetrators Int. J. Powder Metall 28 383–94
[9] Bose A and Petaluma C 1999 Ternary heavy alloy based on tungsten-nickel-manganese US Patent No. 5,863,492
[10] Belhadjhamida A and German R M 1992 Effects of atmosphere, temperature, and composition on the densification and properties of tungsten-nickel-manganese Met. Powder Rep. 47 54
[11] Okamoto H et al (ed) 1996 Binary Alloy Phase Diagrams (Materials Park, OH: ASM international)
[12] Zahraee S M, Salehi M T, Arabi H and Tamizifar M 2007 Development of a tungsten heavy alloy, W–Ni–Mn, used as kinetic energy penetrator Iran. J. Mater. Sci. Eng. 4 9–13
[13] Zahraee S M, Arabi H, Salehi M T and Tamizifar M 2008 Effect of Mn/Ni ratio variation on microstructure of W–Ni–Mn alloy Powder Metall. 51 303–9
[14] Hong M H, Noh J W, Kim E P, Song H S, Lee S and Baek W H 1997 A study on the improvement of the sintered density of W–Ni–Mn heavy alloy Metallurgical and Materials Transactions B 28 835–9
[15] Hong M H, Baek W H, Noh J W, Song H S, Lee S and Kim E P 1999 US Patent No. 5,970,307
[16] Liu H, Cao S, Zhu J, Jin Y and Chen B 2013 Densification, microstructure and mechanical properties of WC–Ni–4Mn–6Ni heavy alloy Int. J. Refract. Met. Hard Mater 37 121–6
[17] Pan Y L, Ding L and Xiang D P 2017 Microstructure evolution and mechanical properties of spark plasma sintered W–Ni–Mn alloy Transactions of Nonferrous Metals Society of China 27 1588–93
[18] Pan Y, Ding L, Li H and Xiang D 2017 Effects of Y2O3 on the microstructure and mechanical properties of spark plasma sintered fine-grained W–Ni–Mn alloy J. Rare Earths 35 1149–55
[19] Pan Y, Xiang D, Wang N, Li H and Fan Z 2018 Mechanical milling-assisted spark plasma sintering of fine-grained W–Ni–Mn alloy Mater. Sci. Eng. A 713 6–11
[20] Fan Z S, Xiang D P, Pan Y L and Jiang H 2019 Effect of two-time spark plasma sintering on microstructure and mechanical properties of W–6Ni–4Mn alloy Mater. Sci. Eng. A 745 300–6
[21] Gao Y, Luo B H, He K J, Jing H B, Bai Z H, Chen W and Zhang W W 2017 Mechanical properties and microstructure of WC–Fe–Ni–Co cemented carbides prepared by vacuum sintering Vacuum 143 271–82
[22] Selcuk C, Bentham R, Morley N and Wood J V 2004 Microhardness as a measure of homogeneity of porous tungsten Mater. Lett. 58 1873–6
[23] German R M and Park S J 2009 Handbook of Mathematical Relations in Particulate Materials Processing: Ceramics, Powder Metals, Cermetts, Carbides, Hard Materials, and Minerals 3 (New York: Wiley)
[24] German R M 2013 Liquid Phase Sintering (Springer Science & Business Media)
[25] Somiya S and Moriyoshi Y (ed) 2012 Sintering Key Papers (Springer Science & Business Media) 595–614
[26] Chen B, Cao S, Xu H, Jin Y, Li S and Xiao B 2015 Effect of processing parameters on microstructure and mechanical properties of WC–Ni–4Mn–6Ni heavy alloy Int. J. Refract. Met. Hard Mater 48 293–300
[27] Upadhyay A, Tiwari S K and Mishra P 2007 Microwave sintering of W–Ni–Fe alloy Scr. Mater. 56 5–8
[28] Muthuchamy A, Yadav D, Agrawal D K and Annamalai R 2018 Structure-property correlations of W–Ni–Fe–Mo heavy alloys consolidated using spark plasma sintering Mater. Res. Express 5 062545
[29] Smith J H, Paxton H W and McCabe C L 1964 Manganese vapor pressures in equilibrium with manganese—iron—nickel solid solutions J. Phys. Chem. 68 1345–54
[30] Ren S, Li P, Jiang D, Shi S, Li J, Wen S and Tan Y 2015 Removal of Cu, Mn and Na in multicrystalline silicon by directional solidification under low vacuum condition Vacuum 115 108–12