TENSILE BEHAVIOR CHANGE DEPENDING ON THE VARYING TUNGSTEN CONTENT OF W–NI–FE ALLOYS

Syed Humail Islam[1], Farid Akhtar[2], Syed Jawaid Askari[2], Muhammad Tufail Jokhio[1], Xuanhui Qu[2]

ABSTRACT

Tungsten heavy alloys (WHAs) are metal–metal composites consisting of nearly pure spherical tungsten particles embedded in a Ni–Fe–W or Ni–Co–W or Ni–Cu–W ductile matrix. In this dual phase alloy, there are several complicated relations between the ductile matrix and hard tungsten particles. The aim of this research was to examine the effect of varying tungsten content on the microstructure and mechanical properties of tungsten heavy alloys. The microstructural parameters (grain size, connectivity, contiguity and solid volume fraction) were measured and were found to have a significant effect on the mechanical properties of tungsten-based heavy alloys. The result shows that the binding strength between the W and the matrix phase has a major influence on the ductility of tungsten-based alloys. The larger this binding force is, the better the ductility is.

Keywords: Tungsten heavy alloys; mechanical properties; microstructure; fracture morphology

1. INTRODUCTION

Tungsten heavy alloys are two phase composites consisting of nearly pure tungsten grains dispersed in a low melting temperature ductile matrix of other metals such as iron (Fe), nickel (Ni), cobalt (Co), or copper (Cu) [1,2]. The typical mean tungsten grain size varies from 20 μm (66 μft) to 60 μm (197 μft) depending on the initial particle size, volume fraction of tungsten, sintering temperature, and sintering time. Due to their high density and high strength associated with the bcc tungsten phase, and high ductility attributed to the fcc matrix, these alloys are used in application such as kinetic energy penetrators, radiation shielding, counter balance, vibrational damping devices, and other military and civil applications [3,4].

During the last two decades, the research of tungsten heavy alloys has concentrated on strengthening methods, which do not compromise their density. This is especially important in military applications. The combination of a powder with a particular microstructure and a consolidation technique that can maintain that microstructure is an effective method for obtaining bulk samples with a unique microstructure. The mechanical properties of tungsten heavy alloys are determined by various factors; in particular, the strength of W/W and W/matrix interfaces [5]. Microstructural factors, such as tungsten particle size, matrix volume fraction and tungsten–tungsten contiguity, affect the mechanical properties of tungsten heavy alloys [6]. The main focus of this study is to investigate

[1] *Department of Industrial and Manufacturing Engineering, NED University of Engineering and Technology Karachi 75270, Pakistan*

[2] *School of Materials Science and Engineering, State Key Laboratory for Advanced Metals and Materials, University of Science and Technology Beijing, Beijing 100083, PR China*

Syed Humailul Islam is an Associate Professor in the Department of Industrial and Manufacturing Engineering at NED University of Engineering and Technology, Karachi, Pakistan. He received his Beng and MEng in Mechanical Engineering in 1998 and 2003, respectively. He received his PhD in Materials Science and Engineering from the University of Science & Technology Beijing, China in 2007.

Farid Akhtar received his Beng in Metallurgical and Materials Engineering and MEng in Materials Engineering in 1999 and 2002, respectively. He received his PhD in Materials Science and Engineering from the University of Science & Technology Beijing, China in 2007. His research interests include powder metallurgy science, particularly in alloy design for sintering, infiltration and rapid manufacturing of aluminium and titanium systems

Syed Jawaid Askari received his BEng and MEng in Mechanical Engineering in 1990 and 1994, respectively. He received his PhD in Materials Science and Engineering from the University of Science & Technology Beijing, China in 2007. His research interests include an investigation of the processing, structure, and mechanical property characterization of diamond films grown using a variety of deposition conditions and substrate materials.

Muhammad Tufail Jokhio received his BEng in Mechanical Engineering and MEng in Manufacturing Systems in 1991 and 1994, respectively. He received his PhD in Mechanical Engineering from University of Nottingham in 1999. His research interests include Development of Composite Materials

Xuanhui Qu received his BEng and MEng in Metallurgical Engineering in 1984 and 1986, respectively. He received his PhD in Materials Science and Engineering from the Central South University Changshaw, China in 1992. His research interests include Development of Part by Powder Metallurgy and Powder Injection Moulding Techniques

and identify trends in microstructure behaviour relative to variations in W content and the influence of microstructure change on the mechanical properties of tungsten heavy alloys.

2. EXPERIMENTAL DETAIL

Elemental powders of tungsten, nickel and iron were mixed to produce tungsten heavy alloys with compositions of 88%, 93% and 95 wt% of tungsten with Ni:Fe in the ratio of 7:3. **Table 1** summarizes the characteristics of the powders. The powders were consolidated into green compacts with 55–65% of theoretical density by die pressing. The green compacts were liquid phase sintered at a temperature of 1500 ^{o}C (2732^{o}F) for 30 min and in hydrogen atmosphere. The sintering cycle followed for all experiments was 10 ^{o}C/min (50 ^{o}F/min) up to 800 ^{o}C (1472^{o}F) and 5 ^{o}C/min (41^{o}F/min) thereafter. During the cooling cycle, at 1400 ^{o}C, the atmosphere changed from hydrogen to argon. The sintered samples were subsequently annealed in a vacuum at a temperature of 1100 ^{o}C (2012^{o}F) for 8 h, in order to reduce the content of absorbed hydrogen and prevent embrittlement, and then water quenched to circumvent the impurity segregation problem. The densities of the sintered specimens were measured by the Archimedes water immersion method. Quasi-static tensile testing was carried out using an Instron testing system with a constant cross head displacement rate of 0.5 mm/min (0.02in./min) in ambient air at room temperature. Three specimens were used for each measurement. Samples were prepared for microstructural evaluation by cutting, mounting, grinding and polishing to a 0.3 ìm (0.98 µft) surface finish using standard metallographic procedures. The size of the tungsten particles, the volume fraction of the matrix phase, the connectivity and tungsten–tungsten contiguity of the sintered tungsten heavy alloys were characterized using LEO-1450 SEM (scanning electron microscope). The volume fraction, connectivity and contiguity were measured manually by point counting method. Fractographical observations of tensile tested specimens were conducted by LEO-1450 SEM.

Table 1. Characteristics of Ni, W and Fe Powder

Powder	W	Ni	Fe
Purity	99.2%	99.6%	99%
Shape	Irregular	Spiky	Nearly spherical
Particle size (μm)			
D_{10}	3.1	4.3	1.9
D_{50}	7.6	14.6	3.4
D_{90}	19.1	33.5	6.3
Apparent density (g/cm^3)	4.3	3.1	2.6
Tap density (g/cm^3)	6.3	3.6	4.1
Surface area (m^2/cm^3)	1.138	0.734	2.236

3. RESULTS AND DISCUSSION

3.1 Microstructure

The microstructures of heat treated alloys containing 88%, 93% and 95% weight tungsten are presented in **Figure 1a–c**. As can be seen, the tungsten particles in Figure 1a are smaller and rounder than those in Figures 1b and c. The difference is attributable to the difference in the amount of matrix phase present in each alloy. In 88 wt% tungsten alloys, there is a greater amount of matrix phase available which promotes the Ostwald ripening and results in smaller and rounder grains. The difference in size between the particles in Figures 1b and c is also attributable to the difference in the amount of matrix phase present in each alloy. In Figures 1b and c the tungsten particles are very irregular in shape. It is important to note that this irregularity increases the contact area of the tungsten–matrix interphase, thereby considerably increasing the strength of the alloys [7].

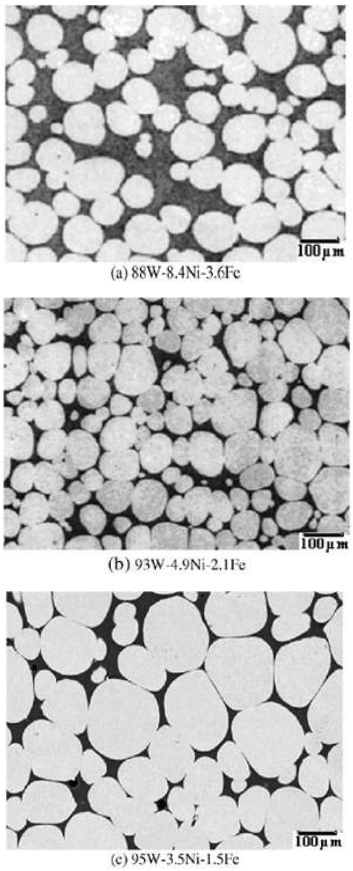

Figure 1. Microstructure of WHAs sintered at 1500°C (2732°F) for 30 min and vacuum annealed at 1100°C (2012°F) for 8 h.

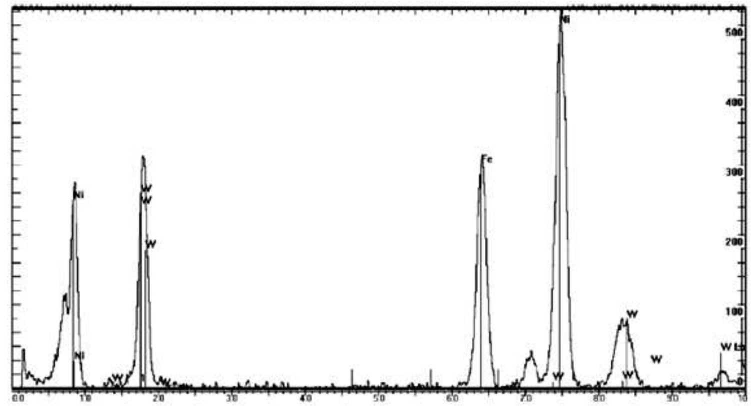

Figure 2. EDX spectrum of matrix phase in 93W-4.9Ni-2.1Fe

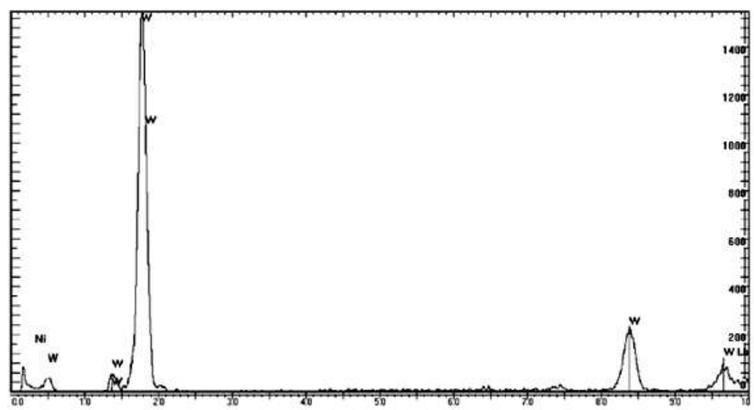

Figure 3. EDX spectrum of matrix phase in 93W-4.9Ni-2.1Fe

Quantitative EDX analysis showed that W–Ni–Fe matrix phase consists of about 24wt%W–22wt%Fe–54%Ni in 93%W. **Figure 2** shows the EDX spectrum of matrix phase of 93 wt%W. **Figure 3** shows the EDX spectrum for the tungsten phase which showed imperceptible presence of iron and nickel making it pure tungsten phase. Interestingly, the compositions of matrix phase of 88% and95%Ware not very different from the 93%W.

The microstructure measurements of grain size, solid volume fraction, contiguity and connectivity are taken from SEM micrographs. There is a major change in microstructure as the tungsten content increases from 88% to 95 wt%. The measured volume fraction of the tungsten grains increases linearly from 0.73 for the 88%W alloy to approximately 0.91 for the 95%W alloys. **Figure 4** shows the variation of tungsten grain size, contiguity and two dimensional connectivity with the increase of tungsten content in the alloy composition from 88% to 95 wt% sintered at 1500 ^{o}C (2732^{o}F) and vacuum heat treated at 1100 ^{o}C (2012^{o}F) for 8 h. It is important to note that not only contiguity but also connectivity, tungsten grain size and matrix volume fraction is largely affected by the tungsten content.

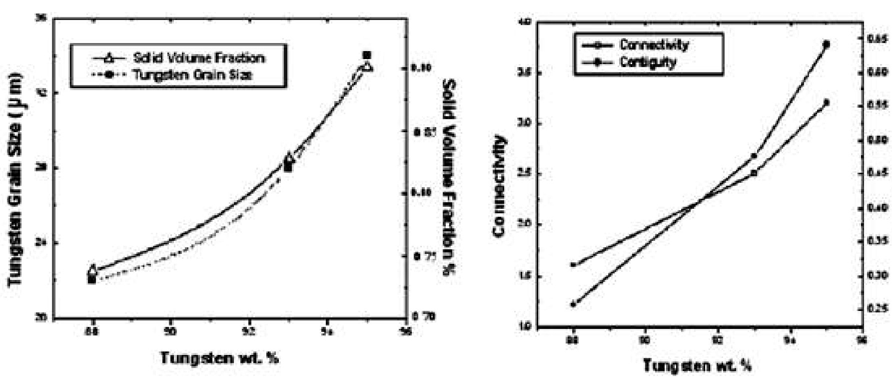

Figure 4. Solid volume fraction, contiguity, connectivity and grain size variations with sintering temperature for 88%, 93% and 95% tungsten.

Table 2. Tensile properties of 88%, 93% and 95% W-based heavy alloys sintered at 1500 °C for 30 min and vacuum annealed at 1100 °C for 8 h

Mechanical properties/composition	88W-8.4Ni-3.6Fe	93W-4.9Ni-2.1Fe	95W-3.5Ni-1.5Fe
Density (g/cm^3)	16.60	17.52	17.98
Tensile strength (MPa)	894	996	916
Elongation (%)	30	23	11

3.2. Tensile Properties

The mechanical properties shown in **Table 2** can be explained by considering the effect of tungsten content on alloy strengthening. **Table 2** shows that the tensile strength of the 93 wt% tungsten is higher than the 88% and 95 wt% tungsten-based alloys. This is first because of the tungsten content and the size of the tungsten particles after sintering and heat treatment. Secondly, uniform distribution of the matrix phase and the tungsten particles appear to be well bonded to the Ni–Fe–W matrix. However, at the same time, the ductility of the alloy decreases as the tungsten content is increased, and above 93%W the ductility of the alloys decreases drastically. This in turn causes the tensile strength of the alloys to decrease at above 93%. This phenomenon is attributable to a higher number of W–W grain boundaries at high contiguities which are the weakest interfaces. Though alike in some aspects, the microstructures of the three alloys are different enough to present a range of mechanical properties. At lower tungsten content (88%W), the higher ductility is a result of lower contiguity and connectivity, the availability of more matrix phase and the uniform distribution of the matrix phase between the tungsten particles. At higher tungsten content (95%W), the ductility of the alloys decreases noticeably because of higher contiguity and connectivity, as the tungsten–tungsten particle interfaces are the most brittle parts. These interfaces split easily and micro cracks soon appear even at very low load, acting as fracture sites and helping easy crack propagation because the amount of matrix phase available is not sufficient to arrest the proliferation of these cracks. Thus, they cause deterioration of the overall properties of tungsten heavy alloys. Important thing is to deal with the matrix phase inconsistency by properly control the grain growth of the tungsten particle during the sintering process.

3.3. Fracture Morphology

Scanning electron micrographs (QBSD) of the fracture surfaces of alloys containing 88%, 93% and 95% are shown in **Figure 5**. The W grains appear light and the matrix phase appears darker in these pictures. It is well known that there are four possible fracture paths [8] for the heavy alloy microstructure: matrix failure, W cleavage, W–W intergranular failure and W–matrix interfacial separation. By investigating the fracture surfaces, differences in the mechanisms of fracture in the 88%, 93% and 95 wt%. W alloys are readily observable and these indicate that the fracture behaviour and tensile properties of the tungsten heavy alloys are strongly influenced by the variation in the tungsten content of the alloy. In **Figure 5a**, the intergranular cleavage and fracture, separation of W–W facets, W–matrix decohesion, and isolated matrix rupture is visible for 95 wt% W alloys. **Figure 5b** shows that the processing method used in this study resulted in a strong interface, as evidenced by excellent W–matrix adhesion and a minimum amount of interfacial separation in the 93 wt%W alloys. The other three failure modes can also be observed on the fracture surfaces; however, the proportion of each feature depends upon W content. The amount of W–W separation is high in the case of the 95%W, whereas the amount of W cleavage is much greater for 88 wt% alloy. A close examination of the fracture surfaces reveals several interesting phenomena. For example, it appears that W cleavage occurs more frequently in larger W grains. The amount of W–W grain boundary failure is fairly uniform over the three different compositions of the alloy. These results further confirm that the W–W grain boundary is the weakest interface since all fracture surfaces exhibit approximately the same amount of failure by this path. The 95%W tensile tested samples show predominantly intergranular fracture (**Figure 5a**). This is expected, because the low volume fraction of binder ensures a high degree of contiguity and higher contiguity helped in microcrack nucleation. As the W content is reduced, the fracture develops into a cleavage in the W grains, and is commonly observed in this type of alloy [9–11]. SEM images of the 88%W, as shown in **Figure 5c** and **d**, reveal partial W–matrix separation, cracks in W due to its brittle quality and thin areas of matrix between W grains. **Figure 5d** shows that tensile failure of the 88% alloy

starts by separation of W/W and develops by producing cleaved tungsten grains after strain hardening the matrix and then matrix rupture occurs. Failure of the strain-hardened matrix around the smaller W grains is evident in this alloy, as shown in **Figures 5e** and **f**. The higher the ductility, the greater is the proportion of W cleavage and matrix phase failure. Also, decohesion of the W–matrix interphase is evident with low ductilities. This study also shows that crack formation in the tungsten heavy alloy mostly starts principally through W–W interfaces rather than through interfaces between W grains and the matrix phases. The matrix phase plays an important role in hindering crack propagation. For a fixed contiguity, the ductility depends on the W matrix interfacial properties. These results show that the binding strength between the W and the matrix phase has a major influence on the ductility of tungstenbased alloys. The larger this binding force is, the better the ductility.

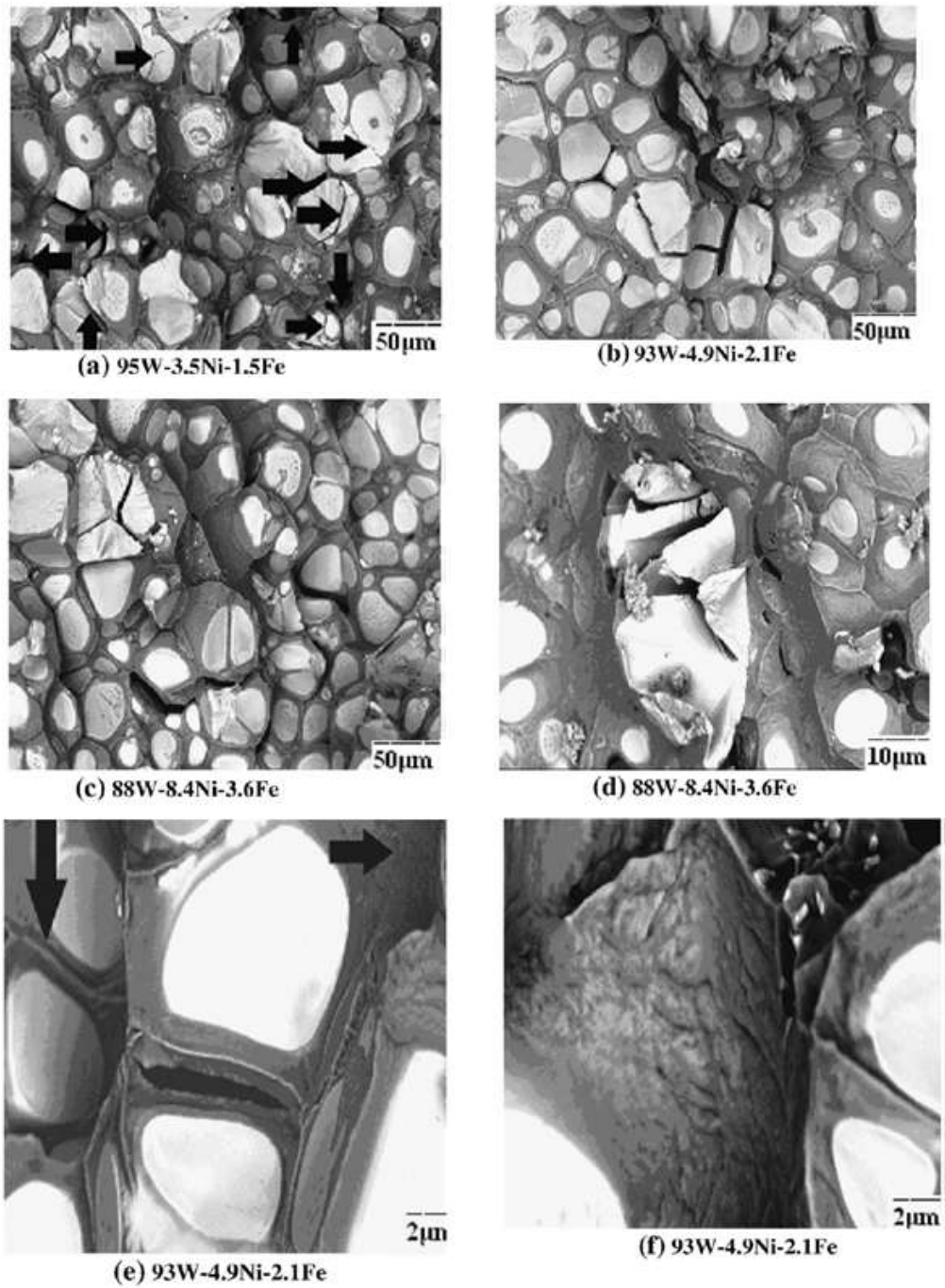

Figure 5. Fracture morphology of WHAs sintered at 1500°C (2732°F) for 30 min and vacuum annealed at 1100°C (2012°F) for 8 h.

4. CONCLUSIONS

This study has determined the variation in mechanical properties associated with different compositions and microstructural parameters of tungsten heavy alloys produced by die pressing and liquid-phase sintering. The inherent property of tungsten at various compositions does not change. The variation in mechanical properties at three different compositions is a result of the difference in tungsten grain size, matrix volume fraction and weak W–W contiguity. Good cohesion between tungsten and the matrix results in a material that is capable of transferring the stresses between W grains and the matrix. The crack formation is attributable to tensile force acting on poorly bonded areas. The ultimate tensile strength is at a maximum at 93%W and this is because of optimal tungsten grain size, better bonding energy between tungsten and the matrix, and a homogeneous distribution of the matrix phase.

REFERENCES

[1] Upadhyaya A. Processing strategy for consolidating tungsten heavy alloys for ordnance applications. Mater Chem Phys 2001;67:101–110.

[2] Ryu HJ, Hong SH, Baek WH. Microstructure and mechanical properties of mechanically alloyed and solid state sintered tungsten heavy alloys. Mat Sci Eng A 2000;291:91–6.

[3] Cai WD, Li Y, Dowding RJ, Mohamed FA, Lavernia EJ. Rev Particulate Mater 1995;3:71.

[4] German RM. Critical developments in tungsten heavy alloys. In: Bose A, Dowding RJ, editors. Tungsten and tungsten alloys. Princeton (NJ): MPIF; 1992. p. 3–13.

[5] Noh JW, Kim EP, Song HS, Baek WH, Churn KS, Kang SJL. Matrix penetration of W/W grain boundaries and its effect on mechanical properties of 93W–5.6Ni–1.4Fe heavy alloy. Metall Trans A 1993;24:2411–6.

[6] Rabin BH, German RM. Microstructure effects on tensile properties of tungsten–nickel–iron. Metall Trans A 1988;19:1523–32.

[7] Hong MH, Kim EP, Baek WH, Moon IH. The effect of manganese addition on the microstructure of W–Ni–Fe heavy alloy. Metall Mater Trans A 1999;30A:627–32.

[8] German RM, Churn KS. Sintering atmosphere effects on the ductility of W–Ni–Fe heavy metals. Metall Trans A 1984;15A:747–54.

[9] Gero R, Borukhin L, Pikus I. Some structural effects of plastic deformation on tungsten heavy metal alloys. Mat Sci Eng A 2001;302:162–7.

[10] Rabin BH, Bose A, German RM. Characteristics of liquid phase sintered tungsten heavy alloys. Int J Powder Metall 1989;25:21–7.

[11] O'Donnell RG, Woodward RL. The composition and temperature dependence of the mechanical properties of tungsten alloys. Metall Trans A 1989;21:744–8.