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Comparison of mechanical and microstructure properties of tungsten alloys for special purposes

Aida Imamović[1*], Šaban Žuna[2], Ensar Mulaosmanović[3], Zijad Alibašić[4] Borut Kosec[5]
[1] Faculty of Metallurgy and Technology, University of Zenica, Zenica, Bosnia
[2,3,4] Center for Advanced Technologies, Sarajevo, Bosnia
[3] Faculty of Natural Sciences and Engineering, University of Ljubljana, Ljubljana, Slovenia

*Corresponding author E-mail: aida.imamovic@unze.ba, saban.z@cnt.ba

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Abstract

Tungsten belongs to a group of refractory metals that possess extraordinary resistance to heat and wear and it is the heaviest engineering material. Because of its properties tungsten is used for special purposes.

This paper presents the results of mechanical and microstructure research on the example of the characteristic heavy tungsten alloys 91W-6Ni-1,8Fe-1Co and 93W-5Ni-1,6Fe-0,3Co with different Ni/Co ratios.

The proper Ni/Co ratio is important to obtain a favorable microstructure and mechanical properties of these materials. The distribution of the W, Ni, Co and Fe elements in tungsten phase and binder phase, which can influence on mechanical properties of tungsten alloys.

The SEM analysis and the results of mechanical tests show that the alloy, which is within the exact limits of the Ni/Co ratio, has a finer microstructure and better mechanical properties, which is very important for maintaining the quality of tungsten alloys for special purposes.

Keywords: Tungsten alloys, Special purposes, SEM analysis, Mechanical properties

1. Introduction

Tungsten heavy alloys belong to material that possess a very high melting temperature and excellent mechanical properties. These properties have led to tungsten being used in various fields, including military industry, and for nuclear reactors, radiation shields, balancing elements, vessels, jet engines, tanks and missile parts. The defense and aerospace industries are also large customers of tungsten heavy alloys.

Tungsten heavy alloys have very high melting temperature, high density, high elastic modulus, high strength, plasticity, and impact strength, high thermal conductivity, and excellent mechanical properties at elevated temperatures, useful properties for application in radiation shields, vibration dampers, counterbalance, missile parts and rocket nozzles [1]. For such high requirements, it is necessary to adjust the chemical composition, size, shape and distribution of tungsten particles in the matrix and the strength of the interface bonds between the tungsten particles and the matrix. The properties of the structure can be influenced during mechanical alloying, liquid-phase sintering and, finally, during post-sinter plastic deformation or/end heat treatment. Nickel matrix phase, which has a high solubility for tungsten, is melted during liquid-phase sintering. After sintering, the final microstructure consists of spherical tungsten phase (particles size of 20 μm – 60 μm) dispersed in a hardened matrix, containing some dissolved tungsten.

The requirements for the kinetic energy (KE) penetrator material are particularly high, for example punching steel plates with thickness of 500 mm at a speed of 1600 m/s and depend on grain size, alloying elements content sintering time, post-sinter plastic deformation and heat treatment parameters. In the case of coarser tungsten particles, strength properties decrease [2].

On the other hand, the ductility of heavy tungsten alloy decreases with increasing tungsten content, and when the tungsten content exceeds 93%, the ductility then starts to decrease drastically [3]. Modeling of tungsten heavy alloy for kinetic energy penetrators is presented in Figure 1. The requirements for the capability of kinetic energy penetrators, such as high density and good penetration, are of particular importance for modern militaries of global superpowers [4].

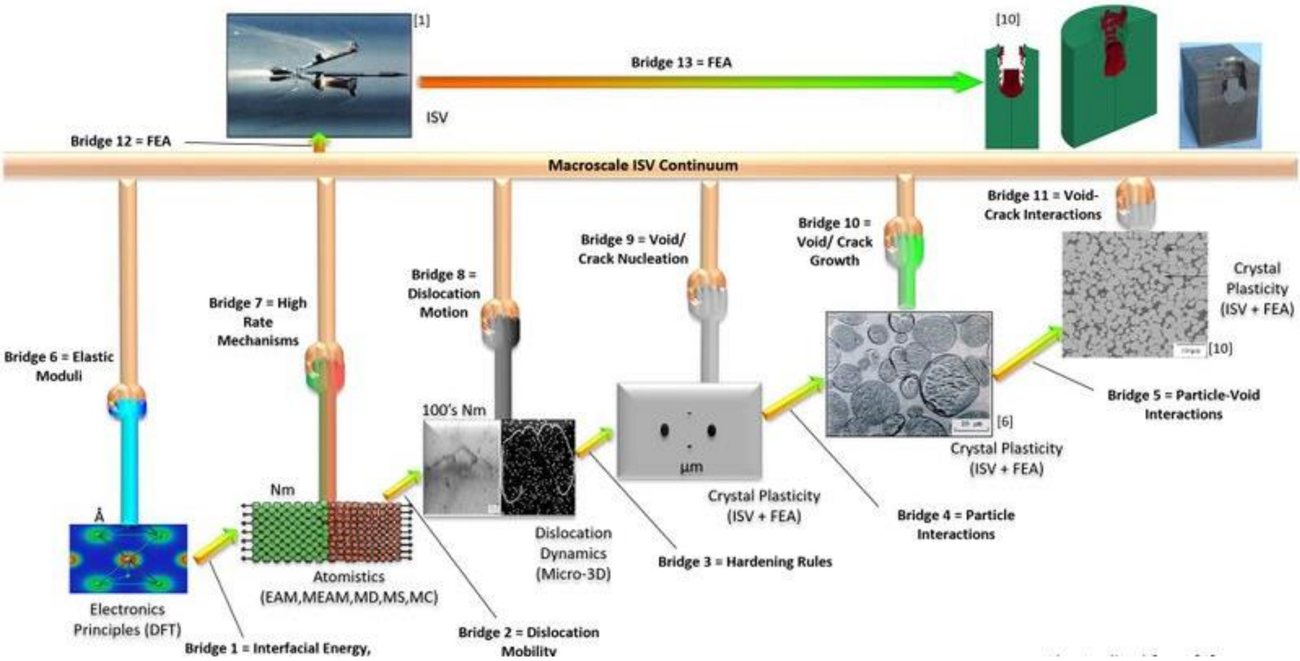

Figure 1. Modeling of tungsten heavy alloy for kinetic energy penetrators [4]

The Ni/Co ratio and tungsten particles size, shape and distribution can be adjusted in the process of mechanical alloying which has an important role in obtaining microstructural characteristics and mechanical properties of the tungsten-based materials.

The characteristics of the microstructure also can be influenced during solid phase sintering with high Ni/Co ratio or liquid-phase sintering with low Ni/Co ratio and, finally, during post-sinter plastic deformation or/end heat treatment. Nickel based matrix which has a high solubility for tungsten, is melted during liquid-phase sintering. In the case of liquid phase sintering was found that the low Ni/Co ratio condition corresponds with a coarse-grained structure and decrease in hardness [5].

The tungsten heavy alloys, which correspond to class 1 and class 2 according to ASTM B777-15, [6], with a defined Ni/Co ratio have been investigated in this study. The aim of this paper is to investigate microstructure of two tungsten alloys 91W-6Ni-1,8Fe-1Co and 93W-5Ni-1,6Fe-0,3Co, with their chemical and microstructure analysis, hardness measurement and tensile test.

2. Research method

The samples of tungsten alloys 91W-6Ni-1,8Fe-1Co (named 91W) and 93W-5Ni-1,6Fe-0,3Co (named 93W) were tested, to determine the microstructural and mechanical properties of these samples in according to their quality from the aspect of a two-component binder based on Ni-Co. The chemical and mechanical analysis were performed at the "Kemal Kapetanović" Institute, University of Zenica, and examinations on a scanning electron microscope at the Faculty of Science and Technology of the University of Ljubljana.

3. Results and discussion

2.1 Chemical analyses of tungsten alloys

The results of chemical content of the tungsten alloys 91W and 93W are presented in Table 1, [6, 7].

Table 1. Chemical properties of the tungsten alloys 91W and 93W [6, 7]

Type of tungsten alloys	Chemical analysis, %							
	Ni	Fe	Co	Si	Cr	Mn	S	W
91W (91W-6Ni-1,8Fe-1Co)	6.00	1.81	1.05	0.11	0.05	0.03	0.002	rest.
93W (93W-5Ni-1,6Fe-0,3Co)	4.99	1.58	0.30	-	0.002	0.04	-	rest.

2.2. SEM test results of tungsten alloys

The analysis of tungsten alloy microstructure was carried out with the aim of defining the phase content, size and distribution of tungsten phase. The detailed SEM/EDS analyses of phases were performed by scanning electron microscope SEM ThermoFisher Science Quatro S with attached energy-dispersive x-ray spectroscopy (EDS) system. Tungsten alloys are a typical class of two-phase composites consisting of spherical tungsten-based phase (particles) surrounded by a ductile phase of a lower melting point matrix consisting of Ni, Fe, Cu and Co. The samples of 91W and 93 W were analyzed in the longitudinal sections, Figures 2 and 3 [6].

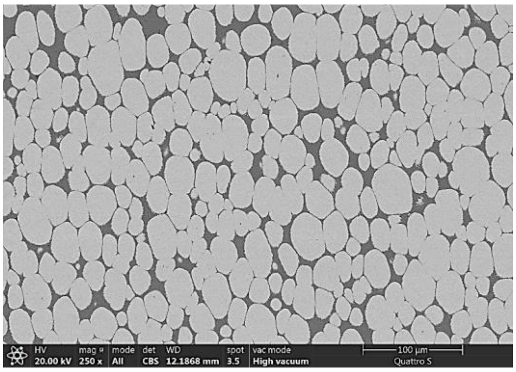

Figure 2. SEM image of the longitudinal sample 91W, 250x

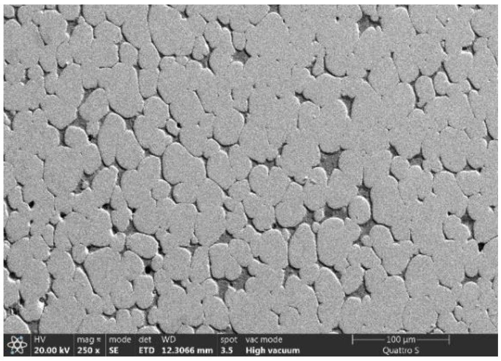

Figure 3. SEM image of the longitudinal sample 93W, 250x

In the samples presented in Figures 2 and 3, the average size of tungsten-based phase is approximately 30 µm and a certain slight deformation in the longitudinal direction can be noticed for the sample 91 W. Figures 2 and 3 show a difference in terms of the size and distribution of the mentioned phases, whereby alloy 91 W is characterized by more spherical phases tungsten based "light" phase (particles) surrounded with larger amount of continuous binder ductile "dark" phase. The matrix – "dark" phase indicates lower strength properties of and therefore this phase has lower resistance to plastic deformation and its shape is deformed significantly compared to the "light" phase.

As can be seen from Figures 4 and 5, tungsten heavy alloys are composite materials which consisted of two different phases, which were investigated in more detail by individual regions with SEM analysis. These two phases differ notably in chemical composition as well as mechanical properties for both 91W and 93W tungsten alloys [6].

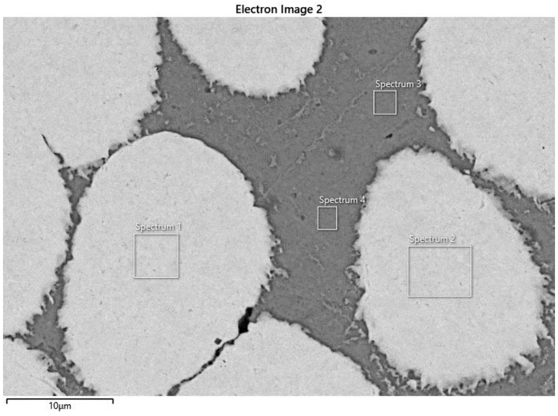

Figure 4. SEM image of the longitudinal sample 91W, 2500x

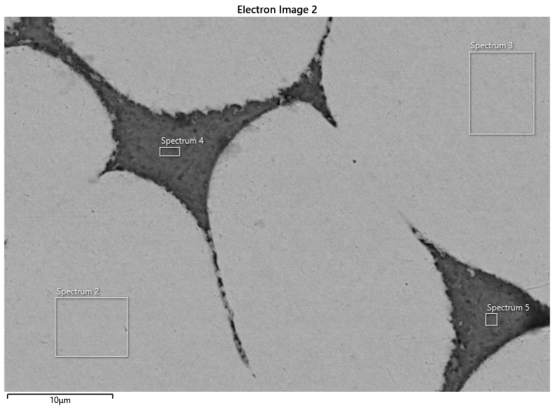

Figure 5. SEM image of the longitudinal sample 93W, 2500x

"Dark" phases are in fact a binder phase which consists of elements Fe, Ni, W and Co.

2.3. Results of SEM examination of tungsten alloy phases

2.3.1 SEM analyses of 91W tungsten alloy phases

Examination of the phases on the scanning electron microscope gives most data of the type of phases and their composition. SEM image for spectrum regions 1 and 2 of samples 91W (Figure 4) can be seen in Figure 6 and Figure 7 [7].

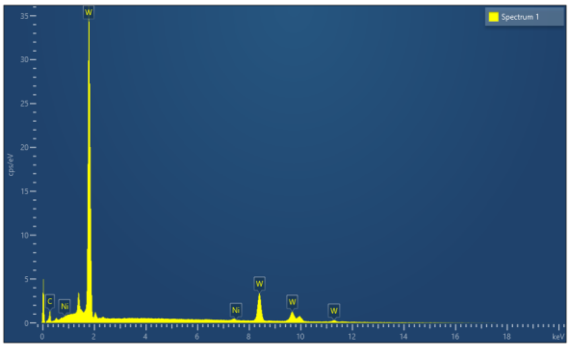

Figure 6. SEM analysis in region 1 of 91W (from Figure 4) [8]

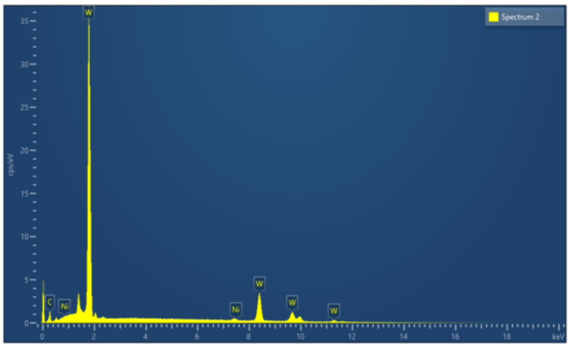

Figure 7. SEM analysis in region 2 of 91W (from Figure 4) [8]

SEM analysis of the 91W-6Ni-1.8Fe-1Co sample in area 3 and area 4 (from Figure 4) are presented in Figure 8 and Figure 9 [8].

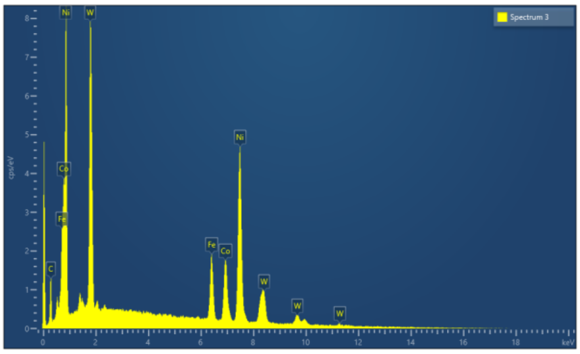

Figure 8. SEM analysis in region 3 of 91W (from Figure 4, [8]

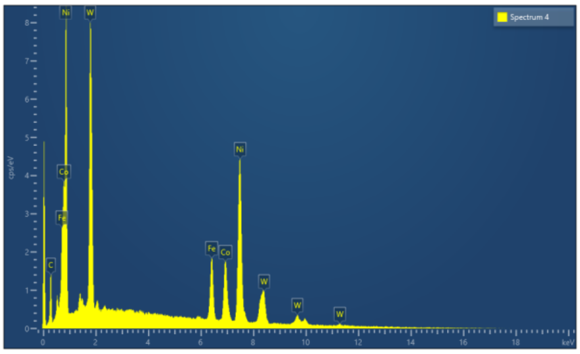

Figure 9. SEM analysis 2 in region 4 of 91W (from Figure 4) [8]

In this material, different distributions between phase and matrix were registered, with regard to the elements Fe, Co, Ni and W. The results of spectral analysis on SEM images of 91W (91W-6Ni-1.8Fe-1Co) samples from the region 1-4 from (Figure 4) is shown in the Table 2. Table 2 presents the contents of W, Ni, Co and Fe on the sample of materials for the spectral regions marked with 1, 2, 3 and 4 from Figure 4.

Table 2. W, Ni, Co and Fe contents for spectrum regions 1, 2, 3 and 4 from Figure 4, [8]

Spectrum Label	Spectrum 1	Spectrum 2	Spectrum 3	Spectrum 4
Fe,%			10.51	10.73
Co,%			13.47	13.90
Ni,%	0.17	0.90	44.29	43.73
W,%	99.83	99.10	31.74	31.65

From Table 2 can be seen the differences in the distribution of elements in tungsten particles ("light") phase and binder matrix ("dark") phase. Thus, in the "light" phase 1 in the regions 1 and 2 the tungsten dominated by with over 99%, while in binder ("dark") phase 2 the share of tungsten is less than one third. Also in the tungsten phase is the proportion of Ni in the traces from 0,17% to 0,90%, while Ni, Co and Fe are present in the binder phase.

2.3.2 SEM analyses of 93W tungsten alloy phases

Examination of the phases on the scanning electron microscope gives most data on the type of phases and their composition. SEM image for spectrum regions 2 and 3 of samples 93W-5Ni-1.6Fe-0.3Co (Figure 5) can be seen in Figure 10 and Figure 11, [6].

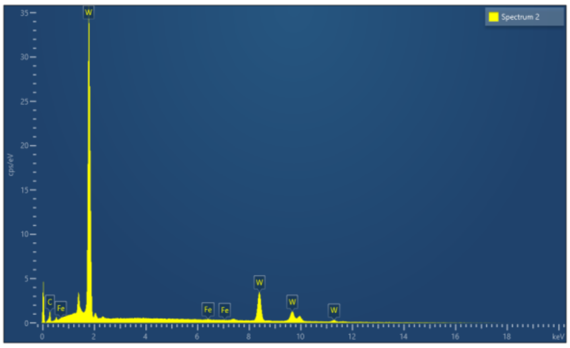

Figure 10. SEM analysis in region 2 of 93W (from Figure 5)

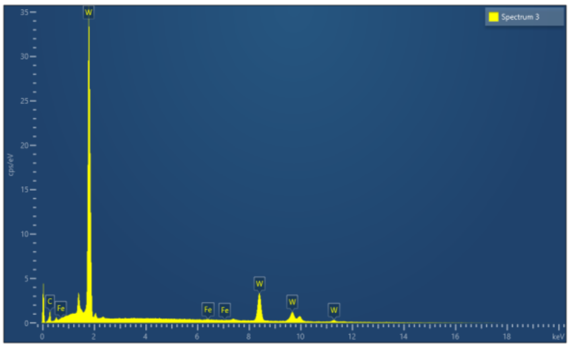

Figure 11. SEM analysis in region 3 of 93W (from Figure 5)

SEM analysis of the 93Wsample in area 4 and area 5 (from Figure 5) are presented in Figure 12 and Figure 13.

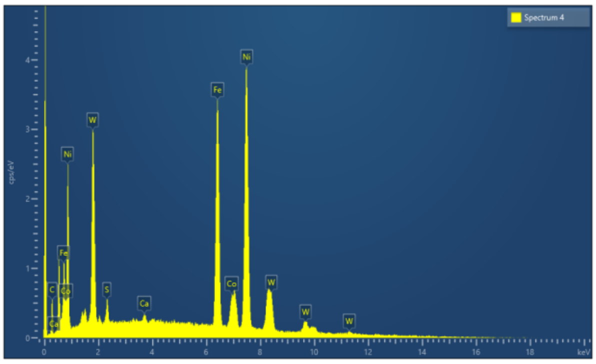

Figure 12. SEM analysis in region 4 of 93 W (from Figure 5)

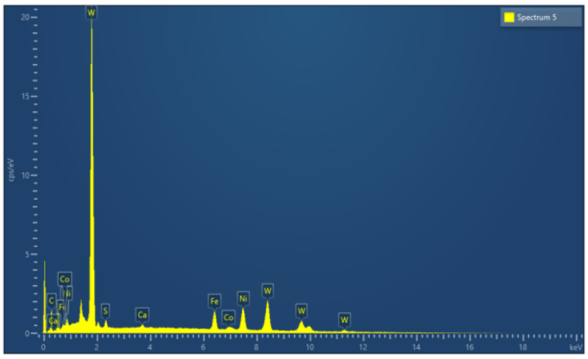

Figure 13. SEM analysis in region 5 of 93W (from Figure 5)

Table 3 presents the contents of W, Ni, Co and Fe on the sample of materials for the spectral regions marked with 2, 3, 4 and 5 from Figure 5 [6].

Table 3. W, Ni, Co and Fe contents for spectrum regions 2, 3, 4 and 5 from Figure 5 [6]

Spectrum Label	Spectrum 2	Spectrum 3	Spectrum 4	Spectrum 5
Fe,%	0.35	0.22	25.51	8.34
Co,%			3.69	1.49
Ni,%			46.05	13.82
W,%	99.65	99.78	23.48	74.63

From Table 3 can be seen the differences in the distribution of elements in tungsten phase 1 and binder phase 2. In phase 1 in the regions 2 and 3 the tungsten dominated by with over 99%.

2.4 Mechanical properties of tungsten alloys

A higher level of mechanical properties of the sample materials 91W-6Ni-1,8Fe-1Co could be achieved only by using powders of smaller granulation or correcting the chemical composition (for example replacing Fe with Co), otherwise by reducing the cross section with cold plastic deformation.
The results of mechanical properties such as tensile strength, hardness, and elongation of the 91W and 93W samples are presented in Table 4 [6].

Table 4. Mechanical properties of the 91W and 93W samples

Type of tungsten alloys	Mechanical properties		
	Tensile strength, MPa	Elongation, %	Hardness, HRC
91W	1485	10	48-50
93W	900	18	37-40

The results of mechanical tests of tensile strength and hardness confirm that they are in accordance with the prescribed standard for machined this type of tungsten alloy. Mechanical properties can also be somewhat adjusted by the chemical composition, primarily by the Ni/Co ratio (ratio 2-9), so alloy 91W, which has a Ni/Co ratio within the given limits, shows significantly better mechanical properties.

4. Conclusions

- The results of mechanical and microstructural research on the example of a characteristic heavy tungsten alloy with a defined Ni/Co ratio, so that alloy 91W, which has Ni/Co within the specified limits, shows significantly better mechanical properties than alloy 93W, which does not.
- Tungsten heavy alloys are tungsten composites with two-phase microstructure consisting of spherical tungsten-based phase and a binder - matrix which is a nickel solution with the addition of iron, cobalt or copper.
- It was presented with SEM analysis the distribution of the W, Ni, Co and Fe elements in tungsten phase and binder phase, which can influence on mechanical properties of tungsten alloys.

Declaration of competing interests

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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