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EFFECT OF ALLOY COMPOSITION ON THE MECHANICAL PROPERTIES AND FRACTURE BEHAVIOR OF TUNGSTEN HEAVY ALLOYS

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ABSTRACT

The objective of this experimental study is to investigate the effect of the alloy composition on the mechanical properties and the fracture behavior of the liquid phase sintered tungsten heavy alloys. Tungsten alloy with three different compositions 93%W-4.9%Ni-2.1%Fe, 91%W-6%Ni-3%Co and 90.5%W-5.6%Ni-2.4%Fe-1.5%Co were prepared and used in this investigation.

Elemental powders were mixed using planetary mixer for 5 hours to ensure suitable homogeneity. Uni-axial compaction pressure of 200 MPa was applied to obtain standard tensile and impact specimens. Vacuum liquid phase sintering was carried out under different temperatures from 1470°C up to 1530°C for 90 minutes.

The effect of changing the alloy composition particularly, the binder constituents was characterized in terms of density, hardness, impact resistance and tensile properties for samples in the as sintered state. Fracture behavior of the used tensile fracture specimens having different compositions was studied, and the relation between the obtained fracture modes and tensile properties of these alloys was indicated.

The obtained results indicated that hardness increases with increasing the cobalt content, Moreover, the tensile strength increases, in a first stage, by adding cobalt up to 1.5wt.%, due to the strengthening effect of cobalt. Further increase in cobalt content decreases strength. On the contrary, the ductility and impact resistance showed a continuous decrease with increasing the cobalt content. The results, also, clearly showed that the addition of cobalt to tungsten heavy alloy has a great beneficial hardening effect. On the other hand, it causes embrittlement due to the formation of brittle intermetallic compounds, particularly, with tungsten at the tungsten-matrix interface leading to degradation of alloy properties, which makes the dissolution of these intermetallics by a post sintering heat treatment of great importance.

It was also shown that the strength of the matrix or the bonding strength of the interface (between tungsten particles and matrix) was the controlling criterion of the

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nature of final fracture. Poorer matrix strength or interfacial strength was found to initiate the fracture by separation of tungsten particles either by matrix failure or by interface failure. On the other hand, tensile fracture takes place predominantly by cleavage fracture of tungsten particles, if both the matrix and interface are stronger than the tungsten particles. The tensile fracture surfaces clearly indicated that failure in case of W-Ni-Fe based heavy alloys was due to matrix or interface failure. Whereas, W-Ni-Fe-Co heavy alloys were failed predominantly by cleavage fracture of tungsten particles. While, in case of W-Ni-Co based heavy alloys, the dominant fracture mode was intergranular tungsten separation. This fracture behaviour was in good correlation with the obtained mechanical properties, and indicates that the cobalt content in the binder plays a key role in dictating the failure behaviour.

Keywords

Tungsten heavy alloy, Alloy composition, Matrix constituents, Cobalt content.

INTRODUCTION

Tungsten Heavy Alloys (WHAs) are two phase metal matrix composites that typically contain 90 to 98wt% W, in combination with some mix of nickel, iron, copper, and/or cobalt. Some alloying elements are added as Mo, Ta, Re and Cr, ... etc for improving the alloy properties. The principal phase, being hard, is the pure tungsten, in association with a ductile binder phase containing the transition metals plus some dissolved tungsten.

As a consequence, WHAs derives their fundamental properties from those of the principal tungsten phase, which provides both the high density and the high elastic stiffness. Nickel, iron, cobalt and copper serve as a binder matrix, which holds the brittle tungsten grains together and makes tungsten alloys ductile and easy to machine. Which gives sintered WHAs a unique combination of properties. One of the strategic applications for these alloys is in ordnance, such as kinetic-energy (KE) penetrators and counter-balance weights in gyroscope [1].

The choice of composition is driven by several considerations. The primary factor is the density required by the given application. Further considerations include corrosion resistance, magnetic character, mechanical properties. This alloy composition determines the post sintering heat treatment options [2].

The first tungsten alloy developed was a W-Ni-Cu alloy [3]. Alloys of this ternary system are still occasionally used today, primarily for applications in which ferromagnetic character must be minimized or electrical properties must be enhanced. W-Ni-Cu alloys otherwise offer inferior corrosion resistance and lower mechanical properties than the present industry standard W-Ni-Fe alloys.

The majority of current uses for WHAs are best satisfied with the W-Ni-Fe system. Nickel-iron is the most popular binder additive, and it was found that a ratio of 7Ni:3Fe or 8Ni:2Fe (by weight)[4] is the most adequate for optimum mechanical properties. It is also known that the composition ratio of alloying additions to tungsten must be kept within a range that avoids formation of intermetallic compounds which

causes embrittlement in the alloy. For example, in the commercially important tungsten-nickel-iron alloy system the nickel to iron ratio is generally held within the range of about 1:1 to 4:1. Outside this range, brittle intermetallic phases form in the binder phase which rapidly degrade the properties[3,5,6,7].

The propensity of the iron and nickel alloys to form an intermetallic phase with tungsten is well known. At low nickel to iron ratios the excess iron forms a series of intermetallic phases, Fe_7W_6 known as (μ) phase which is stable below a temperature of about 1637°C, down to a temperature of about 1190°C, and may be retained at room temperature, in addition to Fe_2W known as (λ) phase and FeW known as (δ) phase which may persist to room temperature [8].

Above the ratio of about 4:1 nickel to iron, excess nickel forms a series of Ni/W intermetallics, including NiW_2 , NiW and Ni_4W which are stable below about 1000°C down to room temperature [8].

The addition of cobalt to a W-Ni-Fe alloy is a common approach for enhancement of both strength and ductility. The presence of cobalt within the alloy provides, from one hand, solid-solution strengthening of the binder, leading to increasing the strength and hardness of the matrix and, from the other hand, improves wettability of liquid matrix for tungsten grains, thus enhancing tungsten-matrix interfacial strength. Cobalt additions of 5 to 47.5% of the nominal binder weight fraction are most common [3].

Furthermore, W-Ni-Co system with nickel-to-cobalt ratios ranging from 9 to 2[3] could be used for extremely demanding applications, where higher mechanical properties are required. Due to the presence of cobalt and during cooling down from the sintering temperature, tungsten with cobalt form a series of intermetallic compounds (Co_3W , Co_7W_6) [8]. These compounds have deep harmful influence, from one hand, on the mechanical properties of the matrix phase particularly its ductility, and from the other hand on the interfacial strength between the matrix phase and the hard tungsten particles.

The increasing amount of these different intermetallic compounds formed between the matrix ingredients and the tungsten particles deteriorate the mechanical properties and limit the applications of these alloys. That is why it is not recommended to use these alloys in the as sintered state particularly when cobalt is added to the alloy composition [3,9], and it is ultimately necessary to apply particular heat treatments in order to minimize the presence of such compounds. The recommended heat treatment consists of dissolution of the formed intermetallics by heating the alloy to the appropriate temperature (most of these intermetallics are not stable at temperatures above 1000°C) followed by water quenching, to suppress their formation during cooling [3,10].

In this research work, the effect of cobalt additions on the mechanical and metallurgical properties of this family of tungsten heavy alloys is investigated to reveal the effect of the addition of this important alloying element either as a replacement of the whole content of iron or as an additional alloying element to the matrix conjointly present with nickel and iron. It is essential that the cobalt be at least about 5% to 47.5% and, preferably, about 12% to 35% by weight of the binder phase

of the alloy in order to obtain the improved properties [3]. The concentration ranges for the alloying elements in the binder phase are recommended to be about 30-90% nickel, 5-65% iron and 5-47.5% cobalt with the amount of cobalt being at least equal to or less than the nickel content of the binder phase [3].

EXPERIMENTAL PROCEDURE

Characteristics of Used Powders

The main constituents of the adopted tungsten heavy metal alloy are commercial pure tungsten, nickel, cobalt and iron powders. The different powders were chemically analyzed by X-ray fluorescence (XRF) technique to determine their composition and purity. The obtained chemical compositions are illustrated in Table (1).

Table (1). Chemical composition of the used powders (in wt.%).

Composition Powders	W%	Ni%	Fe%	Si%	Al%	Mg%	Ca%	Ga%	P%	S%	Na%	F%
Tungsten powder	99.825	--	--	--	--	--	0.036	0.021	0.062	0.056	--	--
Nickel powder	--	99.496	0.132	0.204	0.115	0.046	--	--	0.003	0.003	--	--
Iron powder	--	--	99.396	0.335	0.172	0.062	0.02	--	0.01	0.005	--	--
Cobalt powder	--	--	--	0.06	0.02	0.02	--	--	--	--	0.01	1.14

The apparent densities of these powders were measured by Hall flowmeter, and the tap densities were determined after standard tapping. The results of both densities were compared with the values of the theoretical densities as shown in Table (2).

Table (2). Theoretical, apparent and tap densities of the used powders

Powders	Tungsten powder	Nickel powder	Iron powder	Cobalt powder
Measured density				
Theoretical density, g/cc	19.3	8.9	7.9	8.8
Apparent density, g/cc	3.6	0.93	1.4	1.3
Tap density, g/cc	6.75	1.65	2.63	2.4

The morphology and the particle size of the used powders were revealed by SEM as shown in Fig.1(a-d). Tungsten powder appeared to have polygonal shape, nickel powder is of spongy shape, cobalt powder has flake shape, while the iron powder shows nearly spherical shape. It can be noted that Tungsten, Nickel, Cobalt and Iron powders have an average particle size of about 1-2 μm , 1-3 μm , 1-3 μm and 3-5 μm , respectively.

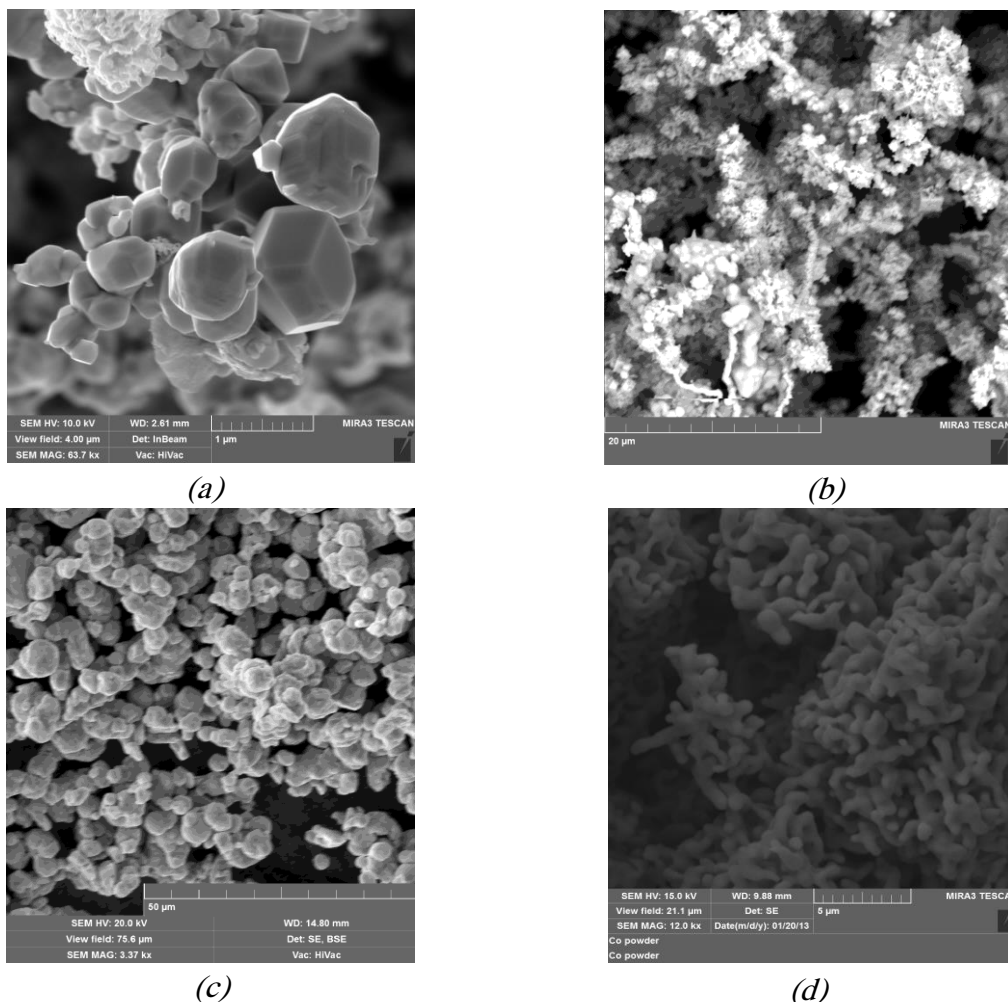


Fig. (1). SEM images of as received (a) tungsten, (b) nickel, (c) iron and (d) cobalt powders.

Preparation of Sintered Specimens

In this study, Three different compositions were prepared as follows: The first alloy is the conventional adopted alloy, having the composition 93%W-4.9%Ni-2.1% Fe. The second alloy has the composition 91%W-6%Ni-3%Co, where, the iron is substituted completely with cobalt, which represents about 33% of the amount of the binder. The third alloy has the composition 90.5%W-5.6%Ni-2.4% Fe-1.5%Co, where the cobalt represents about 15% of the amount of binder, while, the nickel to iron (Ni:Fe) ratio being maintained at 7:3. The W-Ni-Co and the W-Ni-Fe-Co alloys are compared to the conventional W-Ni-Fe alloys, in a first stage, in the as-sintered condition.

All compositions of powders were homogeneously blended, shaped into standard tensile and impact test specimens and subjected to an uni-axial compaction pressure of 200MPa. All the compacted samples were also sintered in a vacuum atmosphere. Sintering temperature was varied from 1470°C up to 1530°C for a period of 90 minutes in accordance with the sintering cycle applied in [11].

Characterization of Samples

The samples with different compositions were tested in the as-sintered condition in an identical procedure explained in [11], and the following properties were determined.

RESULTS AND DISCUSSION

Mechanical Properties

The results of the measured hardness on the different alloy compositions indicated that hardness increases with increasing the cobalt content, and attain maximum values for all sintering temperatures when cobalt completely substitutes iron in the constitution of the binder. Moreover, it can clearly be noted that hardness values decreases generally with the sintering temperature for all compositions. Furthermore, the percentage decrease in hardness, when the sintering temperature is increased from 1470°C to 1530°C, is sensibly lower when cobalt completely replaces iron in the matrix as shown in Fig.(2). The decrease in hardness with sintering temperature can be attributed, as mentioned before, to the normal grain growth and the increased matrix volume fraction due to dissolution of smaller tungsten grains. The increase in the hardness with the cobalt addition is directly explained by the solid-solution strengthening of the binder by the solubility of cobalt. Furthermore, cobalt has deep effect on hindering the diffusion of tungsten atoms [12],and consequently the processes of grain growth, which explains the slight decrease in hardness at elevated sintering temperatures with increasing cobalt content.

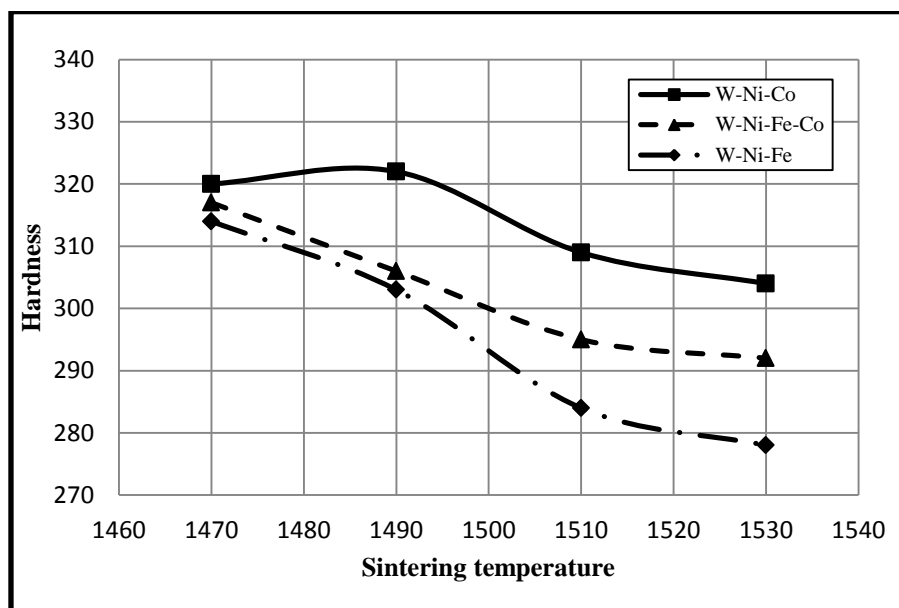


Fig. (2). Hardness variations versus sintering temperature for tungsten heavy alloys having different chemical compositions compacted at 200 MPa and sintered for 90 minutes.

To confirm and evaluate the effectiveness of solid solution strengthening by the cobalt addition to this family of alloys, micro-hardness values were measured in the matrix (binder) of the three alloys in different locations sintered at 1510°C for 90 minutes. The results of these measurements are illustrated in Fig.(3). It is clearly evident that the addition of cobalt substantially hardens the matrix, relative to iron. Maximum hardening effect is obtained when cobalt completely substitutes iron in the binder composition.

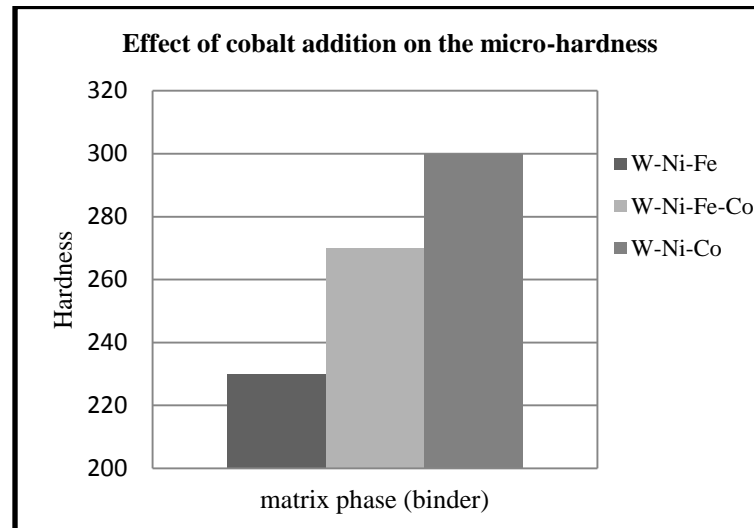


Fig. (3). Effect of cobalt addition on the micro-hardness of the matrix phase of three different alloy compositions sintered at 1510°C for 90 minutes.

The ultimate tensile strength and ductility, for the various tungsten heavy alloys, after compaction under pressure 200 MPa, and sintered at different temperatures namely 1470°C, 1490°C, 1510°C and 1530°C for 90 min. are shown in Figs.(4) and (5).

It can be noted that, the tensile strength generally decreases with the sintering temperature as it was explained before and attributed to grain growth. Moreover, the tensile strength increases, in a first stage, by adding cobalt, due to the strengthening effect of cobalt. Further increase in cobalt content decreases noticeably this strength due to the increased embrittlement caused by the formation of intermetallic phases.

This proves that tensile strength as a mechanical property reflecting the load carrying capacity of the alloy phase constitution is more sensitive to the presence of brittle phases in the structure relative to the hardness reflecting only the surface characteristics.

This also, clearly indicates that the addition of cobalt must be taken with very great care, to make use of its beneficial hardening effect, and to avoid its embrittlement effect resulting from its strong affinity to form brittle intermetallic compounds, particularly, with tungsten. That is why the dissolution of these intermetallics by a post sintering heat treatment became of vital importance to obtain the utmost benefit from the addition of this element.

The ductility, on the other hand was found to increase with the sintering temperature up to a maximum value at 1510°C due to the increased matrix volume fraction, and then decreases for higher sintering temperatures by the occurrence of excessive

grain growth. Also, the ductility showed a continuous decrease with increasing the cobalt content, indicating that this property is more deeply sensitive to the presence of cobalt even than tensile strength.

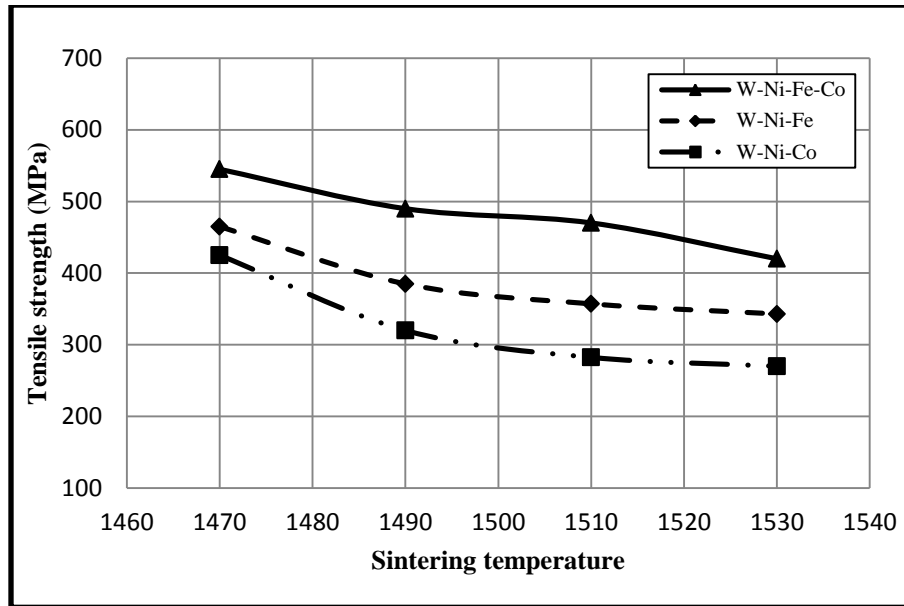


Fig. (4). Tensile strength variations with sintering temperature for tungsten heavy alloys with different chemical compositions compacted at 200 MPa and sintered for 90 minutes.

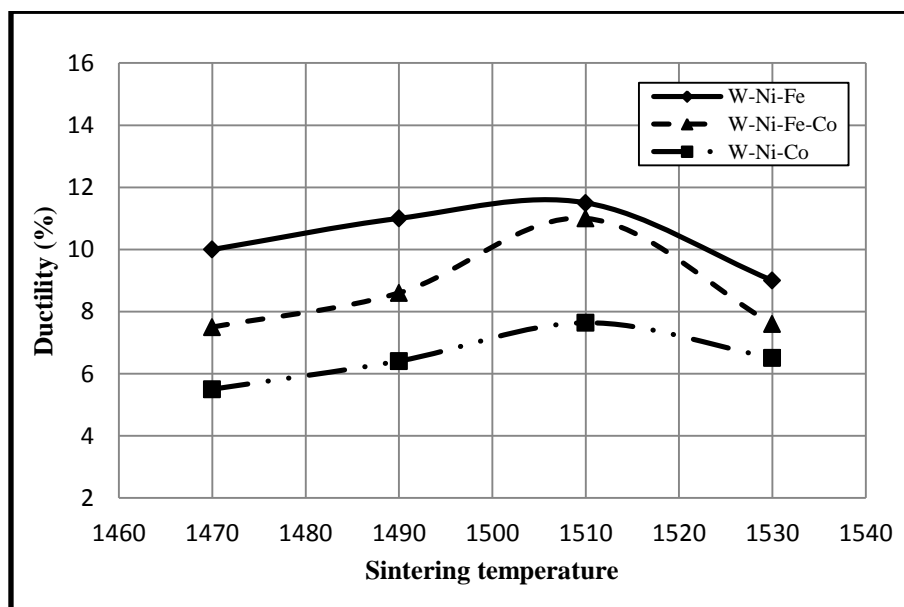


Fig. (5). Ductility variations with sintering temperature for tungsten heavy alloys with different chemical compositions compacted at 200 MPa and sintered for 90 minutes.

Fig.(6) illustrates the influence of alloy composition and sintering temperature on the impact resistance of three different alloys. It can be noted that, the impact resistance decreases, continuously, by increasing the cobalt content in a similar behaviour measured for ductility of these alloys.

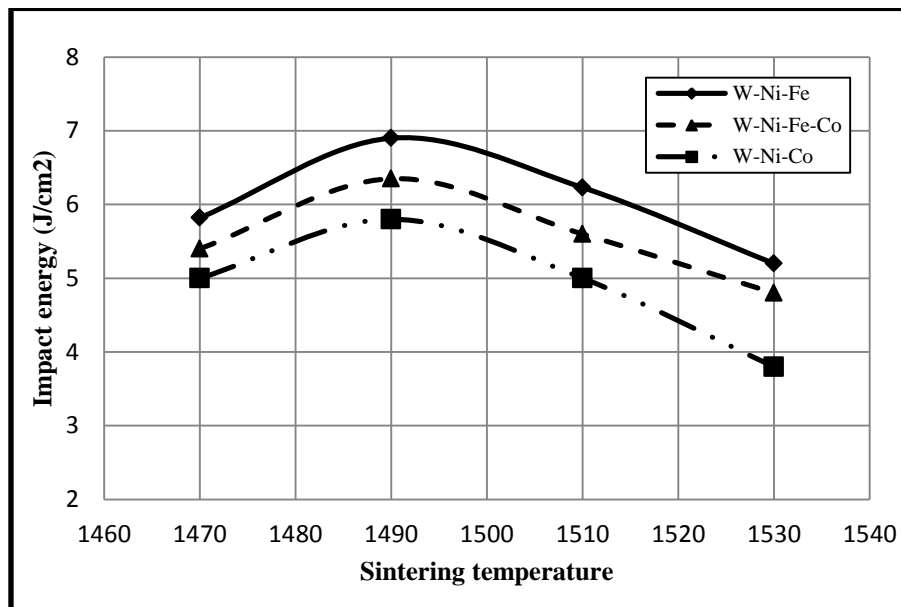


Fig.(6). Impact energy variations with sintering temperature for tungsten heavy alloys with different chemical compositions compacted at 200 MPa and sintered for 90 minutes.

Results showed that hardness is more seriously affected by the variation of binder composition and that toughness, strength and hardness of the alloy are not affected in entirely the same way. The results disclose that a small cobalt addition to tungsten heavy metal alloys containing nickel and iron has a positive effect on the strength, in a first stage, and on the hardness as a surface property. Then, with increasing cobalt, a sensible deterioration of strength and toughness occurs.

It was reported that the addition of cobalt to W-Ni-Fe alloys leads to increase in strength and hardness, but also results in embrittlement of alloys due to formation of intermetallics [9]. Pierce et al. [9,13] reported an approach to solve the problem of embrittlement in W-Ni-Fe-Co alloys. In this approach, the sintered specimens are heated to 1200°C to 1400°C in a flowing argon gas for 1 to 3 hours and is then rapidly quenched. This process removes any residual hydrogen present and dissolves any intermetallics formed during liquid phase sintering.

Dowding et al. [9] stated that a post sintering heat treatment is often performed in an effort to prevent the formation of intermetallic phases at the interfaces of W-Ni-Fe alloys.

Sintered Density

The effect of alloy composition and sintering temperature on the sintered density of the tungsten heavy alloy specimens, is illustrated in Fig.(7). We can note that, the sintered density of the adopted alloy 93%W-4.9%Ni-2.1%Fe is superior, compared with the other two alloys where cobalt was introduced, either in combination with nickel and iron, or completely replaces iron in the constitution of the matrix (binder). Although, cobalt has higher density than iron (8.8 gm/cm³) its addition in the alloy composition used by the NATO, where tungsten content is reduced from 93% to 91% results in decreasing the values of the sintered densities. A drop of the sintered density, in the order of 5%, was recorded when the iron in the adopted 93%W-4.9%Ni-2.1%Fe alloy was completely replaced by cobalt in the 91%W-6%Ni-3%Co alloy. This indicates that the values of the alloy density is ultimately controlled by the content of tungsten rather than the content of the other minor ingredients. In spite of the fact that the alloy composition 91%W-6%Ni-3%Co has a relatively lower density, the presence of cobalt in this alloy provides a noticeable hardening effect.

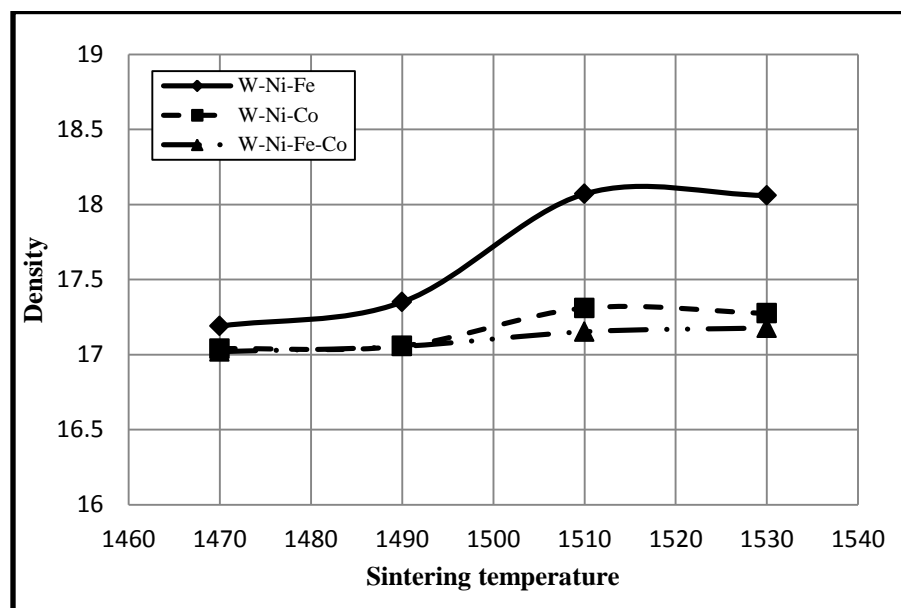


Fig. (7). The measured values of sintered density of tungsten heavy alloys with different chemical compositions compacted at 200 MPa and sintered for 90 minutes as a function sintering temperature.

Fracture Behavior

Scanning electron micrographs of the fracture surfaces of the tungsten heavy alloys, having different chemical compositions, in the as sintered state, are shown in Figs.(8), (9) and (10).

By investigating these fracture surfaces, differences in the mechanisms and modes of fracture in the adopted alloys are readily observable. These indicate that the fracture behavior and tensile properties of the tungsten heavy alloys are strongly

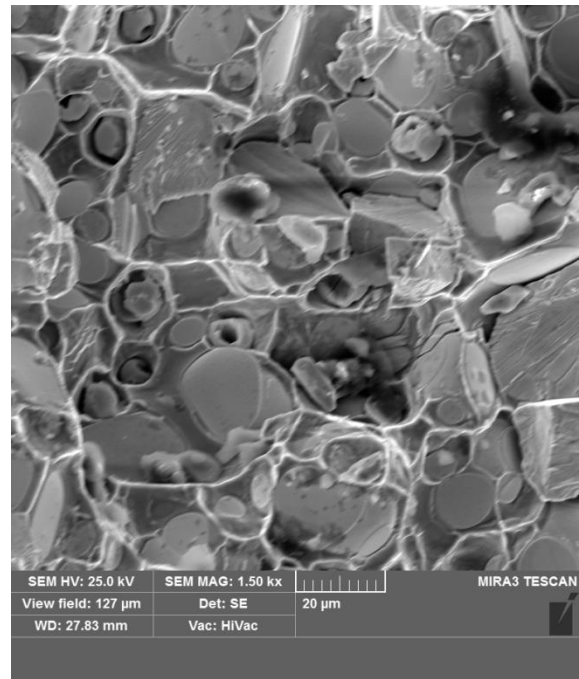
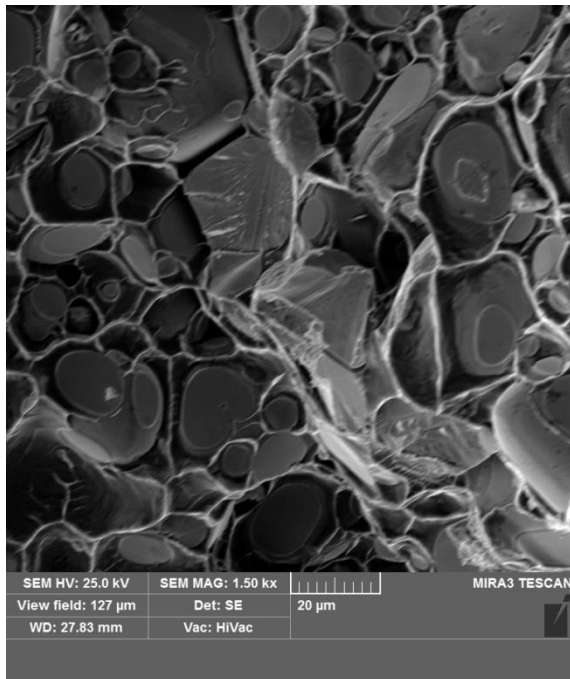


Fig. (8). Tensile fracture surfaces taken at two different locations of 93%W-4.9%Ni-2.1%Fe heavy alloy, uni-axially compacted under 200 MPa and sintered at 1510°C for 90 minutes.

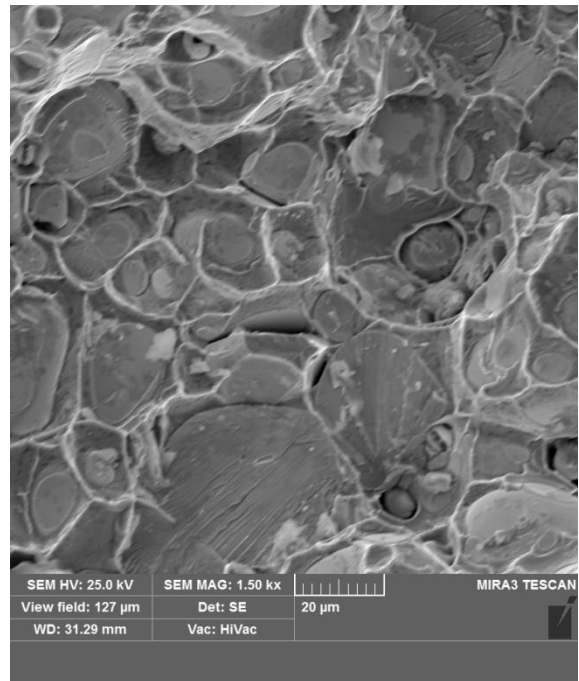
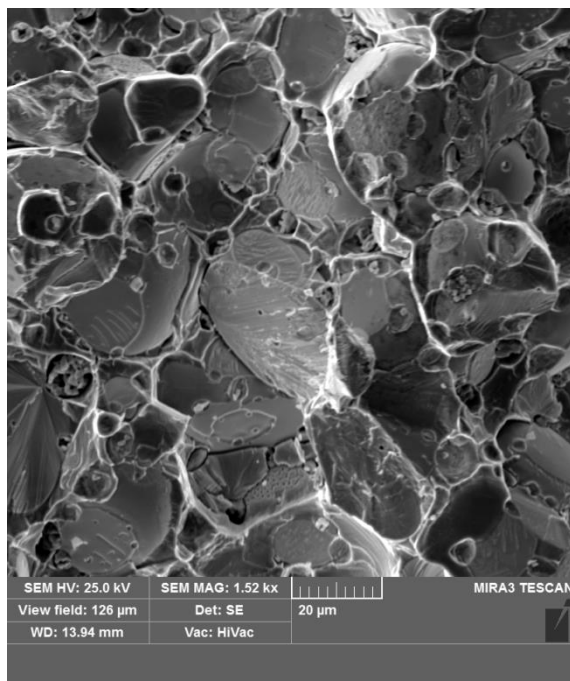


Fig. (9). Tensile fracture surfaces taken at two different locations of 90.5%W-5.6%Ni-2.4%Fe-1.5%Co heavy alloy, uni-axially compacted under 200 MPa and sintered at 1510°C for 90 minutes.

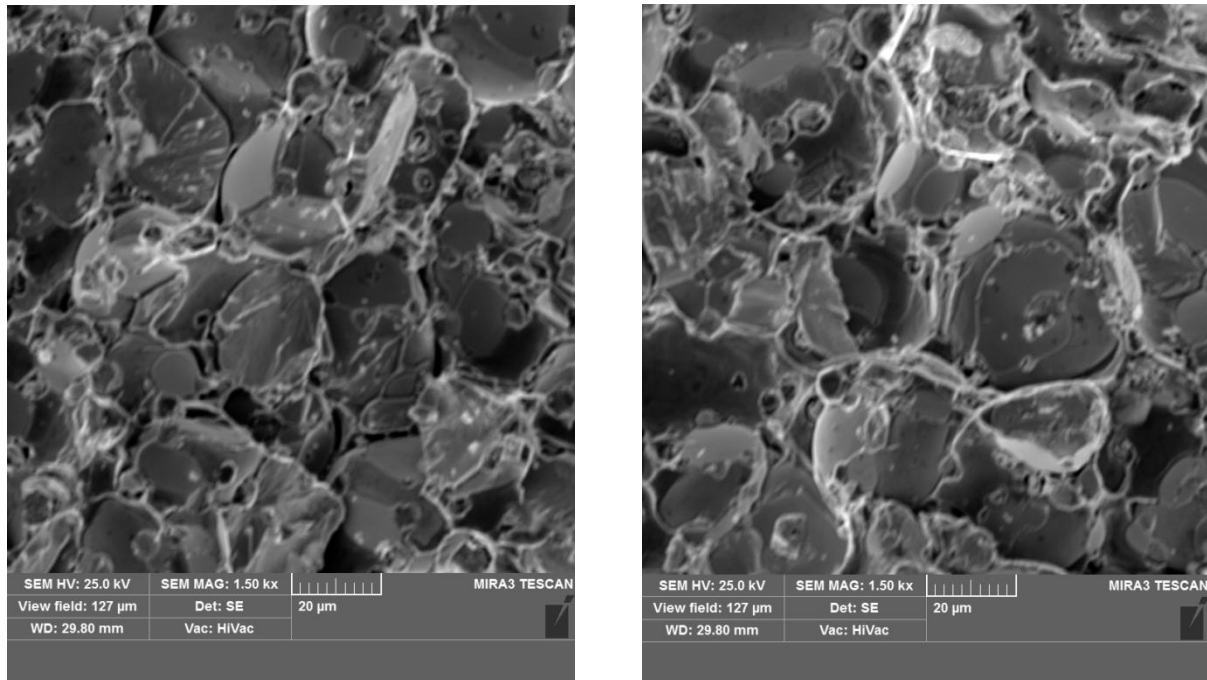


Fig.(10). Tensile fracture surfaces taken at two different locations of 91%W-6%Ni-3%Co heavy alloy, uni-axially compacted under 200 MPa and sintered at 1510°C for 90 minutes.

influenced by the variation in the alloy composition, particularly, the type and percentage of the different ingredients of the binder phase.

The fracture surfaces of the as sintered specimens of the W-Ni-Fe based heavy alloys, shown in Fig.(8), were characterized by the presence of a pronounced brittle intergranular separation either between W-W particles or W-matrix phase, together with a limited appearance of ductile matrix failure and brittle tungsten cleavage.

The addition of 1.5% wt. Co to the matrix composition, improved the tensile strength of the alloy by strengthening the matrix composition. This was directly reflected on the nature of the fracture modes that appeared on the examined fracture surface, as shown in Fig.(9). A dominant tungsten cleavage fracture can be clearly observed, all over the fracture surface, with limited existence of regions failed either by ductile dimple matrix failure or brittle intergranular separation. sintered specimens of W-Ni-Fe-Co based heavy alloys showed that occurred more frequently.

Moreover, the fracture surfaces of the W-Ni-Co based heavy alloys where cobalt completely replaces iron in the matrix composition, are shown in Fig.(10). The increased amount of cobalt in the matrix composition allowed the formation of considerable amount of brittle intermetallic phases between cobalt and tungsten which are localized on the surface of the tungsten particles at the interface between these particles and the matrix phase. This behavior has, from one hand, a devastating effect on the mechanical properties as previously shown, and on the other hand a considerable visible effect on the nature of the brittle fracture mechanisms during failure. This can clearly explain the dominant tungsten matrix

intergranular separation observed on the examined fracture surface of this category of alloys.

These results further confirm that W-W interface is the weakest interface and is related to lower tensile properties. The greater the proportion of tungsten cleavage and matrix phase failure, the higher the tensile properties. Also, W-matrix separation is evident with low tensile properties.

The effect of a post sintering heat treatment on the mechanical properties of tungsten heavy alloys is not established in this study. Further studies are in progress in order to determine the effect of heat treatment on the mechanical properties and fracture behavior of tungsten heavy alloy with different chemical compositions.

PHASES IDENTIFICATION BY X-RAY ANALYSIS

X-ray diffraction was used to determine and analyze the phases present in tungsten heavy alloy specimens of different chemical compositions and to follow up the evolution of these phases during sintering. On the other hand, X-ray diffraction graphs was used to reveal the effect of alloy composition on the nature of the diffusion processes that take place among the different constituents present in the alloy.

Figure (11) demonstrates the X-ray diffraction pattern obtained using tungsten heavy alloy having the composition 93%W- 4.9%Ni -2.1%Fe uni-axially compacted under 200 MPa and sintered for 90 minutes at 1510°C. XRD examination clarifies only two phases in the alloy, BCC structured W-rich phase and FCC structured Ni-Fe rich phase (solid solution) as shown in Fig.(11).

The diffraction peaks and their corresponding position 2θ for the previous pattern obtained for W-Ni-Fe based heavy alloy together with their relative intensities are shown in Table (3).

Figure (12) demonstrates the X-ray diffraction pattern obtained using tungsten heavy alloy having the composition 91%W- 6%Ni -3%Co uni-axially compacted at 200 MPa and sintered for 90 minutes at 1510°C. This pattern reveal the co-existence of three series of peaks corresponding to three different phases, the first series of peaks correspond to the W-BCC structure, and the second series correspond to the FCC structure of the binder phase. This binder phase is a solid solution with nickel as a host lattice and both cobalt and tungsten as guest atoms, while the third series refers to the formation of an intermetallic compound between tungsten and cobalt having the composition (Co_3W).

The obtained diffraction peaks and their corresponding position 2θ obtained for W-Ni-Co based heavy alloy together with their relative intensities are shown in Table (4).

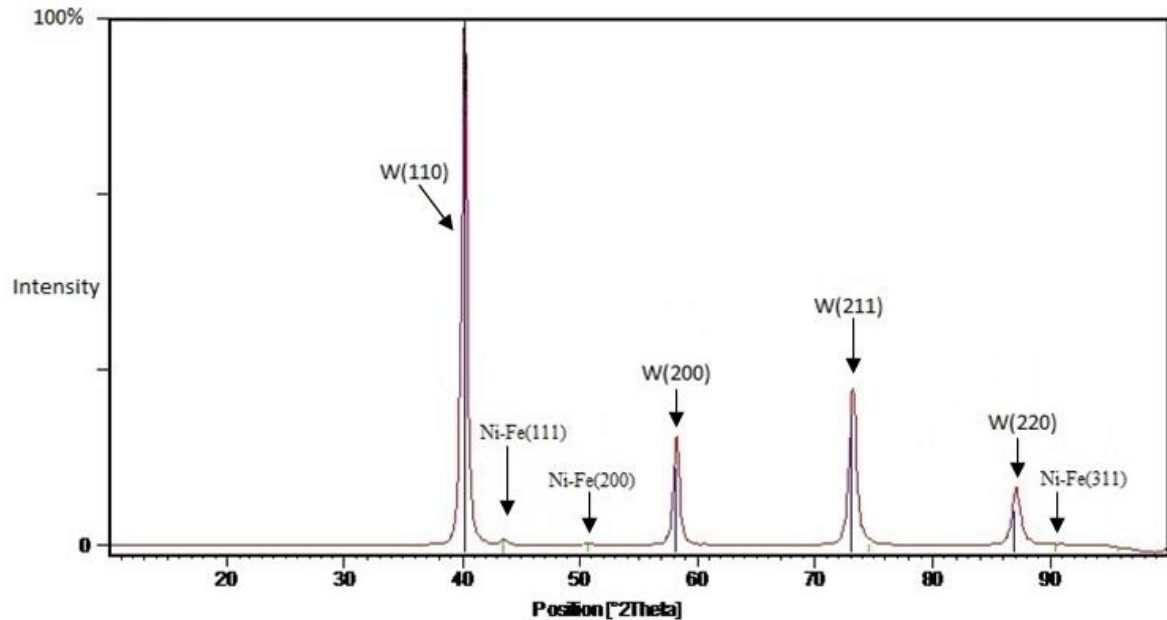


Fig.(11). X-ray diffraction pattern obtained using tungsten heavy alloy having the composition 93%W- 4.9%Ni -2.1%Fe uni-axially compacted under 200 MPa and sintered for 90 minutes at 1510°C.

Table (3). Diffraction results obtained from W-Ni-Fe sintered at 1510°C

No.	Phase	Diffraction plane	Position 2 θ	Relative intensity %
1	W	1 1 0	40.2534	100
2	Ni-Fe	1 1 1	43.509	1.09
3	Ni-Fe	2 0 0	50.576	0.24
4	W	2 0 0	58.2588	21.04
5	W	2 1 1	73.2051	30.28
6	W	2 2 0	87.0949	11.23
7	Ni-Fe	3 1 1	90.4778	0.04

The comparison of the absolute intensities of the tungsten diffraction peaks in the two alloys 93%W-4.9%Ni -2.1%Fe and 91%W-6%Ni-3%Co shown in Fig.(13), indicates that the absolute intensities of these peaks, in the case of the alloy with cobalt, is significantly higher than that in the case of the alloy with iron, although the tungsten content is lower in this alloy. This directly indicates that tungsten solubility in the Ni-Co matrix is lower than this solubility in the alloy having Ni-Fe matrix. Consequently, this result proves that the presence of cobalt in the solid solution of the matrix substantially suppresses the solubility of tungsten in this matrix. In fact, nickel and cobalt have higher mutual solubility than nickel and iron which influence further solubility of tungsten.

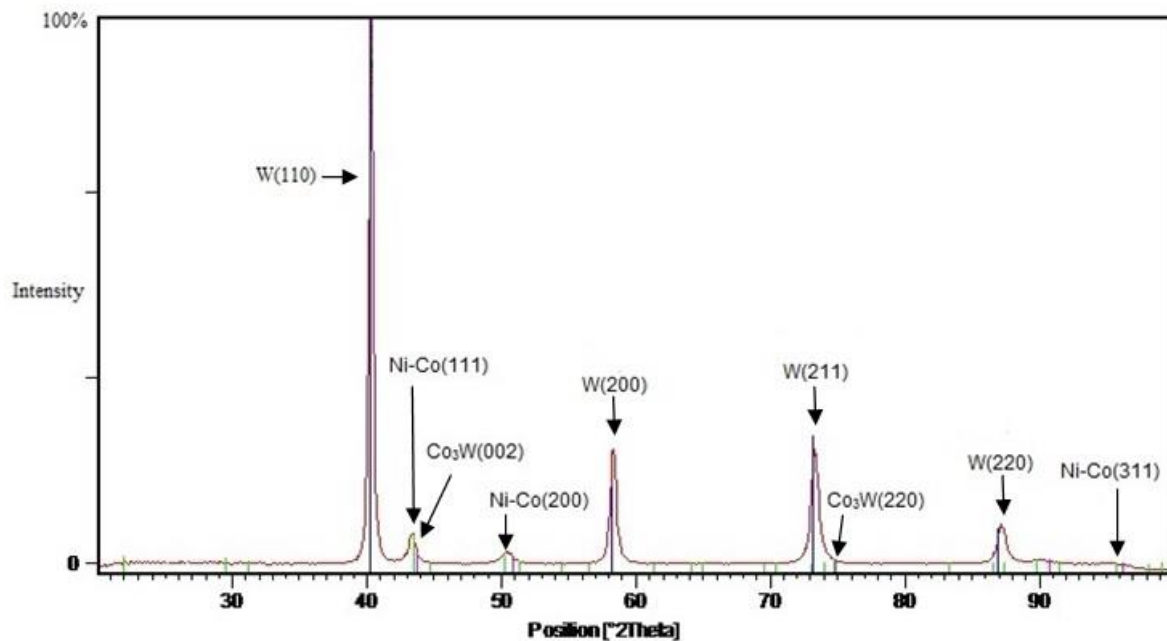


Fig.(12). X-ray diffraction pattern obtained using tungsten heavy alloy having the composition 91%W- 6%Ni -3%Co uni-axially compacted under 200 MPa and sintered for 90 minutes at 1510°C.

Table (4). Diffraction results obtained from W-Ni-Co sintered at 1510°C

No.	Phase	Diffraction plane	Position 2 θ	Relative intensity %
1	W	1 1 0	40.2821	100
2	Ni-Co	1 1 1	43.4348	5.28
3	Co ₃ W	0 0 2	43.91	12
4	Ni-Co	2 0 0	50.2843	2.08
5	W	2 0 0	58.2637	20.47
6	W	2 1 1	73.2306	20.72
7	Co ₃ W	2 2 0	74.99	5
8	W	2 2 0	87.1319	6.92
9	Ni-Co	3 1 1	95.2811	0.05

This result is in accordance with other researches [9] that refer to the effect of some alloying elements that have important solubility in the matrix thus reducing tungsten solubility. It was reported by Bose et al. [12] that cobalt has a sensible effect on reducing the solubility of tungsten in the matrix alloy and promotes the formation of tungsten intermetallic precipitate. On the other hand this reduced solubility of tungsten diminishes the re-precipitation process which consequently leads to hindering tungsten grain growth and, consequently improving micro-structural refinement of the alloy [12].

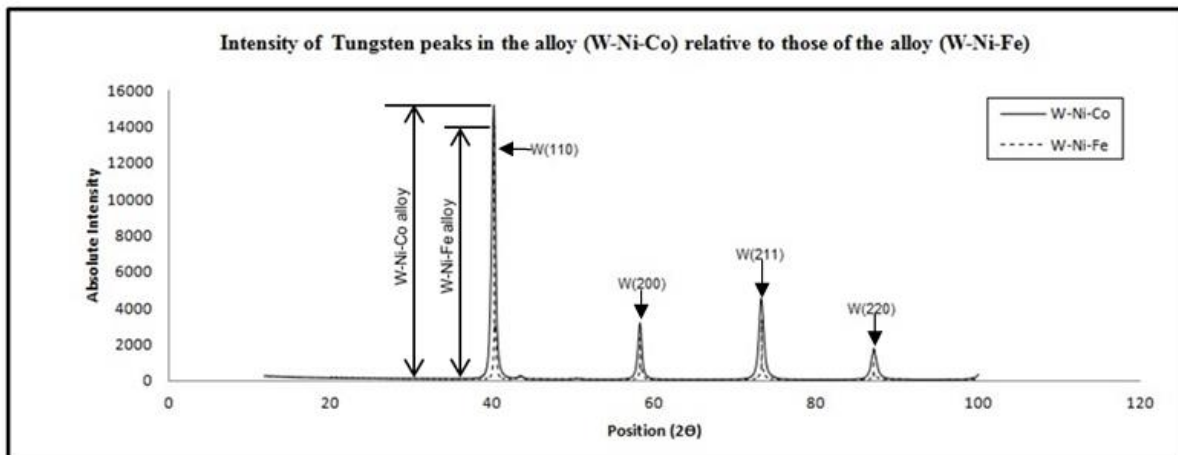


Fig. (13). Comparison between the absolute intensity of peaks of the tungsten phase in the tungsten heavy alloys 91%W- 6%Ni -3%Co and 93%W- 4.9%Ni -2.1%Fe uni-axially compacted under 200 MPa and sintered for 90 minutes at 1510°C.

We can conclude that cobalt addition to the matrix alloy has a very beneficial effect in strengthening the matrix of these alloys, by its high solubility in nickel, and also in refining the tungsten grains. On the other hand, cobalt has a strong affinity to form several intermetallic compounds with tungsten that usually precipitates along the interfacial boundary between tungsten grains and the matrix leading to a serious embrittlement effect. Thus, when cobalt is recommended to be added to get its utmost benefit, a post heat treatment process should be recommended in order to dissolve and prevent its formation.

CONCLUSION

This study has determined the variations in mechanical properties and fracture behavior for tungsten heavy alloy with different chemical composition particularly matrix constituents. The effect of addition of cobalt as an important alloying element to this family of tungsten heavy alloys in the as sintered condition was revealed.

- Hardness increases with increasing the cobalt content, and attain maximum values of 322 Hv when cobalt completely substitutes iron in the constitution of the binder (6wt.% Ni, 3wt.%Co).
- Hardness values decreases generally with the sintering temperature for all compositions due to to the normal grain growth and the increased matrix volume fraction. Moreover, the decrease in hardness with increasing the sintering temperature, is sensibly lower when cobalt completely replaces iron in the matrix, since, it serves as grain growth inhibitor.
- The tensile strength increases, in a first stage up to 545 Mpa, by adding cobalt, due to the strengthening effect of cobalt. Further increase in cobalt content decreases this strength due to the embrittlement caused by the formation of intermetallic compounds.

- Both the ductility and the impact resistance of these alloys showed a continuous decrease with increasing the cobalt content.
- W-Ni-Fe based heavy alloys, failed predominantly by brittle intergranular separation either between W-W particles or W-matrix phase, together with a limited appearance of ductile matrix failure and brittle tungsten cleavage during tensile testing.
- W-Ni-Fe-Co based heavy alloys, were fractured predominantly through tungsten cleavage fracture, which results from improving the tensile strength of the alloy by strengthening the matrix composition by the addition of limited amount of Co (1.5% wt.) to the matrix composition
- W-Ni-Co based heavy alloys, where cobalt completely replaces iron in the matrix composition, shows brittle fracture mechanisms during failure, and were fractured predominantly by tungsten matrix intergranular separation. This is attributed to the formation of considerable amount of brittle intermetallic phases between cobalt and tungsten, resulting in decreasing the interfacial strength between the tungsten particles and the matrix phase and decreasing the mechanical properties.

REFERENCES

- [1] Anish Upadhyaya, "Processing strategy for consolidating tungsten heavy alloys for ordnance applications", *Materials Chemistry and Physics*, Vol.67, pp. 101–110, 2001.
- [2] W. Leonard, L. Magness Jr. and D. Kapoor, "Improving mechanical properties of tungsten heavy alloy composites through thermo-mechanical processing", *Tungsten and tungsten alloys*, edited by A. Bose and R.J. Dowding. MPIF, Princeton, NJ., pp.127, 1992.
- [3] Penrice et al., "High density tungsten-nickel-iron-cobalt alloys having improved hardness and methods for making same", U.S patent, Patent number 4,762,559, Aug.1988.
- [4] Heung Sub Song et al., "The effect of Ni/Fe ratio on the mechanical properties for tungsten heavy alloys", *Advanced in powder metallurgy and particulate materials*, pp. 77–93, 1992.
- [5] J.P.Wittenauer and T.J.Nieh, "Development of fine grained ductile tungsten alloys for Armor/Anti Armor ", AD-A231 857, Lockheed missiles and space company ,Inc. ,Palo Alto, 1991.
- [6] B.H.Rabin, A.Bose and R.M.German, "Characteristics of liquid phase sintered tungsten heavy alloys", *International journal of powder metallurgy*, Vol.25, No.1, pp. 21, 1980.
- [7] K.F.Ryen and R.J.Dowding, "Yield properties of tungsten and tungsten heavy alloys", ARL-TR-143, Army Research Laboratory, Watertown, MA.
- [8] ASM Handbook, "Alloy phase diagrams", Vol.3.

- [9] W.D.Cai, Yi Li, R.J. Dowding and F.A. Mohamed, "A review of tungsten based alloys as kinetic energy penetrator materials", Third international conference on tungsten and refractory metals, edited by A.Bose and J.Dowding, 1995.
- [10] H.K.Yoon, S.H.Lee, L.Kang, D.N.Yoon, "Effect of vacuum-treatment on mechanical properties of W-Ni-Fe heavy alloy", Journal of materials science, Vol.18, pp. 1374-1380, 1983.
- [11] A.S.Abdallah, A. Fayed, G.Abdou, M.Tolba Sallam, "Effect of processing parameters on the mechanical and structure properties of 93W–4.9Ni–2.1Fe Tungsten heavy alloy", Fifteenth International Conference on Aerospace Sciences & Aviation Technology, ASAT-15, MTC, Cairo, 2013.
- [12] A.Bose and R.M.German, "Microstructural Refinement of W-Ni-Fe Heavy Alloys by Alloying Additions", Metallurgical Transactions A, Vol. 19A, pp. 3100-3103, December 1988.
- [13] T.W.Penrice, "Cold working of high density tungsten alloys", The carbide and tool journal, No.11-12, pp. 30, 1979.