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EFFECT OF PROCESSING PARAMETERS ON MECHANICAL PROPERTIES OF 4.2% Ni – 1.8% Fe – 0.5% Co (wt %) TUNGSTEN HEAVY ALLOY

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ABSTRACT

Tungsten heavy metal alloys (WHA) with elemental metal powders of tungsten, nickel, iron, and cobalt which correspond to a chemical composition of 93.5% W-4.2% Ni-1.8 Fe-0.5% Co (wt.%) were mixed in milling machine for two hours. The mixture was then subjected to uniaxial compaction varied from 60 MPa up to 180 MPa. Sintering of specimens was carried out in a Vacuum sintering furnace. Sintering temperature was varied from 1420℃ up to 1550℃ while sintering time was changed from 60 minutes up to 120 minutes.

Sintered density, hardness, and impact tests were performed to find out the effect of processing parameters (compaction pressure, sintering temperature, and sintering time) on the mechanical and physical properties of the adopted tungsten alloy. It was found that the a compaction pressure of 120 MPa and a combination of sintering parameters of (1450℃ for 120 minutes) or (1520℃ for 60 minutes) can provide optimum mechanical and physical properties of this alloy.

KEY WORDS

Tungsten heavy metal alloys, Sintering parameters.

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INTRODUCTION

The powder technology permits manufacture of parts that would be impracticable or even impossible by any other method. Such industrial applications are probably the better known because of the myriad of uses and trade names that have become prominent such as cemented carbides, filters, self-lubricating bearings, and generator brushes. Some special applications of powder metallurgy have been implemented for the previous advantages such as ductile tungsten, contacts and electrodes, permanent magnets, friction materials, metal-to-glass seals, metallic coatings, mixtures of metal powders and other materials, structural parts of aircraft, and tungsten heavy metal alloys.

The production of tungsten heavy metal alloys (WHA) are one of the special applications of powder metallurgy products. Tungsten is the main component and the systems Ni-Fe, Ni-Cu, Ni-Co… etc serve as the ductile binder phase for the brittle tungsten grains.

In conventional heavy alloys, the tungsten content varies from 90 to 98 weight percent. Commonly the remaining alloy constituents are usually nickel, iron, cobalt, or copper. The most eminent additive being the nickel and iron in the ratio of 7Ni:3Fe or 8Ni:2Fe (weight ratio). These alloys are characterized by a unique combination of high density (17-19 g/cm3), high strength and ductility. They are used as counter weights in airplanes, rotating inertia members, radiation shielding, as rigid tools for machining, for darts, for weights in golf club heads, vibration damping devices, several medical devices for containment of radioactive isotopes, heavy duty electrical contact materials, balancing crank shafts for internal combustion engines used in racing motor cars, gyroscopes, as well as, for ordnance purposes (kinetic energy penetrators, fragmentation devices, etc.).

The environmental concern over the use of depleted uranium (DU) alloys as kinetic energy (KE) penetrator for high strain rate applications has focused the interest in replacing DU alloys by alternate materials. Clearly, WHA emerges as one such potential candidate for KE penetrators. However, in general, tungsten-based alloys exhibit about 10% lower performance than DU at high strain rate [1, 2].

In this paper, an experimental study was performed to assess the effect of WHA processing parameters on its mechanical properties. These parameters include compaction pressure and sintering parameters (sintering temperature and sintering time).

EXPERIMENTAL STUDY

The production of sintered specimens was achieved by conventional powder metallurgy technique. Specimens having a chemical composition of 93.5% W-4.2% Ni-1.8 Fe-0.5% Co (wt. %) were mixed to secure homogeneous distribution of elements. The mixture was then subjected to uniaxial compaction varied from 60 MPa up to 180 MPa to find out the optimum value and to investigate the effect of compaction pressure on the structural and mechanical characteristics of the alloy, using hydraulic press, on a floating die with the required dimensions to achieve the required shape and size of the test specimens.

Sintering of specimens was carried out in a Vacuum sintering furnace. Sintering temperature was varied from 1420℃ up to 1550℃ while sintering time was changed from 60 minutes up to 120 minutes to evaluate the effect of these sintering parameters on the structural and mechanical characteristics of sintered alloy. The test specimens which prepared at different compaction pressures and sintering parameters are shown in Table 1.

Table 1. Test specimens prepared at different powder compaction, and sintering parameters.

Powder composition	**Compaction pressure (MPa)**	**Sintering parameters**	
		Temperature (ºC)	**Time (min)**
93.5% W-4.2% Ni-1.8 Fe-0.5% Co (wt. %)	60	1520	120
	120	1520	120
	180	1520	120
	120	1550	120
	120	1520	120
	120	1480	120
	120	1450	120
	120	1480	60
	120	1480	90
	120	1480	120
	120	1520	30
	120	1520	60
	120	1520	90
	120	1520	120

Determination of Mechanical Properties of Sintered Specimens

Initial impact unnotched specimens after compaction were 80 x 8 x 8.7 mm. The impact resistance of produced tungsten heavy alloys was measured using a charpy pendulum impact machine.

The measurement of the hardness of produced tungsten heavy alloys with different sintering conditions has been carried out according to the standard specifications Number BS 240(1986) using the Brinell hardness tester.

Microstructure and Micro Chemical Analysis

Primary observations of the structure of tungsten heavy alloys had been done using optical microscope with magnification up to 1500X. The used etchant was concentrated (HNO_3, HF, HCL).

Microstructures, micro chemical analysis and fractures of tungsten heavy alloys were examined using a scanning electron microscope (SEM) type SEMMA 202-M.

RESULTS AND DISCUSSION

The effects of compaction pressure, sintering temperature, and sintering time on the sintered density, hardness, and impact resistance of investigated tungsten heavy alloys were studied. Different specimens having chemical composition of 93.5% W-4.2% Ni-1.8 Fe-0.5% Co (wt. %) were mixed in a milling machine for two hours. Compaction was done, in a floating die, under various compaction pressures from 60 to 180 MPa. Sintering was then carried out in a vacuum sintering furnace at different temperatures from 1450°C to 1550°C to allow liquid phase formation. Sintering times were varied from 60 min. up to 120 min.

Effect of Compaction Pressure

The effect of compaction pressure on the resulting hardness of sintered tungsten heavy alloys is illustrated in Fig.1.This group of alloys was sintered at a fixed temperature of 1520°C for two hours. We may notice that by increasing the compaction pressure from 60 MPa up to 120 MPa, the hardness of the alloy was increased from 300 HB to 320 HB. By increasing the compaction pressure above 120 MPa, no significant change in the hardness can be revealed.

This can be directly attributed to the reduction of the volume fraction of pores by increasing the compaction pressure up to 120 MPa. Moreover higher compaction pressures lead to development of more friction between powder particles and induce extra work hardening that can retard densification and consequently the increase of hardness.

The process which takes place when loose powder is compacted in a closed die have been described by Seeling and Wulff [3] who postulated a series of stages, each corresponds to different mechanism of compaction. The first stage is characterized by restacking and rearrangement of powder and it does not contribute significantly to the densification process. The second stage involves simultaneous elastic and plastic deformations of powder particles and it is highly controlled by ductility of the metal powders. The induced work hardening diminishes the amount of further deformation under the applied stress. This eventually leads to the third stage in which some particles may also fracture to small fragments.

The effect of compaction pressure on the resulting density of sintered tungsten heavy alloys is illustrated in Fig.2.By increasing the compaction pressure from 60 MPa up to 120 MPa, the density of the produced tungsten heavy alloys was increased and reaches a maximum value of 17.55 g/cm^3 at a compaction pressure of 120 MPa then it slightly decreases.

The observed decrease of the density with the increasing of the compaction pressure above 120 MPa may be attributed to the trapped gas inside the pores which retard further densification as seen in Fig.3. Moreover, extra compaction pressure above 180 MPa results in an explosion of gas pockets inside the specimen causing extra vents which in turns leads to the observed decrease in density.

The effect of compaction pressure on the impact resistance of these specimens is illustrated in Fig.4. By increasing the compaction pressure from 60 MPa up to 180 MPa, the impact resistance decreases by about 13 % until reaching the minimum value of 13 J/cm^2 at 180 MPa. This may be attributed to the hardening effect induced by compaction and the resulting decrease of ductility. Contrary to the behavior of conventional alloys where the compaction pressure increase the mechanical locking of particles and consequently enhance densification after sintering which leads to increasing the value of the impact resistance with increasing the compaction pressure, in this type of hard alloys, compaction pressure decrease the distance and clearance between tungsten hard particles which results in decreasing the thickness of the binding layer of the cemented material (Nickel and Cobalt) consequently the impact energy for fracture becomes lower.

Effect of Sintering Temperature

The effect of sintering temperature on the resulting hardness of sintered tungsten heavy alloys is illustrated in Fig.5.This parameter was investigated in the temperatures range from 1450ºC up to 1550ºC, under a constant compaction pressure of 120 MPa for a constant sintering time of 120 min. We can note that as the sintering temperature increases, the hardness decreases. A sharp decrease between 1450℃ and 1480℃ can be recorded, followed by an interval of slight decrease between 1480℃ and 1520℃. Above 1520℃ hardness continue to decrease again in a pronounced manner. This can be attributed to the resulting variations in grain size, the relative volume fraction of liquid phase, and the contiguity of existing grains with the variation of sintering temperature.

The work reported by W. D. Cai. [4] has demonstrated that as sintering temperature increases, the grain size and volume fraction of matrix increase while the contiguity decreases as shown in Fig.6. On one hand, the high sintering temperature results in a partial solubility of tungsten in the matrix, which in turns leads to more matrix phase. On the other hand, high sintering temperature can lead to faster tungsten grain growth rate. Moreover, high sintering temperature leads to a decrease in the dihedral angle. A low dihedral angle corresponds to a lower contiguity [4]. As a result of these changes in microstructure, strength and hardness decrease with increasing sintering temperature.

We can note that the green density of the adopted tungsten heavy alloy specimens, after mixing of powders and compaction stages is 10 g/cm^3. The compact is brittle and its strength, known as green strength is low. After liquid phase sintering at 1450˚C, we have obtained a density of the order of 16.65 g/cm^3. This means that the density increases by about 66.5 % as shown in Fig.7. For structural P/M parts, a higher sintered density is very desirable, as it leads to better mechanical properties. The nature and strength of the bond between the particles, and hence of the sintered compact, depend on the mechanisms of diffusion, plastic flow, evaporation of volatile materials in the compact, Recrystalization, grain growth, and pore shrinkage.

The effect of sintering temperature on the resulting density of sintered specimens of tungsten heavy alloys is illustrated in Fig.8. This parameter was investigated on sintered tungsten heavy alloys produced in the temperatures range from 1450ºC up to 1550ºC under a constant compaction pressure of 120 MPa, and a constant sintering time of 120 min. By increasing the sintering temperature from 1450˚C to 1550˚C, the value of density of produced alloys increases and reach a maximum value at about 1490˚C, then it decreases until reaches the value of 17.08 g/cm^3 at sintering temperature of 1550˚C.At higher sintering temperatures, there are fewer but larger tungsten grains, more matrix and consequently greater mean free matrix path. As a result, the dislocation slip paths in the matrix are long and therefore less work hardening is present, which leads to lower strength and hardness. At still higher sintering temperatures, however, the larger tungsten grains promote the formation of large cracks at tungsten-tungsten interfaces as shown in Fig.9, this leads to an increase in stress concentration as the work reported by W. D. Cai. [4]. The excess liquid phase with its metallostatic pressure causes slight displacement of grains of different constituent which leads to the appearance of swelling effect and consequently decrease in density.

The effect of sintering temperature on the impact resistance of produced specimens is illustrated in Fig.10. By increasing the sintering temperature from 1450˚C to 1550˚C, the impact resistance is increase by about 61 %. This means that the absorbed energy in the specimens increases with increasing the sintering temperature. This result is in conformity with the work reported by W. D. Cai. [4] which indicated that at higher sintering temperatures, there are fewer but larger tungsten grains, more matrix and consequently greater mean free matrix path which lead to increase the ductility of the alloy with increasing sintering temperatures.

Effect of Sintering Time

The effect of sintering time on the resulting hardness of sintered specimens is shown in Fig.11. The sintering time was varied from 30 min. up to 120 min., at a constant compaction pressure of 120 MPa, and a constant sintering temperature of 1520˚C. By increasing the sintering time, in this range the hardness of the alloys decreases by about 6 %. This can be attributed to the grain growth of the tungsten particles which leads to a decrease in the hardness as shown in Fig.12. This result is in conformity with the work reported by R. M. German [5] who demonstrated that extended sintering times can generate other microstructure variations besides larger grains. He showed that during sintering, the tungsten grains exhibit grain shape accommodation in agreement with energy minimization calculations. The mean tungsten grain size varies from 20 μm to 60 μm depending on the initial particle size, volume fraction of tungsten, sintering temperature, and sintering time [6]. Prior studies have detected a decrease in the contiguity of the tungsten grains with long sintering times [7, 8, and 9]. This result consequently leads to increasing the impact resistance of the tested specimens by about 16.7 % as shown in Fig.13.

The effect of sintering time on impact resistance of produced tungsten heavy alloys is illustrated in Fig.13. Varying the sintering time between 30 min. up to 60 min. does not reveal any significant improvement in impact resistance. By increasing the sintering time from 60 min. to 120 min., the impact resistance of the specimens increases gradually up to a value of 14 J/cm^2.

The effect of sintering time on density of produced specimens is shown in Fig.14. It is seen that by increasing the sintering time, the density of the produced alloys increases from 17.28 g/cm^3 after a sintering time of 30 min. up to a maximum value of 17.64 g/cm^3 after sintering for 60 min. then slightly decreases to reach a value of 17.55 g/cm^3 after a sintering time of 120 min. Prolonged sintering time up to 120 min. has insignificant effect on the density of the produced alloys which mean that after 60 min. no further densification takes place. This means that in the initial stages of sintering up to 60 min., diffusion processes will contribute in the processes of pores elimination and allow complete wetting of tungsten particles resulting in a near full dense material.

The effect of sintering time on the resulting hardness of sintered tungsten heavy alloys is illustrated in Fig.15.This parameter was investigated on sintered tungsten heavy alloys at times range from 60 min. up to 120 min., under a constant compaction pressure of 120 MPa, and a constant sintering temperature of 1480˚C.

By increasing the sintering time of tungsten heavy alloys specimens, the hardness of the alloy increases. A gain in hardness of about 4 % can be noted when the sintering time is increased from 60 min. up to 120 min. This may be explained by the enhanced diffusion process which leads to an improvement of the hardness of the alloy as shown in Fig.15.

The effect of sintering time on impact resistance of the produced tungsten specimens is illustrated in Fig.16. By increasing the sintering time from 60 min. to 120 min., the impact resistance of the produced alloys decreases by about 28.5 %. The effect of sintering time on density of produced tungsten heavy alloys specimens is illustrated in Fig.17. By increasing the sintering time from 60 min. to 120 min., the density of the produced alloys increases by about 4.3 %.

This can be explained by the enhanced diffusion processes during the prolonged sintering time so that the matrix will fill most of the pores located around the tungsten particles and allow good wetting resulting in a near full dense specimens.

CONCLUSIONS

The main conclusion drawn from the results obtained during the investigation of the effect of compaction pressure on mechanical and physical properties of the adopted tungsten heavy alloy specimens is that:-

- The optimum compaction pressure was 120 MPa.
- The optimum sintering temperature was 1480˚C.
- The optimum sintering time for specimens produced at sintering temperatures of 1520˚C & 1480˚C and under a compaction pressure of 120 MPa was 60 min. & 120 min. respectively.

REFERENCES

[1] Anish Upadhyaya, “Processing Strategy for Consolidation Tungsten Heavy Alloys for Ordnance Applications”, Materials Chemistry and Physics 67, pp.101-110, 2001.
[2] Theodore A. Waniuk and Jan Kajuch, “Tungsten Composites of Liquidmetal Alloys for Kinetic Energy Penetrator Applications”, Sixth International Conference on Tungsten, Refractory & Hardmetals, pp. 266-273, 2006.
[3] Seeling R., and Wulff J., “The Pressing Operation in the Fabrication of Articles by Powder Metallurgy”, Trans. AIME, Vol. 166, pp. 492-504, 1946

[4] W. D. Cai., Y. Li., R. J. Dowding, F. A. Mohamed, and E. J. Lavernia, "A Review of Tungsten-Based Alloys as Kinetic Energy Penetrator Materials", Third International Conference on Tungsten and Refractory Metals, pp. 71-126,1995.

[5] R.M. German, A. Bose, and S.S. Mani, "Sintering Time and Atmosphere Influences on the Microstructure and Mechanical Properties of Tungsten Heavy Alloys", Metallurgical Transactions, Vol. 23A, pp. 211-219, 1992.

[6] Sung-Chul Yang, S.S. Mani, and R. M. German, "Growth Behavior in Liquid Phase Sintered Heavy Alloys", Advanced in Powder Metallurgy and Particulate Materials, Vol. 1, pp. 469-482, 1990.

[7] C.M. Kipphut, R. M. German, A. Bose, and T. Kishi: Advances in Powder Metallurgy, Vol. 2, pp. 415-429, 1989.

[8] H. Fichmeister, A. Kannappan, L. Ho-Yi, and E. Navara: Phys. Sintering, Vol. 1, pp. 1-13, 1969.

[9] V. Srikanth and G. S. Upadhyaya: Metallog. Vol. 19, pp. 437- 445, 1986.

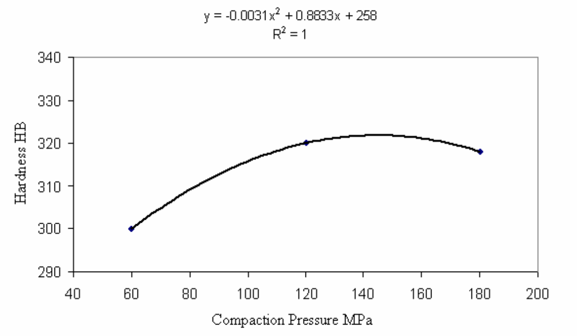


Fig.1. Effect of compaction pressure on hardness of WHA [93.5%W-4.2%Ni-1.8%Fe-0.5%Co] sintered at 1520℃ for 120 min.

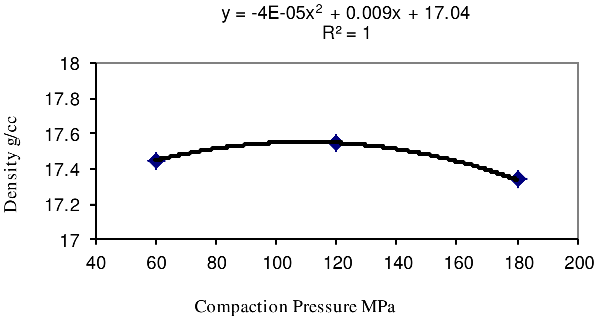
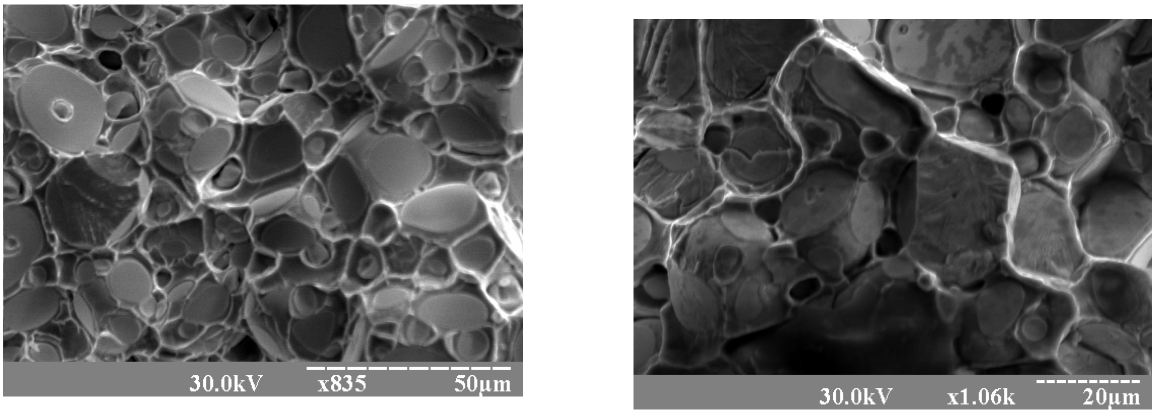


Fig.2. Effect of compaction pressure on density of WHA [93.5%W-4.2%Ni-1.8%Fe-0.5%Co] sintered at 1520℃ for 120 min



(a) (b)

Fig.3. Fractograph of a liquid phase sintered WAH [93.5%W-4.2%Ni- 1.8%Fe-0.5%Co] at 1520℃ for 120 min. (a) at compaction pressure of 120 MPa, (b) at compaction pressure of180MPa

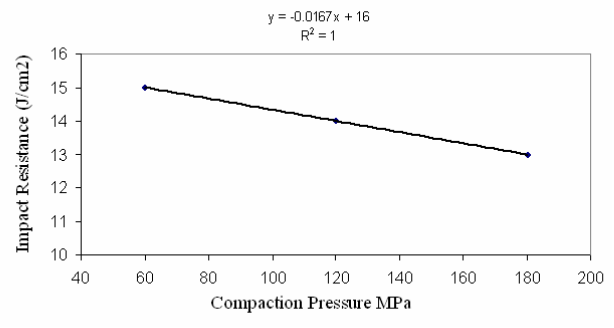


Fig.4. Effect of compaction pressure on impact resistance of WHA [93.5%W-4.2%Ni-1.8%Fe-0.5%Co] sintered at 1520℃ for 120 min.

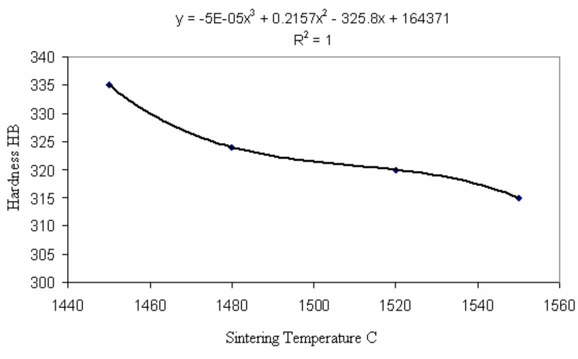


Fig.5. Effect of sintering temperature on hardness of WHA [93.5%W-4.2%Ni-1.8%Fe-0.5%Co] obtained under a compaction pressure of 120 MPa and a sintering time of 120 min.

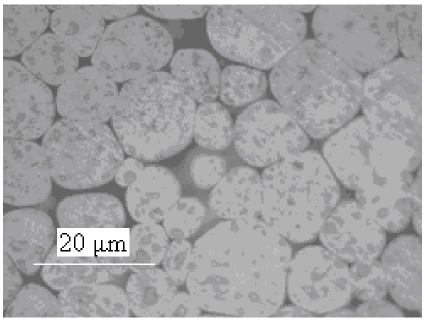


Fig.6. Morphology of a liquid phase sintered WHA [93.5%W-4.2%Ni- 1.8%Fe-0.5%Co] obtained under a compaction pressure of 120 MPa and sintered at 1520℃ for 60 min.

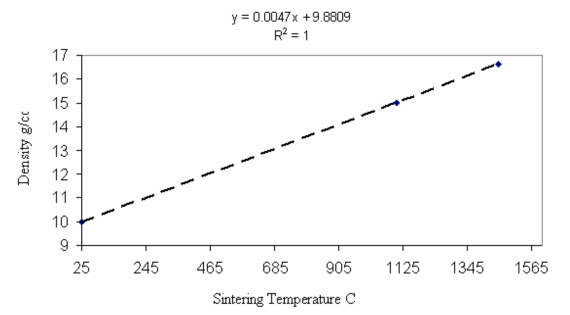


Fig.7. Effect of sintering temperature on density of WHA [93.5%W-4.2%Ni- 1.8%Fe-0.5%Co] in both solid state and liquid phase sintering.

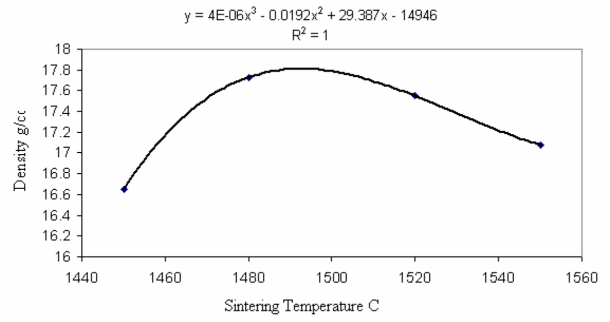


Fig.8. Effect of sintering temperature on density of WHA[93.5%W-4.2%Ni-1.8%Fe- 0.5%Co] obtained under a compaction pressure of 120 MPa and sintering time of 120 min.

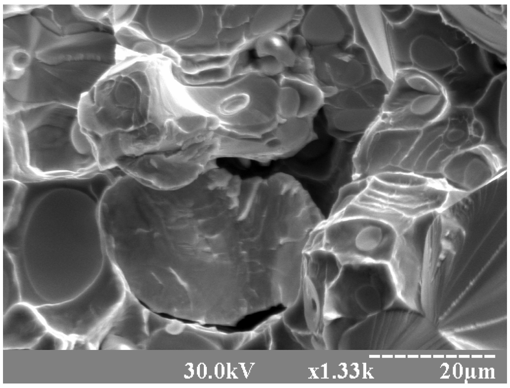


Fig.9. Fractograph of a liquid phase sintered WAH [93.5%W-4.2%Ni-1.8%Fe- 0.5%Co] obtained under a compaction pressure of 120 MPa and sintered at 1520℃ for 120 min.

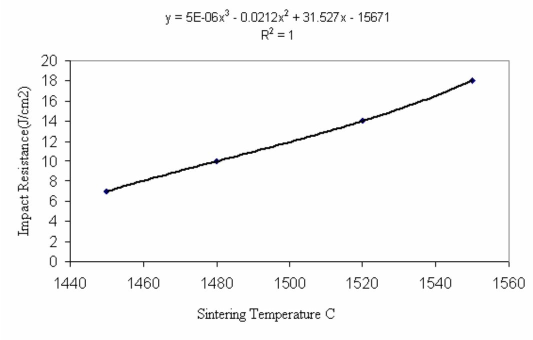


Fig.10. Effect of sintering temperature on impact resistance of WHA [93.5%W-4.2%Ni-1.8%Fe-0.5%Co] obtained under a compaction pressure of 120 MPa and sintering time of 120 min.

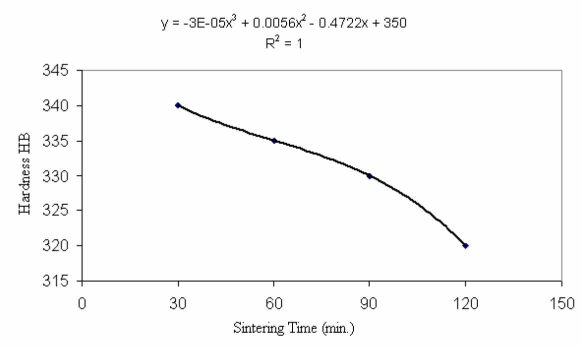


Fig.11. Effect of sintering time on hardness of WHA [93.5%W-4.2%Ni-1.8%Fe-0.5%Co] obtained under a compaction pressure of 120 MPa and sintered at 1520ºC.

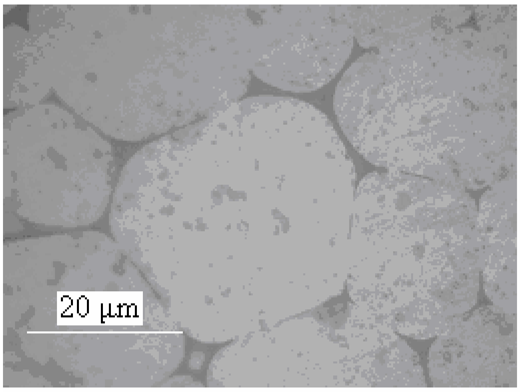


Fig.12. Morphology of a liquid phase sintered WHA [93.5%W-4.2%Ni-1.8%Fe-0.5%Co] obtained under a compaction pressure of 120 MPa and sintered at 1520℃ for 120 min.

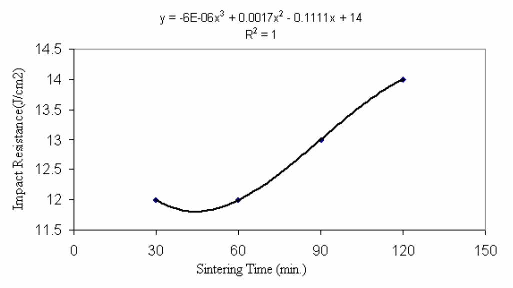


Fig.13. Effect of sintering time on impact resistance of WHA [93.5%W-4.2%Ni-1.8%Fe- 0.5%Co] obtained under a compaction pressure of 120 MPa and sintered at 1520ºC

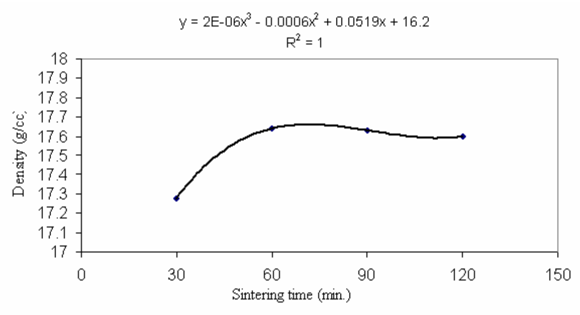


Fig.14. Effect of sintering time on density of WHA [93.5%W-4.2%Ni-1.8%Fe-0.5%Co] obtained under a compaction pressure of 120 MPa and sintered at 1520ºC.

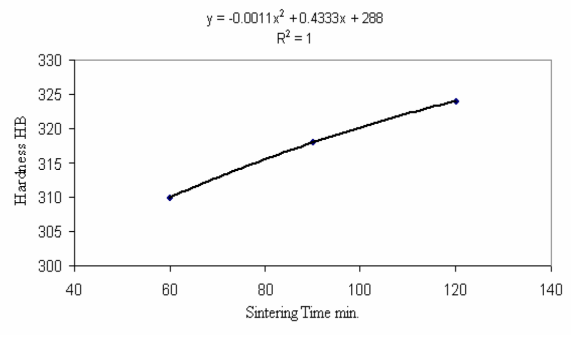


Fig.15. Effect of sintering time on hardness of WHA [93.5%W-4.2%Ni-1.8%Fe-0.5%Co] obtained under a compaction pressure of 120 MPa and sintered at 1480ºC.

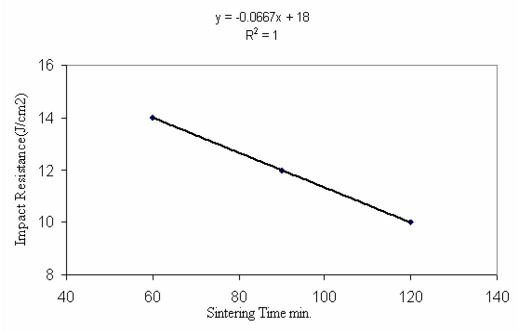


Fig.16. Effect of sintering time on impact resistance of WHA [93.5%W-4.2%Ni-1.8%Fe- 0.5%Co] obtained under a compaction pressure of 120 MPa and sintered at 1480ºC

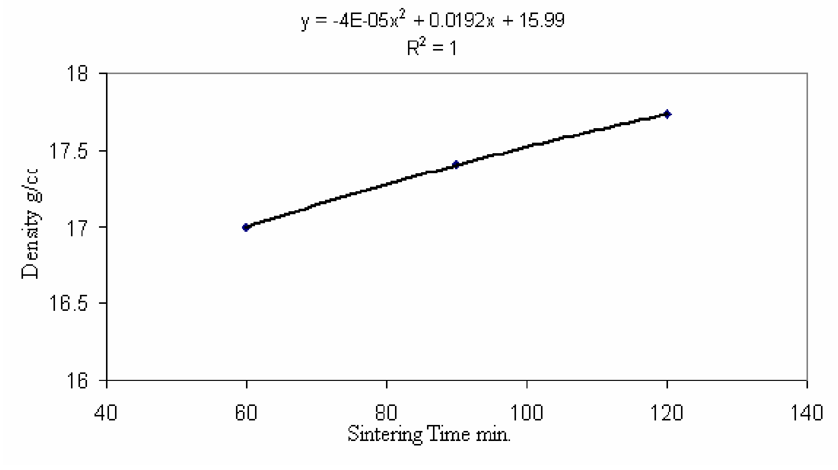


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Fig.17. Effect of sintering time on density of WHA [93.5%W-4.2%Ni-1.8%Fe-0.5%Co] obtained under a compaction pressure of 120 MPa and sintered at 1480 ºC.