Effect of Addition of Tungsten Carbide on the Structural and Physical Properties of an Aluminum-Based System By Powder Method.

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Abstract. The powder technology method was used for the purpose of making samples from the compound (Al-10%Al₂O₃-%WC), where the first support material was used alumina Al₂O₃ at a fixed rate of 10% and the second support material WC was in different proportions (0, 5, 10, 15, 20)%; the three powders were ground together for a period of two hours, then put into a mold and the process was pressed with a hydraulic press at 5 tons for a time of one minute. An English-origin oven was used and the sintering process was done for the samples at 560°C and for a time of only two hours. After that, compositional tests (XRD), physical (real and apparent density, real and apparent porosity) and mechanical (diagonal compressive strength) were performed on the sintered samples. As these tests gave encouraging results with almost distinctive characteristics at a ratio of mixing of 20% WC and thermal sintering of 560°C, as the bulk density was within the limits of 5.51 g/cm³ while the real density was 4.9 g/cm³, while the minimum apparent porosity was 8.83% and the porosity. The real one is 11.76%, while the diagonal compressive strength is 45.33 MPa. As for the structural results of the X-ray diffraction after the sintering process, it showed the emergence of a new phase of the tertiary metal oxide (WO₃) and the (Triclinic) phase, as well as the emergence of tungsten carbide in the cubic phase.

Keywords: Green Density, Hydraulic Press, Mechanical Properties, Powder Mineral.

1. Introduction:

Composite materials, which are a mixture of two or more substances. Each of these materials has different chemical, physical and mechanical properties. Consequently, a new substance is produced with properties that differ from the properties of its constituent substances. The new material has properties that cannot be obtained in traditional materials such as metallic, ceramic and polymeric materials. The resulting new material is called the superimposed. Determining the suitability of composite materials for any job depends heavily on the physical and mechanical properties of these materials. Therefore, it is important to study these properties under the influence of forces and loads and under different conditions [1]. The good specifications of the composite materials have made them occupy a prominent position in the field of industry such as the aerospace industry, construction industries and others. Composite materials are characterized by good (resistance/weight) ratio and good (stiffness/weight) ratio, as well as high corrosion resistance [2]. Metal-based composites are one of the most important types of composite materials and are called advanced engineering materials. As these materials possess distinct properties that made them at the forefront of composite materials. The base material is metallic materials such as aluminum, copper, or magnesium, etc. And supported by one of the strengthening phases such as microelements, fibers or
filaments, etc. such as silicon carbide or graphite and other strengthening materials. Compared with metallic materials, metal-based composites have good quality strength and good quality toughness as well as good wear resistance. The disadvantages of metal-based composites compared to metals are their high cost of manufacture, as well as their low ductility and durability. Due to the good properties of mineral-based composites, they have been widely used in industry, such as the manufacture of some parts of aircraft and satellites, as well as the manufacture of some automotive parts [3,4]. The current research aims to study the effect of adding WC stiffeners on real and apparent density, real and apparent porosity, diagonal compressive strength and XRD on aluminum-based composites to see the extent of applications of these composites in many industrial applications, the most important of which is the manufacture of aircraft and automotive parts.

2. Procedure Part

1. Raw materials Used in the Paper:

   The base material was used from aluminum (Al) with a grain size ≤ 53µm of German origin from the company (Riedel-de Haën) with a purity of 99%, and also a fixed percentage of alumina (Al₂O₃) with a grain size ≤63µm of German origin was used from (Fluka) company. With a purity of 99.99%, the support material was tungsten carbide (WC) of Chinese origin from Changsha Santech Materials Co., with a purity of 99.4% and a grain size of 18µm.

2. Preparation method:

   The mix weights of each component were prepared by following the size ratios so that the alumina percentage was constant and at (10%) for all mixtures, while the tungsten carbide was at rates of (0,5,10,15,20) %. Weighing was done using a Japanese-origin (Sartorius) sensor with an accuracy of (0.00001) grams. After the completion of the grinding and blending process and obtaining a homogeneous powder, the samples were formed by means of (Uniaxial) pressing technology in a hardened steel mold of (60HRC) hardness. The mixed mixture was placed inside the press mold, which was carefully and carefully placed in the press to prevent any movement of the mold parts. Then (5Ton) pressure was applied for one minute to avoid the possibility of flexible return [5,6]. For this purpose, a hydraulic press of (HALIM USTA) Turkish origin with a pressure capacity of (20Ton) was used to obtain samples from cylindrical samples with a diameter (10) mm and a height (6) mm. After the pressing process, the samples are not ready for testing and have a weak resistance, which is the green resistance, which requires care when transporting and handling until the sintering process takes place. The sintering process was carried out using a German-origin (CARBOLITE) furnace at a temperature of (560°C) and a time of only two hours.

3. Measurements Used:

   1. X-Ray Diffraction:

      X-rays are electromagnetic rays with a single wavelength and very short, ranging between (0.25 - 0.5) ankström, with a nature similar to the nature of light, but with a shorter wavelength. It is produced by colliding electrons with the target metal inside the X-ray tube. The English scientist Brack (W.L.Bragg) created a mathematical equation that, through the diffraction of X-rays, was able to determine the distance between the crystal levels. Thus, the phases formed from the substance and the type of substance are known by applying the following equation. [7]

      \[ 2d \sin \theta = n \lambda \]  \hspace{1cm} (1)

      Since: \( d \) = The distance between atomic levels, \( \theta \) = diffraction angle (Bracke angle), \( \lambda \) = wavelength, \( n \) = integer representing the diffraction atom.
2. Apparent Density:

It is defined as the ratio between mass to apparent volume consisting of actual matter and closed pores only. The bulk density can be calculated according to Archimedes' rule by the following relationship [8,9]:

\[ \rho_a = \frac{W_d}{W_d - W_i} \times \rho_w \]  

(2)

Since: \( \rho_a \) = Apparent density (g/cm³), \( \rho_w \) = Density of Water (g/cm³), \( W_d \) = Weight of the Dry Object (g), \( W_i \) = Weight of the Object Suspended in Water (g).

3. Bulk Density:

It represents the ratio between the mass of a material to its total volume consisting of the actual material and the closed and open pores. The volumetric density can be calculated according to Archimedes' theory by the following relationship [8,9]:

\[ \rho_b = \frac{W_d}{W_s - W_i} \times \rho_w \]  

(3)

As: \( \rho_b \) = Bulk Density (g/cm³), \( W_s \) = The weight of the object which is saturated water(g).

4. Apparent Porosity:

It is the ratio of open pores to the total body volume, and the apparent porosity is calculated using Archimedes' theory from the following relationship [10,11]:

\[ A.P. = \frac{W_s - W_d}{W_s - W_i} \times 100\% \]  

(4)

5. True Porosity:

It is the ratio between the size of open and closed pores to the size of the total body, and is calculated from the following relationship [10,11,12]:

\[ T.P. = \frac{T.D. - B.D.}{T.D.} \times 100\% \]  

(5)

As: T.P. = The ratio of total porosity of the sintered body, T.D. = The theoretical sintered body density (g/cm³), B.D. = Sintered body density (g/cm³).

6. Compressive Strength

The compressibility test for brittle materials is performed because the brittle materials have a compressive stress much higher than the tensile stress, such as ceramic materials, bricks, wood, and metallic materials that are made using powder metallurgy technology. The compressibility test is the opposite of the tensile test in terms of the direction of stress shedding. The compressive strength is calculated from the following relationship [13,14,15]:

\[ \sigma_D = \frac{2F}{\pi d h} \]  

(6)

Since: \( \sigma_D \) = Compressive Strength (MPa), \( F \) = force (N), \( d \) = sample diameter (mm), \( h \) = sample thickness (mm).
4. Results and discussions:

1. X-ray diffraction analysis: Figure (1) shows the X-ray diffraction results of the composites (Al-Al₂O₃-WC) and at different support values of tungsten carbide WC (0%, 5%, 10%, 15%, 20%) and before sintering, as it is observed through the figure (1) The emergence of aluminum as a base material at the international card number (Card NO. 96-431-3215) when it was developed with a (Cubic) crystal system, while the reinforcing material for tungsten carbide appeared at the card number (Card NO. 96-150-1582). Figure (2) gives the X-ray diffraction results of the composites (Al-Al₂O₃-WC) and at different reinforcement values of WC (0%, 5%, 10%, 15%, 20%) and after sintering, and what has been observed after Sintering is the emergence of a new phase of tungsten metal oxide, i.e., WO₃, with an international card number (Card NO. 96-101-0619) and a (Triclinic) phase, as well as the emergence of tungsten carbide in a cubic phase, and this can be attributed to the temperature that the models were exposed to during The heat treatment, which gave it thermal energy, helped in the diffusion process between the grains of the materials that make up the compounds, as well as increasing the effectiveness of the chemical reaction between them, which led to the formation of another phase, which is (WO3), which has a high density of (7.16) g/cm³. In addition to an increase in the intensity of the other phases formed compared with the sintering process, and since these phases have high densities, the increase in their concentration in the composites after sintering means an increase in the density of the superpositions.

Figure 1. XRD of the composite at reinforcement ratios of (0,5,10,15,20) % before sintering.
2. The effect of tungsten carbide percentage on the bulk density of composites before and after sintering:

Figure (3) shows the relationship of bulk density with the different cementing ratios of tungsten carbide before and after sintering, as it is noticed that the bulk density increases before sintering from (2.78-5.1) g/cm³, while it increases after performing the sintering process for samples at 560°C from (3.31-5.51) g/cm³ and all the bulk density values were at reinforcement ratios of tungsten carbide from (0-20)%. The reason for the increase in the apparent density before and after sintering is attributed to the same reasons stated in the real density item, and the thermal sintering process has a significant impact and categorically indicates the improvement in the uniformity of the distribution of atoms within the crystal system (lattice) of the grains, and also the reason for the increase in the density values may be attributed. That the thermal sintering, which includes heating all the parts, as well as the two-hour exposure period of the model to heat during sintering, which helped to develop the process of gradual diffusion between the components of the composite as well as the effect of the reaction on improving the properties of the interface between the tungsten carbide grains as stiffening phase and the aluminum grains. Alumina, which represents the base phase, which increased the strength of the bonding between them and the formation of phases and oxides that may have filled the spaces between the grains of the composite materials. It reached [16] similar results for an aluminum-based compound.
3. The effect of tungsten carbide percentage on the true density of composites before and after sintering.

Figure (4) shows the relationship between the true density and the change in the weight ratios of the tungsten carbide of the composites (Al-Al₂O₃-WC) before and after the sintering process at a temperature of (560°C) for a period of two hours. For all carbide ratios, for example, the density increases from (2.57-4.22) g/cm³ at the tungsten carbide content from (0%) to (20%) respectively before sintering, while after sintering it increases from (2.91-4.9) g/cm³ for the same carbide content. Tungsten, and this increase can be attributed to the very high density of tungsten carbide if compared to the density of aluminum, and this is consistent with what was presented by [1] for the aluminum-based composite, as well as the formation of phases resulting from the chemical reaction between the materials that make up the composites during the sintering process and shown in Examination of the X-ray diffraction of the superposition (for example (WO₃), as these phases are characterized by a higher density of (7.16) g/cm³ compared to the theoretical density of the manufactured composites and the base material. Tungsten and this is consistent with what he indicated [17].

Figure 4. The effect of different tungsten carbide percentage on true density before and after sintering.
4. The effect of tungsten carbide ratio on the apparent porosity of the composites before and after sintering.

Figure (5) shows the inverse relationship between the apparent porosity and the various reinforcement ratios of tungsten carbide before and after the thermal sintering process by 560°C, if it is noticed that the apparent porosity value before sintering is reduced from (18.80-11.33)%, and the porosity decreases after sintering from (14.33-8.83) % and when a reinforcement percentage of tungsten carbide ranges from (0-20)%.

That is, we notice a more decrease in the apparent porosity compared to the real porosity. The thermal treatment procedure had an effect on the decrease of the porosity ratios of the manufactured models, and we find through the results that the reason for the decrease in the porosity is due to the fact that the thermal energy supplied to the atoms within the crystalline pattern of the grains of the components of the complexes during the sintering process increased their movement (vibration), which facilitated the possibility of the atoms' transport. This was reflected in the development of the diffusion process and the formation of a new phase (WO₃) as well as the increase in the intensity of those phases formed after the sintering process, and this decrease is consistent with the increase in the density values that occurred after the thermal sintering process.

![Figure 5. The effect of different tungsten carbide percentage on apparent porosity before and after sintering.](image)

5. The effect of tungsten carbide ratio on the true porosity of composites before and after sintering.

Figure (6) shows the inverse relationship between the true porosity and the different reinforcement ratios of tungsten carbide before and after the thermal sintering process by 560°C, if it is noticed that the true porosity value before sintering is reduced from (21.34-15.24)% and the porosity decreases after sintering from (18.40-11.76) % and when a solidification rate of tungsten carbide ranges from (0-20)%.

This can be attributed to several reasons represented by the increase in the amount of added heat and the mode of its transmission to all parts of the models and the time period that allowed for increased chemical reaction between each of the reinforcing material and the base material, improvement of the diffusion process between the grains of the components of the superposition and the increase in the intensity of the emerging phases and the intensity of their peaks, as in the diffraction examination. X-rays, as well as increasing the strength of bonding between grains, shrinking large pores, and getting rid of small pores after expelling gases from inside to outside through their contact with the external pores and that the decrease in porosity is consistent with the increase in the density values because the relationship between them is an inverse relationship.
6. The effect of tungsten carbide percentage on true porosity before and after sintering:

The effect of tungsten carbide percentage on true porosity before and after sintering is shown in Figure 6. The porosity values decrease with increasing the content of tungsten carbide, as shown in the graph. After sintering, the porosity is further decreased, indicating improved densification.

6. The effect of tungsten carbide ratio on compressive strength of composites before and after sintering:

The compressive strength values increase with increasing the content of tungsten carbide, as shown in Figure 7 before and after sintering. After sintering, it also increased from (22.35 MPa) to (45.33 MPa) for the same carbide content. This increase can be attributed to several reasons, foremost of which is the decrease in porosity by increasing the content of tungsten carbide, as the porosity is the center of weakness and failure of the overlays by weakening the bonding between the grains. Tungsten carbide phases formed after the sintering process also played an important role in increasing the bond strength between the grains of the composites components. All of these reasons contributed to increasing the compressive strength values of the composites, and this is consistent with [18] for compositions based on aluminum.

Figure 6. The effect of different tungsten carbide percentage on true porosity before and after sintering.

Figure 7. The effect of different tungsten carbide percentage on compressive strength before and after sintering.
Conclusion:

The most important results were obtained through research after performing the sintering process at 560°C and at a cementation rate of 20% of tungsten carbide, which is that the amount of bulk density is around 5.51 g/cm³ while the real density is 4.9 g/cm³, while the minimum apparent porosity is 8.83% The true porosity is 11.76%, and the diagonal compressive strength is 45.33MPa. The results of X-ray diffraction after the sintering process showed the emergence of a new phase of tungsten metal oxide (WO₃) and the (Triclinic) phase, as well as the emergence of tungsten carbide in a cubic phase, evidence of improved mechanical and physical properties due to this ceramic phase, thus the mixing process reduced the proportion of 20% WC is suitable for mechanical and physical applications and other passive ratios.

References:

[1] William, D. Callister. Fundamentals of Materials Science and Engineering: An Interactive. John Wiley & Sons,( 2001).
[2] Dupen, Barry. "A Materials Engineering Technology Approach to Alloy Design." Journal of Engineering Technology 24.2 (2007): 20.
[3] Abdizadeh, Hossein, et al. "Improvement in physical and mechanical properties of aluminum/zircon composites fabricated by powder metallurgy method." Materials & Design 32.8-9 (2011): 4417-4423.
[4] Rajender Singh , " Introduction To Basic Manufacturing Processes And Workshop Technology", Published by New Age International, (2006).
[5] Yongping Jin , Ming Hu " Densification of Graphite/Copper Compound Powders " PP.1131-1135 , 978-1-4244-9439-2/11© IEEE , (2011).
[6] Chandana Priyadarshini Samal " Microstructure and Mechanical Property Study of Cu-graphite Metal Matrix Composite Prepared by Powder Metallurgy Route " master thesis , Department of Metallurgical and Materials Engineering, National Institute of Technology Rourkela, Orissa, India , (2012).
[7] Thakur Prasad Yadav , Ram Manohar Yadav, Dinesh Pratap Singh " Mechanical Milling : a Top Down Approach for The Synthesis of Nanomaterials and Nanocomposites " Journal of Nanoscience and Nanotechnology, VOL. 2, PP. 22-48, DOI: 10.5923/j.nn.20120203.01, (2012).
[8] Nicholas E. Nanninga, " High cycle fatigue of AA6082 and AA6063 aluminum extrusions ", Master's Theses, Michigan Technological University, Materials Science and Engineering, (2008).
[9] Darwish, Salih Younis, and Zuhair Naji Majid. "Improving the Durability of Streak and Thermal Insulation of Petroleum Pipes by Using Polymeric Based Paint System." Baghdad Science Journal 17.3 (2020): 0826-0826.
[10] Ewaid, S.H.; Abed, S.A.; Al-Ansari, N. Crop Water Requirements and Irrigation Schedules for Some Major Crops in Southern Iraq. Water 2019, 11, 756.
[11] Ewaid, S.H.; Abed, S.A.; Al-Ansari, N. Water Footprint of Wheat in Iraq. Water 2019, 11, 535.
[12] Ewaid, S.H.; Abed, S.A.; Al-Ansari, N. Assessment of Main Cereal Crop Trade Impacts on Water and Land Security in Iraq. Agronomy 2020, 10, 98.
[13] Ewaid, S.H.; Abed, S.A.; Al-Ansari, N.; Salih, R.M. Development and Evaluation of a Water Quality Index for the Iraqi Rivers. Hydrology 2020, 7, 67.
[14] Salam Hussein Ewaid et al 2021 IOP Conf. Ser.: Earth Environ. Sci. 790 012075
[15] Darweesh, Salih Y., et al. "The effect of some physical and mechanical properties of cermet coating on petroleum pipes prepared by thermal spray method." Journal of Failure Analysis and Prevention 19.6 (2019): 1726-1738.
[16] Humeedi, Sufian H., et al. "The Effect of Adding Titanium Nanoparticle Oxide on the Physical Properties of Nickel by Powder Method." *Journal of Physics: Conference Series*. Vol. 1664. No. 1. IOP Publishing, 2020.

[17] Goutam Dutta, Dipankar Bose " Effect of Sintering Temperature on Density, Porosity and Hardness of a Powder Metallurgy Component " *International Journal of Emerging Technology and Advanced Engineering*, ISSN 2250-2459, Vol. 2, No. 8, August (2012).

[18] Mohammed, Sameen F., and Salih Y. Darweesh. "Effect of Thermal Treatment on Some Physical and Mechanical Properties of Cermets Coated by Flame Spraying Technology." *Journal of University of Babylon for Pure and Applied Sciences* 26.7 (2018): 269-280.

[19] Smith, J. MacGregor, and Barış Tan, eds. *Handbook of stochastic models and analysis of manufacturing system operations*. Vol. 20013. Berlin: Springer, (2013).

[20] Darweesh, Salih Y., Ismael K. Jassim, and Amer SH Mahmood. "Characterization of cermets composite coating Al2O3-Ni system." *Journal of Physics: Conference Series*. Vol. 1294. No. 2. IOP Publishing, (2019).

[21] W. M. Khairaldien, A. A. Khalil, M. R. Bayoumi " Production of Aluminum - Silicon Carbide Composites Using Powder Metallurgy at Sintering Temperatures above the Aluminum Melting Point " *J Materials and design*, Vol. 23, PP. 153, (2003).

[22] Peter J. and Barry N. Talor " Hand book of Chemistry and Physic " *ASM Handbook*, (2006).

[23] R. Purohit, R. Sagar " Fabrication of Cam Using Metal Matrix Composites " *Int J Adv Manuf Technol*, Vol. 17, PP. 644, (2001).

[24] Alalaq, S., & Alshaybawee, T. (2019). New Bayesian Single Index Quantile Regression Based on Uniform Scale Mixture. *Al-Qadisiyah Journal Of Pure Science*, 24(4).

[25] Hamid, M., & M. Al-Waaly, A. B. (2020). Effect of Enterobius vermicularis parasite on IgE antibody levels among children in Al-Diwaniyah City, middle Iraq. *Al-Qadisiyah Journal Of Pure Science*, 24(4).

[26] Alfrdji, E. H. O. (2020). An Efficient Technique for solving Lane-Emden Equation. *Al-Qadisiyah Journal Of Pure Science*, 25(1), math 1-10.