Dynamic and physical characterization of the hybrid composites copper-based alloy reinforced with B_4C and Si_3N_4 nanoparticles fabricated via powder metallurgy

Omar A. Alammari, Muhammad Basha, and Essam B. Moustafa

Mechanical Engineering Department, Faculty of Engineering, King Abdulaziz University, P.O. Box 80204, Jeddah, Saudi Arabia

---***---

Abstract

This study examined the dynamic and physical properties of copper powder metallurgy composites that were reinforced with B_4C and Si_3N_4 nanoparticles. The composites were manufactured using the powder metallurgy technique. The study's findings indicate that including ceramic particles in copper composites can effectively regulate their dynamic and physical characteristics. The dispersion of ceramic particles increased grain structure and improved mechanical characteristics. Nevertheless, the inclusion of ceramic particles resulted in a decrease in the total density of the composites. The bulk density of hybrid composites, which integrate the additions of B_4C and Si_3N_4, exhibited a marginal decrease compared to the mono composites containing only a single type of additive. The investigation also encompassed an examination of the mode forms of the composites. The findings indicate that the manipulation of mode forms can be achieved by deliberately selecting ceramic particles and their respective volume percentages. In general, the findings of this work indicate that powder metallurgy composites exhibiting regulated vibration modes have the potential to serve as a highly promising category of materials in contexts where the management of vibrations holds significance.

Keywords: Copper powder metallurgy composites; B_4C, Si_3N_4 nanoparticles; Dynamic characteristics; Physical characteristics; Vibration modes

Introduction

In recent years, the utilization of powder metallurgy has gained recognition as an efficient method for the production of composites. Powder metallurgy is a widely employed technique that has demonstrated significant efficacy in producing nanocomposites [1, 2]. The powder metallurgy (PM) method can manufacture components with diverse characteristics, such as exceptional strength, resistance to wear, and protection against corrosion. This manufacturing technique finds application in many sectors, including but not limited to the automotive, aerospace, and medical industries [3]. This method facilitates a comprehensive comprehension of the reinforcement's function, grain size impact, and metal matrix nanocomposites' compaction abilities[4]. Metal matrix composites have garnered considerable interest over recent decades owing to their distinctive characteristics, including elevated strength, stiffness, and resistance to wear [5, 6]. Copper-based composite materials have garnered significant interest in metal matrix composites due to their favorable mechanical, thermal, and tribological properties [7-10]. Mechanical alloying, often called powder metallurgy, is a solid-state powder processing technology that involves the repetitive cold welding and fracturing of powder particles within a high-energy ball mill. The application of this methodology is widespread in the fabrication of metal matrix composites due to its ability to achieve a homogeneous distribution of nanoparticles within the matrix material. The event commonly referred to [11-13] is significant. Utilizing a powder metallurgy technique is widely employed in fabricating metal matrix nanocomposites. This procedure entails the compaction of powders at elevated pressures, subsequently followed by sintering to get a fully compacted material possessing enhanced characteristics [14-18]. Saravanan et al.[19], examined powder metallurgy-made copper-alumina nanocomposites' mechanical and dynamic properties. According to the study, copper nanocomposites with alumina particles had higher hardness, tensile strength, and yield strength. The best alumina content for mechanical properties was 1% by weight. The study also indicated that alumina particles increased damping and lowered vibration response over pure copper. The copper-alumina nanocomposite dissipated energy better than pure copper, with a damping ratio 0.052. Kumaran et al. [20] studied powder metallurgy-made copper-graphene oxide nanocomposites' mechanical and dynamic properties. Copper nanocomposites with graphene oxide had better mechanical characteristics. Compared to pure copper, adding 0.5% by weight graphene oxide increased hardness by 9%, tensile strength by 14%, and yield strength by 23%. Wang et al. [21] examined powder-metallurgy-made copper-ZrO_2 nanocomposites' mechanical and dynamic properties. Copper nanocomposites with ZrO_2 have better mechanical qualities, according to the study. Compared to pure copper, adding 0.5% by weight of ZrO_2 increased hardness by 13.5%, tensile strength by 12.3%, and yield strength by 17.4%. The characteristics of copper-graphene nanocomposites manufactured by the powder metallurgy process were examined by [22]. The incorporation of graphene nanosheets into copper was undertaken with the aim of enhancing its mechanical, thermal, and electrical characteristics. The present investigation employed the technique of powder metallurgy to manufacture mono and hybrid nanocomposite matrices for copper-based alloys. Subsequently, dynamic and physical characterization was carried out to assess the performance of the hybrid composites and examine the influence of varying percentages of B_4C and Si_3N_4 nanoparticles on their properties.

Materials and experimental setup

The present study used pure copper powder as the primary matrix, with boron carbide (B_4C) and silicon nitride (Si_3N_4) as reinforcing particles. The particles were meticulously blended using a benchtop planetary ball mill. Nanocomposites and powders were produced by subjecting them to air-ground conditions at a rotational speed of 500 revolutions per minute (rpm) for durations of 1, 5, 10, 15, and 20 hours. A quantity of 15 grams of the powder mixture was introduced into the containers, ensuring that a minimum of 50% of the available area remained unoccupied to allow for the movement of the balls and the transmission of energy to the substance. Additionally, a 1% concentration of stearic acid was employed to prevent the formation of particle aggregates. In the current study, two varieties of composites were produced. The compaction procedure involves the addition of a solution containing 100 ml water and 1 ml ethylene glycol to 5% Cu-B_4C or Cu-Si_3N_4 composites in a mortar to bind the particles together. Following this, a disk measuring 1cm in diameter and with dimensions of 4mm by 0.2mm in thickness was fabricated by pouring the mixture into a cylindrical mold and subjecting it to a pressure of 200 bar for one minute at ambient temperature.

Results and Discussion

Mechanical and Physical Properties

This study uses powder metallurgy composites to evaluate the impact of incorporating B_4C and Si_3N_4 particles into pure copper. Specifically, the focus is examining the effects on porosity levels and observing the resulting microstructure. Including both B_4C and Si_3N_4 particles had a notable impact on the porosity of the composite material consisting of pure copper. The tested samples exhibit an absence of flaws or notable pores. The incorporation of B_4C and Si_3N_4 particles resulted in a decrease in porosity and an enhancement in the microstructural characteristics of the material. The decrease in porosity observed can be due to the uniform dispersion of reinforcing particles obtained using the powder metallurgy technique. Furthermore, the composites' microstructure analysis revealed a uniform distribution of B_4C and Si_3N_4 particles within the copper matrix. The dispersion of particles resulted in the enhancement of the grain structure and a corresponding improvement in the mechanical characteristics of the material.

Bulk and theoretical density of the investigated composites

The findings indicate a negative correlation between the quantity of B_4C and Si_3N_4 additions and the bulk density of the composites. The reduction in the overall density of the composites can be attributed to the occupation of space by the ceramic particles. The bulk density of hybrid composites, which incorporate B_4C and Si_3N_4 additions, is marginally lower than the mono composites that contain only one type of additive. This phenomenon can be attributed to the potential interaction between various ceramic particles, forming a more intricate network of impediments. The findings of this study hold academic importance as they demonstrate that incorporating B_4C and Si_3N_4 additives has the potential to decrease the overall density of copper composites. Maintaining awareness of this aspect is crucial during the design and production of powder metallurgy components, including ceramic additives.

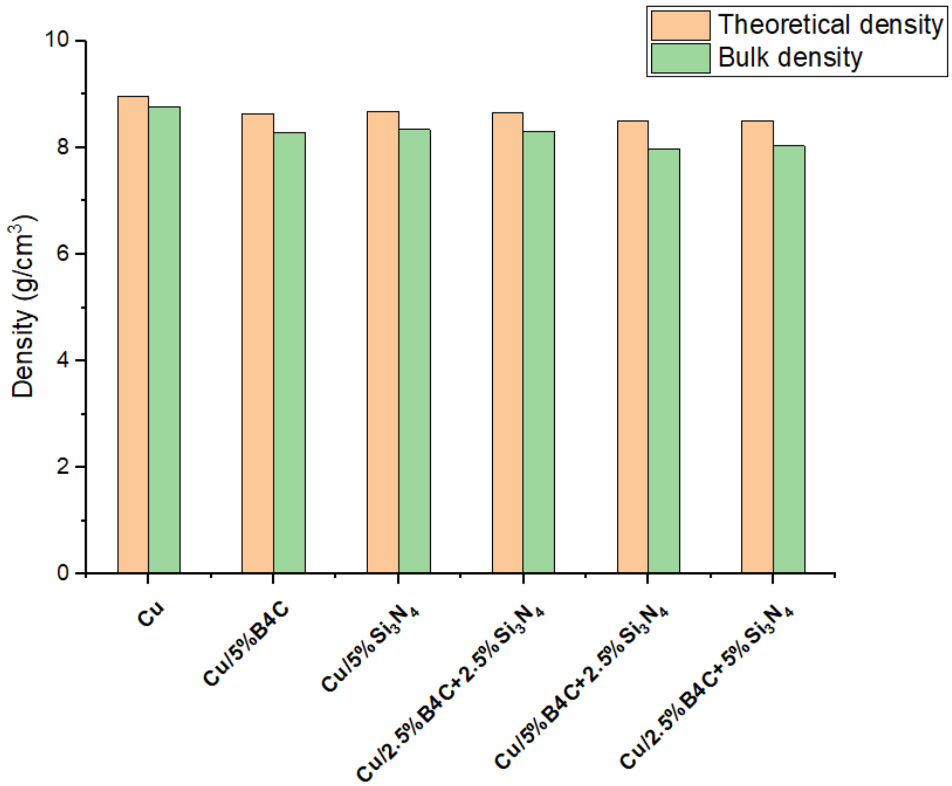

Fig.1 The comparison between the theoretical and bulk density of the investigated samples

Dynamic analysis using finite element method

The present study used a finite element model to examine the dynamic behavior of the manufactured composites. The selection of material attributes was based on prior mechanical properties testing results. The input parameters in the model are determined by calculating Young's modulus, the passion ratio, and density. A rectangular beam with a uniform composition depicting the composite beam. Furthermore, it can be conceptualized as a fundamental metallic element. A comprehensive investigation is conducted on the geometric parameter of the composite beam by a parametric study. The parametric research considered the variability in density and Young's modulus; thus, the boundary condition is imposed by affixing one extremity of the beam. Within the realm of investigating the dynamic properties of a hybrid composite fabricated using powder metallurgy, mode shapes are a significant tool for understanding the deformations and vibrational attributes exhibited by the composite structure. The mode shapes of the composites show that the ceramic particles can affect the copper matrix's vibration in several ways, as illustrated in Table 1. The ceramic particles can localize the vibration in some regions of the composites and interact with each other to form a more complex network of obstacles. By examining mode forms, one can visually perceive the distinct patterns of movement and distortion demonstrated by the constituents of the composite material and how they interact with one another. The more uniform vibration region around the edges of the composite is likely due to the interaction of the ceramic particles with the copper matrix. The ceramic particles scatter the vibration energy, which causes it to spread out more evenly around the edges of the composite. Overall, the fifth mode shape of the Cu-5 vol% B_4C+2.5 vol% Si_3N_4 composite sample shows a complex vibration pattern with localized vibration in multiple composite areas. This is likely due to the interaction of the ceramic particles with each other and the copper matrix, as shown in Fig 2.

Table 2 provides a concise overview of the primary findings derived from the mode shapes of the various composite samples. These observations suggest that the addition of ceramic particles can be used to control the vibration of copper powder metallurgy composites. By selecting the right combination of ceramic particles and their volume fractions, it is possible to achieve the desired mode shape for the composite This information can be used to design powder metallurgy composites for applications where vibration control is important. For example, powder metallurgy composites with localized vibration modes could be used to make components less susceptible to fatigue failure.

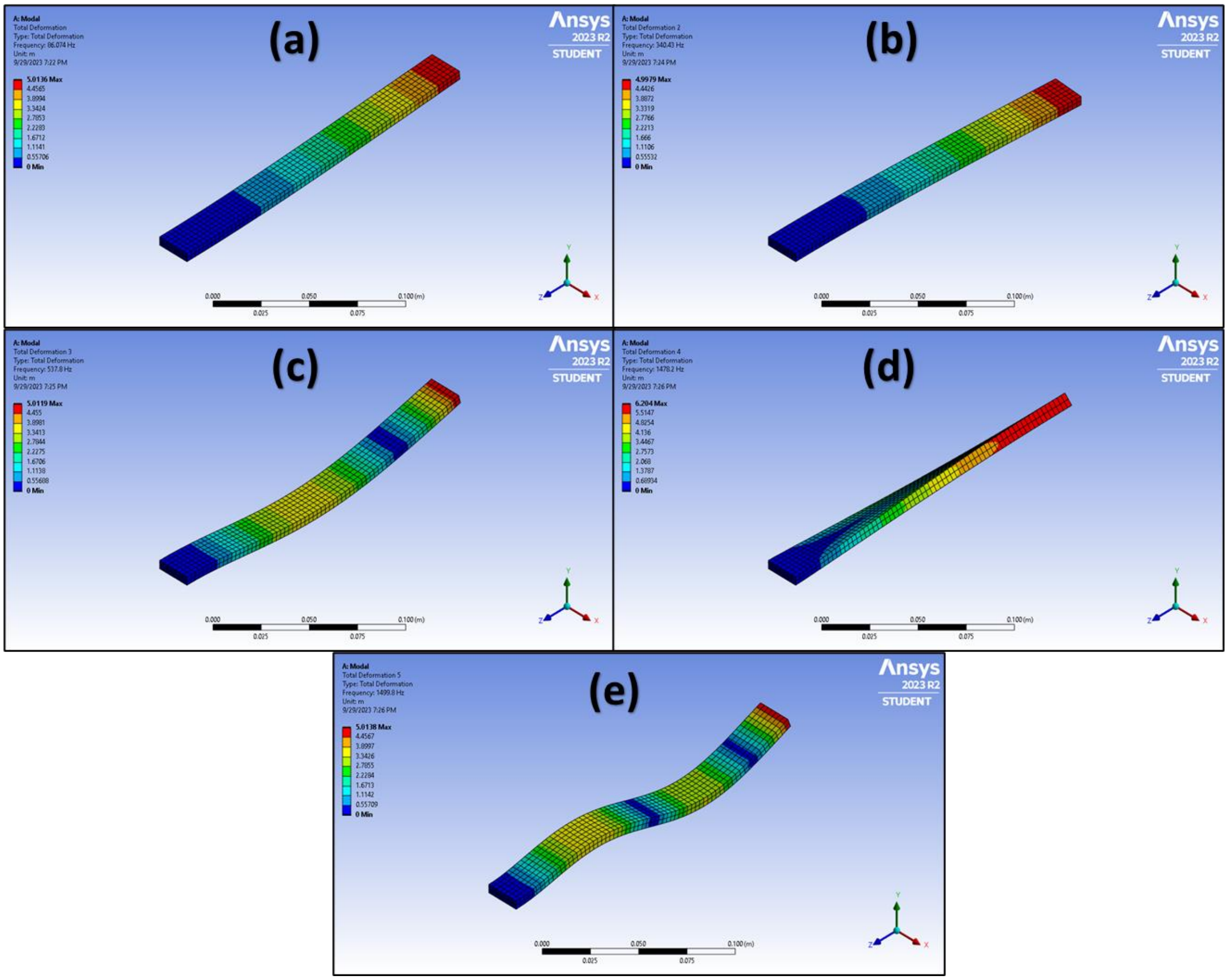

Figure 2: mode shape images of the Cu, 5 vol B_4C+ 2.5 vol Si_3N_4 (a) First mode, (b) Second mode, (c) Third mode, (d) Fourth mode (e) Fifth mode

Figure 3 shows the mode shapes of copper and copper powder metallurgy composites with different amounts of B_4C and Si_3N_4 additives, as simulated using Ansys finite element modeling. The mode shapes of the composites show how the ceramic particles affect the vibration of the copper matrix. The mode shapes of the mono composites (Cu-5 vol% B_4C and Cu-5 vol% Si_3N_4) show that the ceramic particles tend to localize the vibration in certain areas of the composites. This is because the ceramic particles are stiffer than the copper matrix, so they resist vibration more than the copper matrix. The mode shapes of the hybrid composites (Cu-2.5 vol% B_4C-2.5 vol% Si_3N_4, Cu-5 vol% B_4C-2.5 vol% Si_3N_4, and Cu-2.5 vol% B_4C-5 vol% Si_3N_4) show that the ceramic particles can interact with each other to form a more complex network of obstacles.

Table 1: Investigated sample mode shapes and natural frequencies

Investigated Sample	Mode Shape Frequency (Hz)				
	First	Second	Third	Fourth	Fifth
Cu	72.1	285.2	450.4	1240.5	1256.1
Cu -5 vol% B4C	81.7	323.2	510.6	1406.7	1423.8
Cu -5 vol% Si3N4	79.7	315.4	498.1	1375.6	1388.9
Cu -2.5 vol% B4C -2.5 vol% Si3N4	80.4	318.1	502.4	1385.2	1400.9
Cu -5 vol% B4C -2.5 vol% Si3N4	86.1	340.4	537.8	1478.2	1499.8
Cu -2.5 vol% B4C -5 vol% Si3N4	84.4	333.9	527.4	1451.3	1470.7

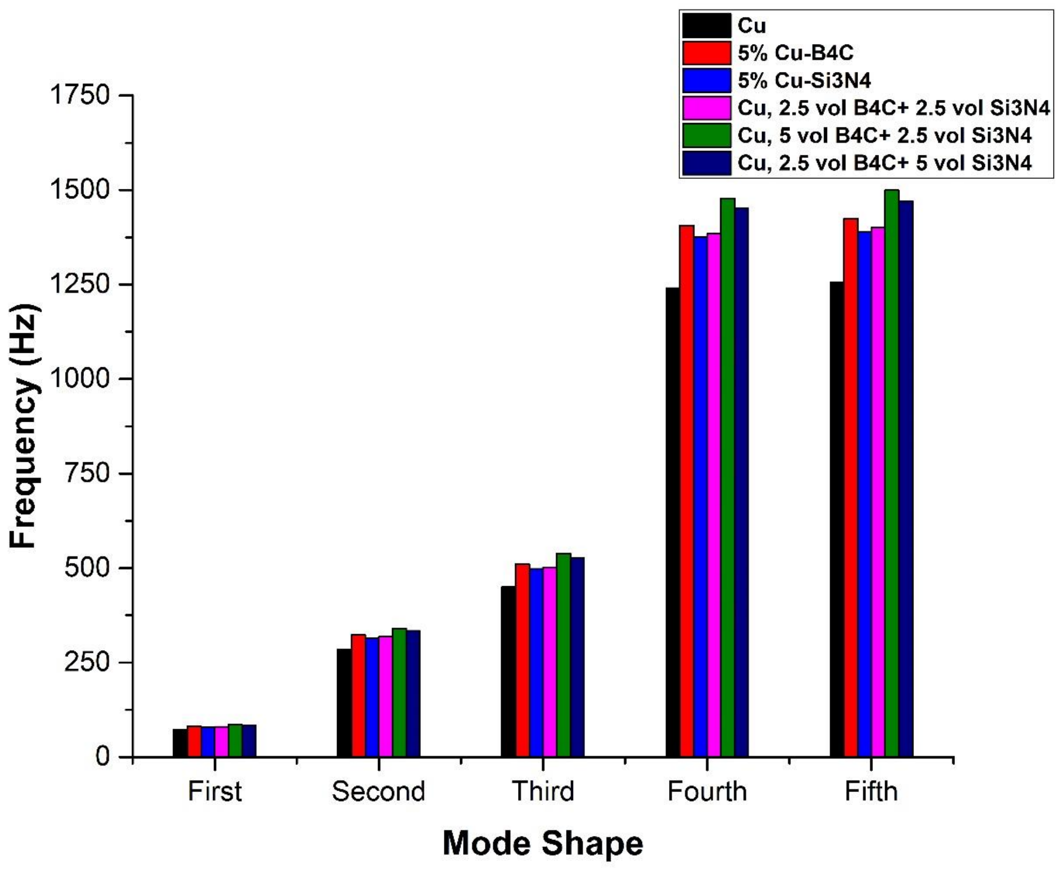

Figure 3: Mode shapes comparison between the investigated samples

Table 2 : Summary of the key observations from the mode shapes of the different composite samples:

Sample	Mode shape	Observations
Cu	Uniform	The copper matrix vibrates uniformly.
Cu-5 vol% B4C	Locally localized	The ceramic particles localize the vibration in certain areas of the composite.
Cu-5 vol% Si3N4	Locally localized	The ceramic particles localize the vibration in certain areas of the composite.
Cu-2.5 vol% B4C-2.5 vol% Si3N4	More localized	The ceramic particles interact with each other to form a more complex network of obstacles, which localizes the vibration more.
Cu-5 vol% B4C-2.5 vol% Si3N4	More localized	The ceramic particles interact with each other to form a more complex network of obstacles, which localizes the vibration more.
Cu-2.5 vol% B4C-5 vol% Si3N4	Most localized	The ceramic particles interact with each other to form the most complex network of obstacles, which localizes the vibration the most.

Conclusion

The findings of this study indicate that the incorporation of ceramic particles into copper powder metallurgy composites offers a viable means of regulating the dynamic and physical characteristics of these composites.

The dispersion of particles led to the augmentation of the grain structure, hence resulting in an associated enhancement of the mechanical properties of the material. Nevertheless, the presence of ceramic particles in the composites leads to a decrease in their total density due to space occupation.

The bulk density of hybrid composites, which include the additions of B4C and Si3N4, exhibits a slight decrease compared to the mono composites consisting of a single additive.

The appropriate mode shape for the composite can be accomplished by carefully selecting ceramic particles and their corresponding volume fractions.

This work's findings indicate that utilizing powder metallurgy composites with regulated vibration modes may present a promising novel category of materials suitable for situations that require effective vibration management.

References

1. Somani, N., et al., *Fabrication of Cu-SiC Composites using Powder Metallurgy Technique.* Materials Today: Proceedings, 2018. **5**(14, Part 2): p. 28136-28141.

2. Leong Eugene, W.W. and M. Gupta, *Characteristics of Aluminum and Magnesium Based Nanocomposites Processed Using Hybrid Microwave Sintering.* Journal of Microwave Power and Electromagnetic Energy, 2010. **44**(1): p. 14-27.

3. Kaviarasu, C. and M. Ravichandran, *Nanomaterials Through Powder Metallurgy: Production, Processing, and Potential Applications Toward Energy and Environment.* Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications, 2021: p. 859-897.

4. Liu, J., et al. *Effect of TiB2 Nanoparticle Content on the Microstructure and Mechanical Properties of TiB2/Mg-4Al-1.5Si Composites*. Materials, 2023. **16**, DOI: 10.3390/ma16072852.

5. Girot, F.A., A.P. Majidi, and T.W. Chou, *Metal Matrix Composites*, in *Encyclopedia of Physical Science and Technology (Third Edition)*, R.A. Meyers, Editor. 2003, Academic Press: New York. p. 485-493.

6. Bedolla-Becerril, E., et al. *Tribological Behaviour of Al-2024/TiC Metal Matrix Composites*. Coatings, 2023. **13**, DOI: 10.3390/coatings13010077.

7. Şap, S., et al., *Investigation on microstructure, mechanical, and tribological performance of Cu base hybrid composite materials.* Journal of Materials Research and Technology, 2021. **15**: p. 6990-7003.

8. Pan, Y., et al., *Tribological and mechanical properties of copper matrix composites reinforced with carbon nanotube and alumina nanoparticles.* Materials Research Express, 2019. **6**(11): p. 116524.

9. Lakshmikanthan, A., et al. *Mechanical and Tribological Properties of Aluminum-Based Metal-Matrix Composites*. Materials, 2022. **15**, DOI: 10.3390/ma15176111.

10. Alazwari, M.A., et al., *Mechanical and wear evolution of in situ synthesized Ti–Cu alloy matrix hybrid composite reinforced by low-cost activated carbon and silica fume waste ceramic for industrial applications.* Journal of Materials Research and Technology, 2023. **22**: p. 2284-2296.

11. Neikov, O.D., *Chapter 3 - Mechanical Alloying*, in *Handbook of Non-Ferrous Metal Powders*, O.D. Neikov, et al., Editors. 2009, Elsevier: Oxford. p. 63-79.

12. Suryanarayana, C., *Mechanical Alloying: A Novel Technique to Synthesize Advanced Materials.* Research. **2019**.

13. Suryanarayana, C., *Mechanical alloying: a critical review.* Materials Research Letters, 2022. **10**(10): p. 619-647.

14. Awotunde, M.A., et al., *Influence of sintering methods on the mechanical properties of aluminium nanocomposites reinforced with carbonaceous compounds: A review.* Journal of Materials Research and Technology, 2019. **8**(2): p. 2432-2449.

15. Reddy, M.P., et al., *Structural, mechanical and thermal characteristics of Al-Cu-Li particle reinforced Al-matrix composites synthesized by microwave sintering and hot extrusion.* Composites Part B: Engineering, 2019. **164**: p. 485-492.

16. Kallip, K., et al., *Microstructure and mechanical properties of near net shaped aluminium/alumina nanocomposites fabricated by powder metallurgy.* Journal of Alloys and Compounds, 2017. **714**: p. 133-143.

17. Schramm Deschamps, I., et al. *Design of In Situ Metal Matrix Composites Produced by Powder Metallurgy—A Critical Review*. Metals, 2022. **12**, DOI: 10.3390/met12122073.

18. AbuShanab, W.S., et al., *Effect of graphene nanoparticles on the physical and mechanical properties of the Al2024-graphene nanocomposites fabricated by powder metallurgy.* Results in Physics, 2020. **19**: p. 103343.

19. Parizi, M.T., et al., *Mechanical and tribological properties of copper-carbon nanotube nanocomposites fabricated by powder metallurgy.* Journal of Materials Engineering and Performance, 2019. **28**(9).

20. Kumaran, S.G., et al., *Mechanical and dynamic behavior of copper-graphene oxide nanocomposites fabricated by powder metallurgy.* Journal of Materials Science, 2017. **52**(17): p. 10262-10275.

21. Wang, Y., et al., *Mechanical properties and dynamic behavior of copper-ZrO2 nanocomposites fabricated by powder metallurgy.* Materials Science and Engineering: A, 2019. **742**: p. 66-74.

22. Ponraj, N.V., et al., *Graphene nanosheet as reinforcement agent in copper matrix composite by using powder metallurgy method.* Surfaces and Interfaces, 2017. **6**: p. 190-196.