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RESEARCH ARTICLE

TAILORED MECHANICAL PROPERTIES OF ALUMINUM-BASED FUNCTIONALLY GRADED CERAMICS COMPOSITES USING VANADIUM CARBIDE AND GRAPHITE REINFORCEMENTS

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Abstract

The study involved the production of Functionally Graded Ceramics (FGCs) using aluminum as the base material and reinforcing it with vanadium carbide (VC) and graphite (G). The research focused on examining the mechanical properties of these FGCs.Adding VC and G significantly improved the compressive strength, bulk modulus, and shear modulus of the FGM composites compared to pure aluminum. The highest compressive strength was achieved with a combination of 5% VC and 10% VC. The increase in bulk and shear modulus is attributed to the presence of VC and G particles, which act as reinforcing phases to disrupt the aluminum matrix's slip planes and increase the composite's load-bearing capacity. These results indicate that FGMs with customized compositions have the potential to serve as promising materials for various engineering applications.

Introduction:-

Functionally graded Ceramics (FGCs) are advanced materials with a continuously varying composition and microstructure along one or more dimensions. This unique property allows FGCs to exhibit a gradient of mechanical properties, enabling them to withstand extreme conditions and perform optimally under various loading scenarios. Powder metallurgy (PM) has emerged as a prominent fabrication technique for FGCs due to its ability to precisely control the composition and microstructure of these materials, leading to significant enhancements in their mechanical properties [1,2]. The fabrication and characterization of FGC composites using powder metallurgy. The authors found that powder metallurgy is an effective method for producing these materials and that the resulting composites have improved mechanical properties[3-5]. Powder metallurgy has emerged as a popular and effective method for fabricating functionally graded materials; the ability of PM to precisely control the composition and microstructure of FGCs makes it a versatile and powerful tool for creating advanced materials with tailored properties for a wide range of applications. [6-8]. Using powder metallurgy as a production approach for functionally graded materials presents a notable advantage in its ability to exert precise control over both composition and mechanical characteristics.Consequently, this method proves to be highly effective in achieving desired outcomes. [9-11].One of the key advantages of FGCs is their ability to mitigate stress concentrations and thermal stresses, which are common causes of material failure. By gradually transitioning between different materials with varying properties, FGCs can effectively distribute stress and minimize stress peaks, enhancing their resistance to cracking and deformation. For instance, an FGC turbine blade can be designed with a ceramic outer layer that can withstand high temperatures and a ductile inner layer that can accommodate thermal expansion and prevent stress-induced cracking[12,13].

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Furthermore, FGMs can demonstrate improved resistance to wear due to their customized composition and microstructure. Integrating durable and abrasion-resistant substances, such as ceramics or metal carbides, into the outermost layer of a Functionally Graded Composite (FGC) can greatly enhance the material's overall ability to withstand wear. To investigate the effect of varying percentages of vanadium carbide (VC) and graphene (GR) reinforcement on the mechanical properties of aluminum-based functionally graded Ceramics(FGCs) fabricated using powder metallurgy.

Experimental Procedure

This study investigated the mechanical properties of FGM composites fabricated using powder metallurgy. We used different combinations of aluminum (Al), vanadium carbide (VC), and graphene (G) as reinforcements.The FGM composites were fabricated using the following steps:Powder mixing: Al, VC, and G powders were mixed in a ball mill for 24 hours.Compaction: The mixed powders were compacted into a shape using a uniaxial compacting press.Sintering: The compacted powders were sintered in a furnace at 500°C for 2 hours.

Results and Discussion:-

Mechanical properties of Functionally Graded Ceramics (FGCs):

The compressive strength of the FGC composites increased with increasing VC and G content. The highest compressive strength was achieved with a combination of 5 % VC and 10 % VC, as shown in Fig. 1. VC is a hard and brittle ceramic reinforcement that increases the load-bearing capacity of the composite. The correlation between the bulk modulus and FGC specimens of aluminum with varying amounts of vanadium carbide (VC) and graphite (G) is being investigated. As the concentration of VC and G increases, the bulk modulus of the FGC sample also increases, as shown in Fig. 2. This is because VC and G are harder and stiffer than aluminum. Hence, their addition to the material increases its resistance to elastic deformation. The results of this study show that the shear modulus of aluminum FGM specimens can be increased by adding VC and G to the material. Since VC and G are stiffer than aluminum, their addition to the material increases its resistance to shear deformation. The increase in shear modulus results from the microstructure of the FGC samples. The VC and G particles are dispersed in the aluminum matrix and act as reinforcing phases. The reinforcing phases disrupt the slip planes of the aluminum matrix and thus make it more difficult for the material to deform under shear stress[14]. The increase in shear modulus depends on the concentration of VC and G in the FGC sample. The higher the concentration of VC and G, the higher the shear modulus of the FGM sample. This is because the reinforcing phases disrupt the slip planes in the aluminum matrix more effectively. The results of this study are consistent with previous research on the effects of VC and G on the shear modulus of aluminum alloys. Previous studies have shown that adding VC and G to aluminum alloys can increase the shear modulus by up to 20%. The results of this study have several implications for the design and development of FGC components.

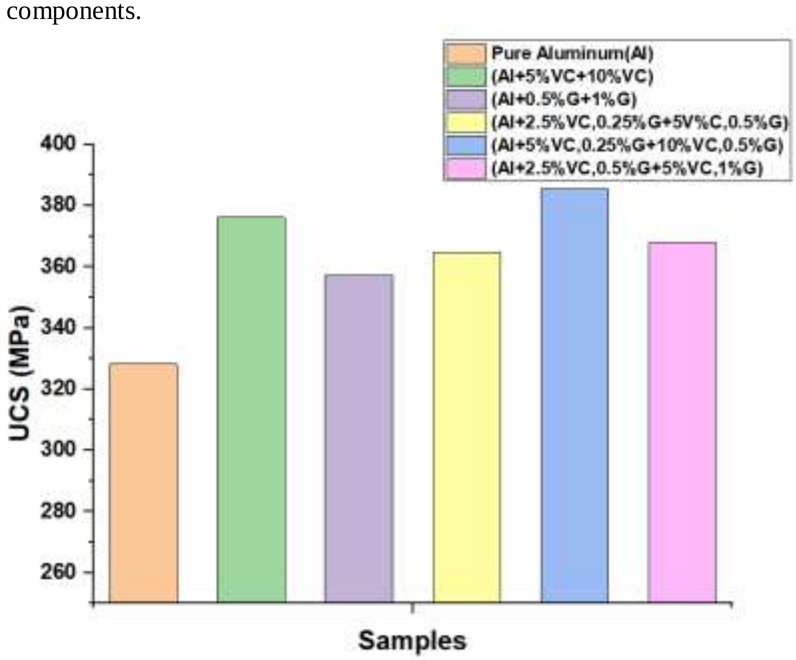

Fig. 1:- Ultimate compression strength.

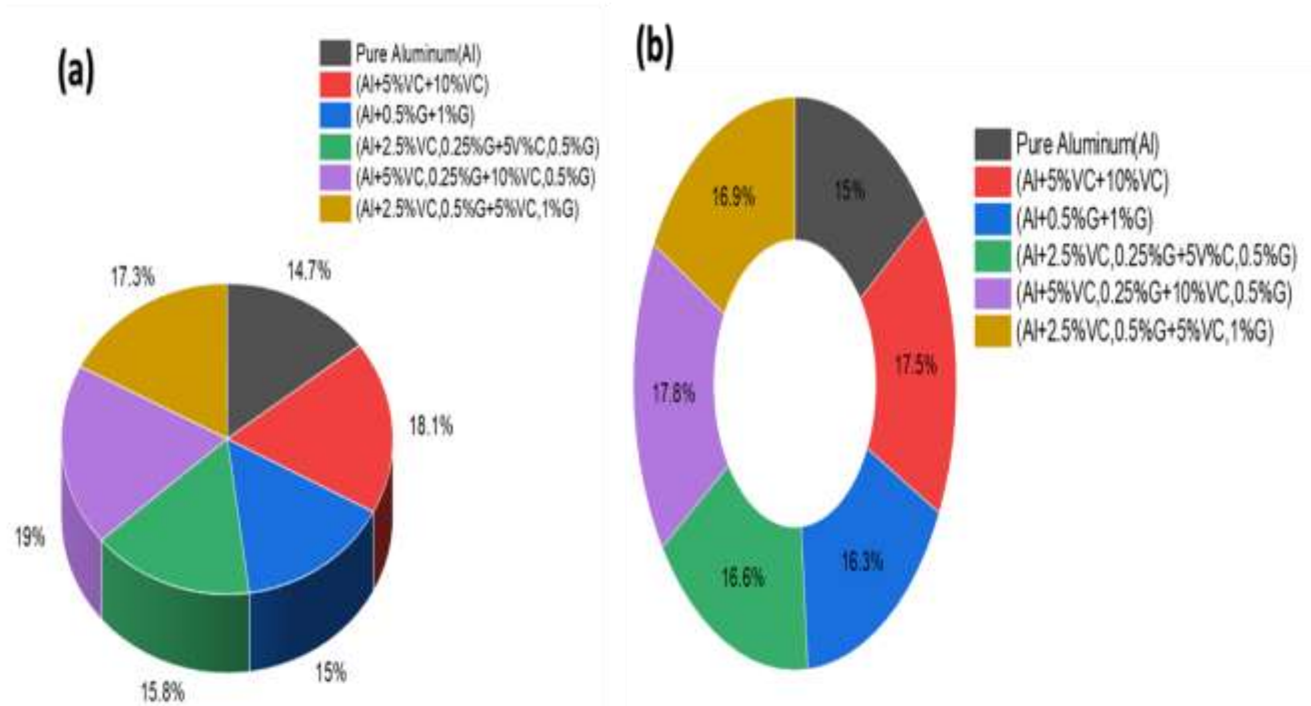

Fig.2:- Mechanical properties (a) bulk modulus, (b) shear modulus.

Thermal Expansion Behavior of Functionally Graded Ceramics (FGCs):
This study investigated the influence of material composition on the thermal expansion of FGCs. Figure 3 depicts the relative length change (dL/L) of FGC samples subjected to temperatures ranging from 50°C to 500°C. The results demonstrate a decreasing trend in dL/L with increasing content of mono and hybrid ceramic reinforcements within the FGC layers. At 300°C, the measured strain (dL/L) for the unreinforced FGC0 material was 7.12×10^{-3}. This value progressively decreased to 4.81×10^{-3}, 5.08×10^{-3}, 4.98×10^{-3}, 4.06×10^{-3}, and 4.38×10^{-3} for samples (Al+5%VC+10%VC), (Al+0.5%G+1%G), (Al+2.5%VC,0.25%G+5V%C,0.5%G), (Al+5%VC,0.25%G+10%VC,0.5%G), and (Al+2.5%VC,0.5%G+5%VC,1%G), respectively.

The observed decrease in thermal expansion with rising reinforcement concentration aligns with the established relationship between these two parameters. Before reinforcement, the CTE values of the FGC samples were $22.3 \times 10^{-6}\ K^{-1}$, $17.7 \times 10^{-6}\ K^{-1}$, $18.5 \times 10^{-6}\ K^{-1}$, $18.0 \times 10^{-6}\ K^{-1}$, $15.4 \times 10^{-6}\ K^{-1}$, and $16.8 \times 10^{-6}\ K^{-1}$, respectively. Reinforcing the second and third layers in the FGCs with materials like aluminum (Al) (CTE = $22.8 \times 10^{-6}\ K^{-1}$) reduced thermal expansion and CTE values compared to unreinforced samples. This can be attributed to the inherently lower CTEs of graphite (G) ($3.2 \times 10^{-6}\ K^{-1}$) and vanadium carbide (VC) ($7.2 \times 10^{-6}\ K^{-1}$) compared to Al. These findings are consistent with previous studies documented in references[15-17]. The significant variations in CTE values observed amongst the FGC samples highlight the dominant role of graphite in influencing the overall thermal expansion behavior compared to vanadium carbide.

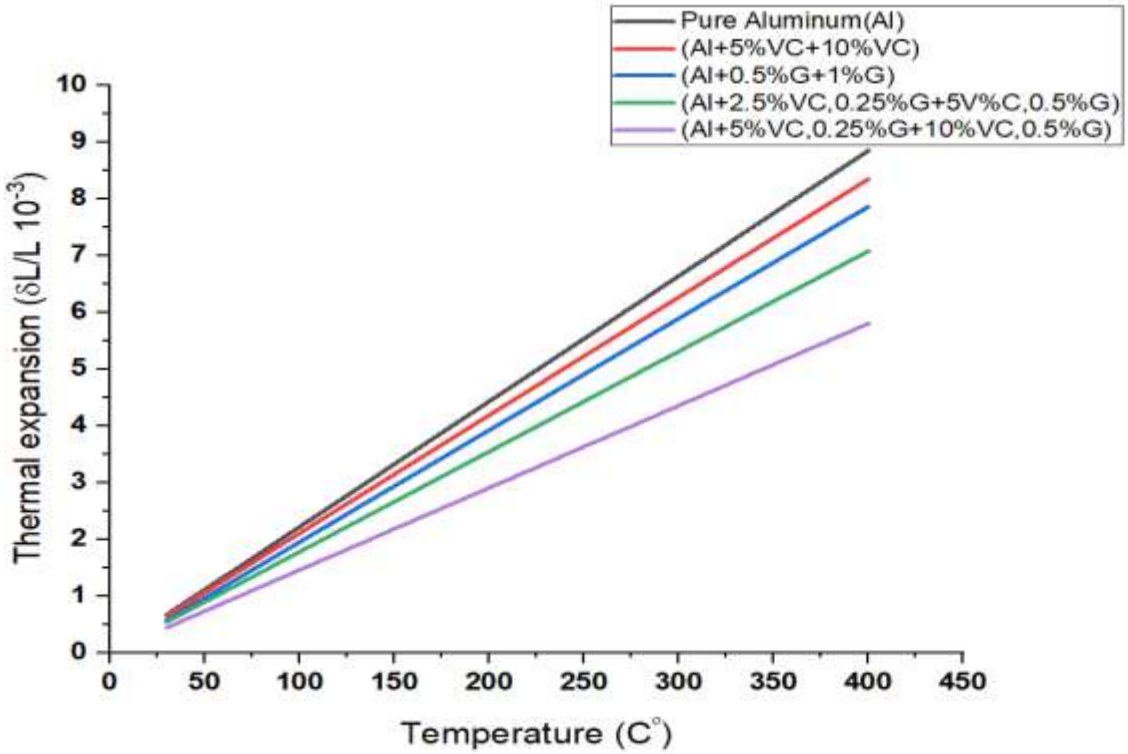

Fig.3:- The changes in the dL/L (relative change in length) of the sintered FGCs samples.

Influence of Reinforcement on Thermal Conductivity in Functionally Graded Ceramics (FGCs)

Figure 4 explores the impact of various reinforcements on the thermal conductivity of FGCs. The unreinforced Al sample exhibited the highest thermal conductivity at 162.1 W/m·K, surpassing all other FGCs except for the graphite (G)-reinforced (Al+2.5%VC,0.25%G+5V%C,0.5%G). Notably, it showcased a thermal conductivity of 171.2 W/m·K, representing a 5.6% increase compared to pure aluminum. In contrast, (Al+5%VC+10%VC) , (Al+2.5%VC,0.25%G+5V%C,0.5%G), (Al+5%VC,0.25%G+10%VC,0.5%G), and(Al+2.5%VC,0.5%G+5%VC,1%G),reinforced with alternative materials, displayed thermal conductivities of 142.4 W/m·K, 158.8 W/m·K, 149.8 W/m·K, and 155.7 W/m·K, respectively. These values translate to 12%, 2%, 7.6%, and 3.9% reductions compared to the unreinforced FGC1.The superior thermal conductivity of (Al+0.5%G+1%G)can be attributed to graphite's inherent high thermal conductivity (2000 W/m·K) compared to aluminum (239 W/m·K)[18,19]..Conversely, the incorporation of vanadium carbide (VC) particles (FGC1) leads to a decrease in thermal conductivity due to its significantly lower value (35 W/m·K) compared to aluminum-based reinforcement. FGC layers reinforced with hybrid ceramics exhibited lower thermal conductivities than those reinforced solely with graphite due to the increased presence of VC, which ultimately reduced the overall conductivity but remained higher than the unreinforced aluminum powder.

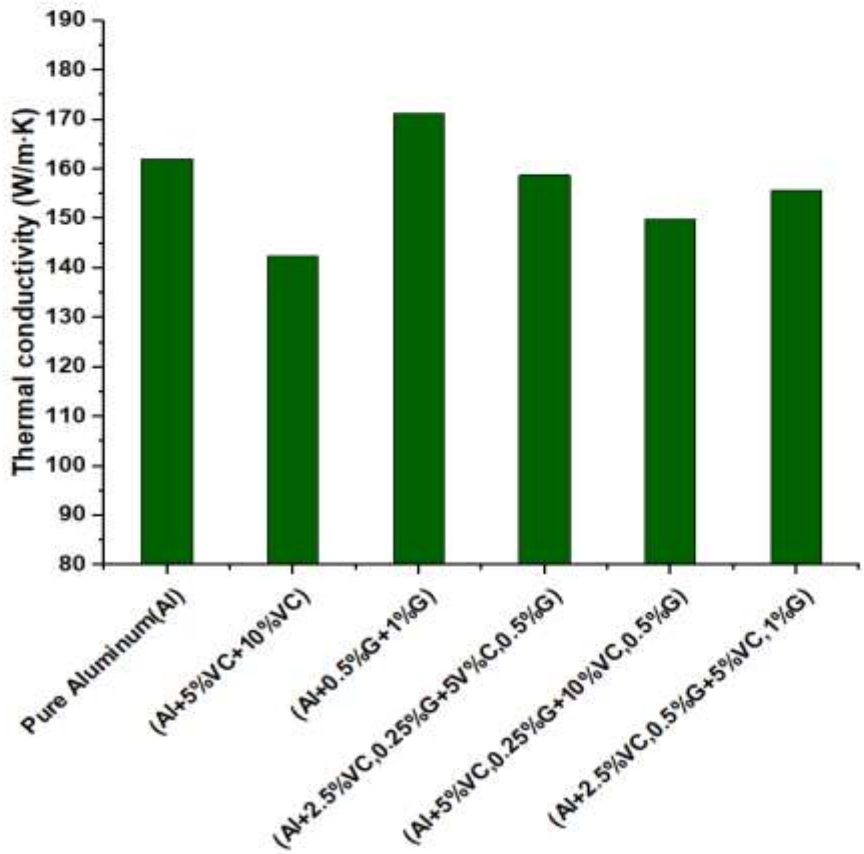

Fig. 4:- Thermal conductivity values of FGC samples.

Conclusion:-

The results of this study show that powder metallurgy is a promising method for fabricating FGM composites with improved mechanical properties.

The addition of VC and G to aluminum can increase the mechanical properties. This increase in shear and bulk modulus results from the FGM samples' microstructure, in which the VC and G particles act as reinforcement phases that disrupt the slip planes in the aluminum matrix. The results of this study have several implications for the design and development of FGM components.

Graphite (G) reinforcement leads to the highest thermal conductivity among the tested materials due to its inherently high thermal conductivity.Conversely, due to its much lower thermal conductivity, vanadium carbide (VC) reinforcement reduces thermal conductivity compared to unreinforced FGC and even FGCs with hybrid reinforcements.Aluminium (Al) based reinforcement offers a middle ground between G and VC, but may not be optimal for maximizing thermal conductivity in FGCs.

References:-

1. Udupa, G.; Rao, S.S.; Gangadharan, K.V. Functionally Graded Composite Materials: An Overview. Procedia Materials Science 2014, 5, 1291-1299, doi:https://doi.org/10.1016/j.mspro.2014.07.442.

2. El-Galy, I.M.; Saleh, B.I.; Ahmed, M.H. Functionally graded materials classifications and development trends from industrial point of view. SN Applied Sciences 2019, 1, 1378, doi:10.1007/s42452-019-1413-4.

3. Takahiro, K.; Hisashi, S.; Eri, M.-F.; Yoshimi, W. New Processing Routes for Functionally Graded Materials and Structures through Combinations of Powder Metallurgy and Casting. In Advances in Functionally Graded Materials and Structures, Farzad, E., Ed.; IntechOpen: Rijeka, 2016; p. Ch. 2.

4. Ismail, N.; Asif Iqbal, A.; Mat Yahya, N.; Sakib, M.N. Fabrication And Characterization of Al/ Sic/ Gr Hybrid Metal Matrix Composite Fabricated By Powder Metallurgy. Journal of Modern Manufacturing Systems and Technology 2022, 4, 98-105, doi:10.15282/jmmst.v4i2.7156.

5. Purohit, R.; Dewang, Y.; Rana, R.S.; Koli, D.; Dwivedi, S. Fabrication of magnesium matrix composites using powder metallurgy process and testing of properties. Materials Today: Proceedings 2018, 5, 6009-6017, doi:https://doi.org/10.1016/j.matpr.2017.12.204.
6. Akshaya, S.L.; Prakash, A.; Bharati Raj, J. Applications of Functionally Graded Materials in Structural Engineering—A Review. In Proceedings of the Proceedings of SECON 2020, Cham, 2021//, 2021; pp. 553-566.
7. Saleh, B.; Jiang, J.; Fathi, R.; Al-hababi, T.; Xu, Q.; Wang, L.; Song, D.; Ma, A. 30 Years of functionally graded materials: An overview of manufacturing methods, Applications and Future Challenges. Composites Part B: Engineering 2020, 201, 108376, doi:https://doi.org/10.1016/j.compositesb.2020.108376.
8. Matuła, I.; Dercz, G.; Sowa, M.; Barylski, A.; Duda, P. Fabrication and Characterization of New Functional Graded Material Based on Ti, Ta, and Zr by Powder Metallurgy Method. Materials 2021, 14, doi:10.3390/ma14216609.
9. Hassan, A.; Abood, A.; Khalaf, H.; Farouq, W.; Khazal, H. A review of functionally graded materials including their manufacture and applications. The International Journal of Mechanical Engineering and Sciences 2022, 7, 744-755.
10. Yoshimi, W.; Hisashi, S. Review Fabrication of Functionally Graded Materials under a Centrifugal Force. In Nanocomposites with Unique Properties and Applications in Medicine and Industry, John, C., Ed.; IntechOpen: Rijeka, 2011; p. Ch. 7.
11. Panchal, Y.; K, P. Functionally graded materials: A review of computational materials science algorithms, production techniques, and their biomedical applications. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 2022, 236, 10969-10986, doi:10.1177/09544062221109261.
12. Li, Y.; Feng, Z.; Hao, L.; Huang, L.; Xin, C.; Wang, Y.; Bilotti, E.; Essa, K.; Zhang, H.; Li, Z.; et al. A Review on Functionally Graded Materials and Structures via Additive Manufacturing: From Multi-Scale Design to Versatile Functional Properties. Advanced Materials Technologies 2020, 5, 1900981, doi:https://doi.org/10.1002/admt.201900981.
13. Wang, Y.; Liu, Q.; Zhang, B.; Wang, H.; Hazell, P.J.; Han, Z.; Li, J.; Li, B.; Li, L.; Liu, F.; et al. Ballistic performance of functionally graded B4C/Al composites without abrupt interfaces: experiments and simulations. Journal of Materials Research and Technology 2023, 25, 1011-1029, doi:https://doi.org/10.1016/j.jmrt.2023.06.021.
14. Arora, R.; Sharma, A.; Kumar, S.; Singh, G.; Pandey, O.P. Compressive strength of the mineral reinforced aluminium alloy composite. AIP Conference Proceedings 2016, 1728, 020630, doi:10.1063/1.4946681.
15. El-Zaidia, M.M.; Zaki, M.Z.; Abomostafa, H.M.; Taha, M.A. Comprehensive studies for evaluating promising properties of Cu/graphene/fly ash nanocomposites. Sci Rep 2024, 14, 2236, doi:10.1038/s41598-024-52563-w.
16. Moustafa, E.B.; Ghandourah, E.; Youness, R.A.; Melaibari, A.A.; Taha, M.A. Ultralight Functionally Graded Hybrid Nanocomposites Based on Yttrium and Silica-Reinforced Mg10Li5Al Alloy: Thermal and Tribomechanical Properties. Materials (Basel) 2022, 15, doi:10.3390/ma15249052.
17. Moustafa, E.B.; Elsheikh, A.H.; Taha, M.A. The effect of TaC and NbC hybrid and mono-nanoparticles on AA2024 nanocomposites: Microstructure, strengthening, and artificial aging. Nanotechnology Reviews 2022, 11, 2513-2525, doi:10.1515/ntrev-2022-0144.
18. Moustafa, E.B.; Abdel Aziz, S.S.; Taha, M.A.; Saber, A.-H. Influence of Graphene and Silver Addition on Aluminum's Thermal Conductivity and Mechanical Properties Produced by the Powder Metallurgy Technique. Metals 2023, 13, doi:10.3390/met13050836.
19. Zhang, L.; Hou, G.; Zhai, W.; Ai, Q.; Feng, J.; Zhang, L.; Si, P.; Ci, L. Aluminum/graphene composites with enhanced heat-dissipation properties by in-situ reduction of graphene oxide on aluminum particles. Journal of Alloys and Compounds 2018, 748, 854-860, doi:https://doi.org/10.1016/j.jallcom.2018.03.237.