Study of Mechanical and Fatigue Behaviors of Nano Scaled B_4C and Al_2O_3 Strengthened Aluminum Matrix Composites AMCs

Salim Azeez Kako

Authors affiliations:
1) Erbil Polytechnic University, Erbil -Iraq.
salim.kako@epu.edu.iq

Paper History:

Received: 23rd Mar. 2022

Revised: 18th May 2022

Accepted: 2nd Sep. 2022

Abstract

The study here under describes the impact of adding a nano-scaled ceramic particles on the mechanical and fatigue behaviors of aluminum matrix composites AMCs containing 0.5 ,1.0 ,1.5, and 2 % wt. of nano-scaled B_4C and Al_2O_3 particles were dispersed in molten aluminum by the stir-casting process. Vickers, tensile, and fatigue devices were utilized to evaluate the mechanical behavior of composites in the fabrication process. The results show that increasing the weight percentage of nano-ceramic particles increased the hardness, maximum tensile stress, and fatigue strengths of the base alloy. Furthermore, all of the above behaviors of AMCs reinforced with B4C particles are better than those of AMCs reinforced with Al_2O_3 particles.

Keywords: Hardness, Ultimate tensile stress, Aluminum matrix composites, nano- ceramic particles.

دراسة الخواص الميكانيكية و الكلال للمواد المتراكبة ذات الاساس المنيوم المقواة بجسيمات نانوية كربيد البورون و اوكسيد الالمنيوم

سالم عزيز كاكو

الخلاصة:

يصف هذا البحث تأثير إضافة دقائق السيراميك ذات القياس النانوي على الخصائص الميكانيكية والكلال لمواد متراكبة ذات اساس الومنيوم AMCs التي تحتوي على 0.5 ، 1.0 ، 1.5 ، و 2 ٪ نسب وزنية من جسيمات كربيد البورون و اوكسيد الالمنيوم B4C و Al_2O_3 النانوية والتي تم اضافتها و دمجها الى مصهور الألومنيوم بطريقة الصب بالخلط . استخدمت اجهزة فيكرز و الشد و الكلال لفحص الخواص المواد المتراكبة المصنعة . أظهرت النتائج أن الصلادة و مقاومتي الشد و الكلال للمادة المقواة تزداد مع زيادة النسب الوزنية لكلا النوعين من جسيمات المادة النانوية المضافة كربيد البورون و اوكسيد الالمنيوم وان خواص المواد المقواة بجسيمات كربيد البورون B_4C كانت افضل من تلك التي تم تقويتها بجسيمات اوكسيد الالمنيوم Al_2O_3 .

الكلمات المفتاحية : الصلادة ،مقاومة الشد القصوى ، مواد متراكبة ذات اساس المنيوم ،جسيمات نانوية سيراميك.

1. Introduction

Metal Matrix Composite (MMC) is a novel type of engineering material in which a strong ceramic reinforcement is dispersed into a metal matrix to enhance behaviors such as strength, elastic modulus , tribological characteristics, excellent corrosion resistance, and high fatigue properties that are impossible to obtain in bulk metals or super alloys[1][2] . MMCs are composed of metals or alloys as matrix phase and particles or whiskers, continuous or discontinuous fibers as reinforcement. There are many reinforcements have been used as functional reinforcement for promoting the mechanical properties of aluminum-based alloys AlN [3], TiO_2[4] , Al_2O_3 [5], SiC [6], and B_4C [7] .

MMCs combine the metallic features of matrix alloys (ductility and toughness) with the ceramic behaviors of reinforcements (high strength and modulus), resulting in increased shear and compression strength [8].

MMCs can be fabricated by different manufacturing processes , including mechanical alloying [9] , powder metallurgy and various melting processes [10]. Melting process which includes the dispersion of ceramic reinforced particles into molten metals and alloys offers certain significant advantages, such as stronger matrix-particle bonding, easier matrix structure control, simplicity, and cheap processing cost when compared with the powder metallurgy. However, the melting process has two

NJES is an **open access Journal** with **ISSN 2521-9154** and **eISSN 2521-9162**
This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License

fundamental problems which are first, the poor wet ability between the molten metal matrix and ceramic particles, and secondly, the ceramic particles tend to be float over the surface of the molten matrix and this due to their low density in compare with the liquid metal, hence, the dispersion of the ceramic particles will not be uniformly as required.

AMCs strengthened with dispersion ceramic particles such as SiC, B4C or Al2O3 are gradually grown and increasingly employed in variety of new applications. They are considered competitive to other materials in many industry fields such as automotive industries like (connecting rods, pistons, cylinder heads), and airplanes due to their improvement against the fatigue failure.[11] .

Fatigue failure usually occurs in a numerous of machine components as well as structures subjected to dynamic and variable loads. Under these conditions , the failure can occur at a stress level that is much lower than the tensile or yield strength for a static load Furthermore, it is both catastrophic and insidious, happening very quickly without forewarning[12][13].

2. Literature review:

A lot of researches have been done to study the mechanical characteristics of AMCs reinforced with nano-ceramic and their fabrication. Alalkawi et al. [14]touched upon using the stir casting technique to manufacture a 10% wt% of Al_2O_3 nano-composites by adding 50nm Al_2O_3 nano-ceramic particles to the 6061 Al alloy. The experimental results observed that the addition of 10 wt% Al_2O_3 improved constant and cumulative fatigues. The experimental outcomes displayed that the dispersion of 10 wt% Al_2O_3 enhance constant and cumulative fatigues. While Faisal and Kumar [15] studied the effect of the presence of nano-SiC on the mechanical & tribological behaviors of AMCs containing 0, 0.5, 1, 1.5, 2, and 2.5 wt.% of nano scaled SiC which are added by mechanical stirring . The results showed that adding these particles had increased wear resistance, tensile strength, elastic modulus, shear modulus, and flexural shear modulus, as well as increased brittle behavior. Meanwhile, Venkatesh and Deoghare [16] created an aluminum-kaoline composite using a powder metallurgical method.

They reported that the addition of hard ceramic particles like Al_2O_3 and SiO_2 in Kaoline improved the hardness, tensile, and compression strength of the manufactured composite. Srivyas and Charoo [17] reviewed different reinforcements , fundamental mechanical and tribological behavior on AMCs in dry and lubricated sliding circumstances. It has been demonstrated that various metal matrix reinforcements may be used to reduce friction and wear in tribological implementations. Bodunrin et al. [18] tried to investigate the various reinforcing material blending used in the manufacture of hybrid AMCS .The findings of this study on different reinforcements are encouraging, since they showed a significant improvement in the properties of the composites produced when compared to the unreinforced alloy.

This study aims to investigate the mechanical and fatigue property of the AAl6061 alloy strengthened with B_4C and Al_2O_3 particles.

2. Experimental work

1- Materials

The matrix material in this study was AAl6061 alloy, which has a wide range of uses , easy to fabricate[19], while 50nm B_4C particles and 50nm Al_2O_3 particles with weight fractions (0.5, 1 , 1.5 , and 2) wt % were employed as reinforcements[20]. Spectro Spark Analyzer machine (CE, Gmb and KG Co., Germany, 2008) was used for the chemical analysis of the AAl6061 alloy. The chemical analysis of materials is shown in Table1.

Table (1): The chemical analysis of (AAl6061), composition in wt %

Element	Mg	Fe	Si	Cu	Mn	V	Ti	Al
Weight %	2.26	0.17	0.6	0.32	0.8	0.52	0.01	Balance

2. Composite Synthesis and Testing Procedure

Initially, 750 grams of AAl6061 alloy were charged into the crucible in tiny cut pieces and heated in an electrical resistance furnace to 700 degrees. After melting 1% magnesium coated with aluminum foil was added to molten alloy with the aim of increasing more wettability of the alloy[21][22] . Also, 0.5, 1, 1.5, and 2% of preheated nano-scaled B_4C were added to the molten mixture and mixed with mechanical stirring until the mixture reached semi-past stage with the goal of achieving good particle distribution in the molten alloy. Finally, the mixture was poured into metallic mold. The billets were air cooled to room temperature after fabrication. Al_2O_3 particles were used in the same way[23] . The resulted composites and unreinforced base alloy billets were machined out to tensile tests [ASTM] and fatigue samples on CNC lathe machine showed in Figs (1) and (2). The surface of samples was grinded on 1000 grit abrasive papers .X-ray diffraction XRD and scanning electron microscope were used for recognizing the base alloy and investigation changings in its structure after adding and dispersion reinforcements in it. Micro-hardness testing for the produced composites was performed using a vickers diamond indenter. The load was applied for 15 seconds. The test was done three times, with the average being kept. While tensile testing machine was used for measuring tensile strengths of base alloy and composite samples. Fatigue samples were tested on fatigue tester machine MT3012, Germany. The tester is driven by an induction squirrel cage motor 3000 r.p.m. On one side, the motor is coupled to a counter mechanism that reads a seven-digit number, and on the other side, it is tied to a shaft with a conical fixture for holding fatigue samples.

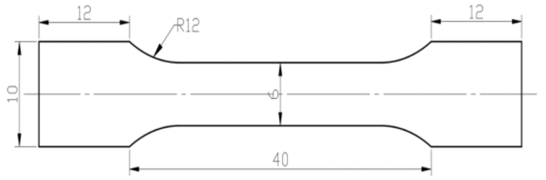

Fig. (1): shows tensile sample

Fig. (2): shows fatigue sample

The loading device is made up of a spherical ball bearing and a tiny switch that shuts down the motor when a failure occurs.

The loading on the test sample is increased by turning the loading wheel clockwise. The loading is measured using a spring balance (F). The value of (F) was discovered to be as follows.

$\sigma_{bending} = FL / d^3$ [24] ……………(1)

$\sigma_{bending} = 0.4$ б σ_{max} ….……..……... (2)

Where: $\sigma_{bending}$ is the bending stress in MPa
F is the applied load in N at the free end of the samples
L and d are the length and diameter of the fatigue sample
σ_{max} is the ultimate tensile stress in MPa for aluminum alloy = 310 MPa.

Fatigue samples subjected to different stresses 50,100,150,200,250,300,350 and 400 MPa, On the other hand, the number of cycles during which the test samples were subjected to fracture was recorded.

4. Results and Discussion:

The fabricating AMCs which containing ceramic particles during casting process is typically problematic due to poor wettability and agglomeration of nanoparticles in the melting alloy. Figure (3) XRD pattern shows Al6061 aluminum solid solution. While figure (4), SEM shows the developed AMCs. Regular distribution and dispersion of nanoparticles besides agglomerated nanoparticles of B_4C were seen in the base matrix.

XRD pattern of the Al_2O_3 reinforced composite presented in Figure (5). It shows that the fabricated composite is consisting of aluminum and Al_2O_3 in addition to spinel (Al Al_2O_3Mg). These phases are formed after the casting and fabrication of the AMCs which all shall modify the properties of the composite.

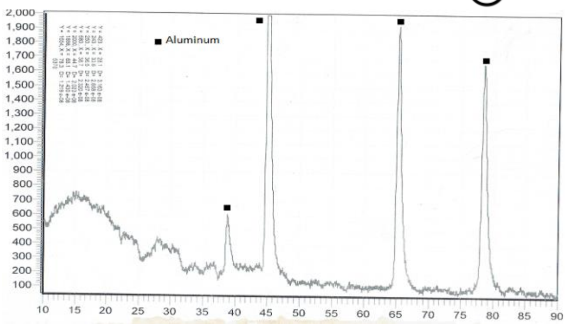

Fig. (3): Explains X-ray diffraction pattern for nano Al_2O_3 reinforced AMCs

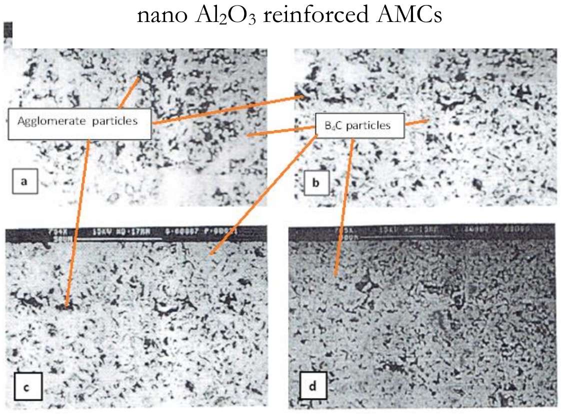

Fig. (4): SEM micrographs showing particle distribution in (a) 0.5 wt% B_4C, (b) 1 wt% B_4C, (c) 1.5 wt% B_4C, and (d) 2 wt% B_4C

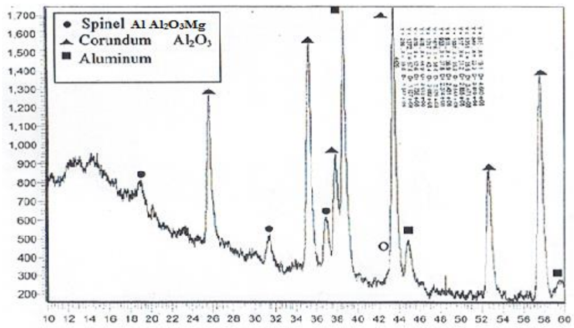

Fig. (5): Shows X-ray diffraction pattern for nanoparticles Al_2O_3 reinforced AMCs.

Figs. (6) and (7) show the result of micro-Vickers hardness number and the ultimate tensile stress of base alloy and composites versus weight fraction of ceramic particles. It was recorded that the hardness and maximum tensile stress of composites are higher than the base alloy because of the function of nano-ceramic reinforcements in the aluminum. These particles act as: firstly, the ceramic particles tend to prevent the mobility of the grain boundaries and limit the grain growth. Secondly, the change in deformation of hard ceramic particles and soft aluminum matrix during plastic deformation assists in the fragmentation of grains. It was also shown that hardness and maximum tensile stress of B_4C reinforced composite is higher than Al_2O_3 because the hardness and stiffness of B_4C higher than Al_2O_3.

Furthermore, the thermal expansion coefficients of B_4C are different. Additionally, the variation in the coefficient of thermal expansion for B_4C and Al_2O_3 ($4.5 *10^{-6}$ /°C for B_4C and $8.8 * 10^{-6}$ /°C for Al_2O_3) also is another factor in reducing the hardness.

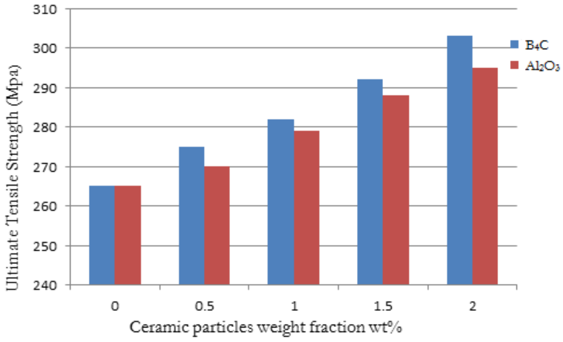

Fig. (6): Shows ultimate tensile strength versus ceramic particles weight fraction

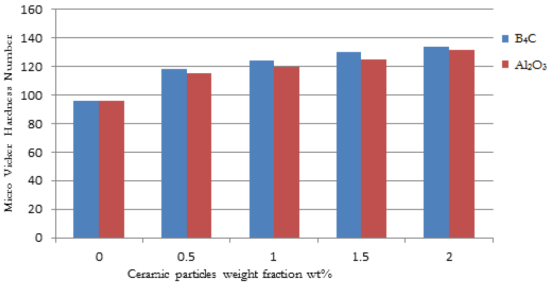

Fig. (7): Shows micro-Vickers number versus ceramic particles weight fraction

Fig. (8), Fig. (9) and Fig. (10) indicate the result of cycles to failure versus composites weight fraction of nano-ceramic particles. The number of cycles to failure increase with increasing of weight percentage of reinforcement due to addition and dispersion of these reinforcement particles in the base alloy. These particles block the movement of dislocations and produce a definite strengthening effect. The average block increase with increasing weight fractions of reinforcement. Also, it was shown that the cycles to failure of AMCs reinforced with B_4C are slightly greater than AMCs reinforced with Al_2O_3 particles. This is attributed to the high mechanical properties of B_4C particles compared with Al_2O_3 particles in which the ultimate tensile strength of B_4C and Al_2O_3 is 6.5 GPa and 1.5 GPa. At the same time Vickers hardness for B_4C and Al_2O_3 is 2500 kg/mm^2 and 1100 kg/mm^2 respectively.

Figures (11) and (12) indicated the relation between the cycles to failure versus fluctuating stress for the base alloy and AMCs. Increasing cycles to failure result from elastic–plastic fracture mechanism. This mechanism causes the nucleation and growth of a crack due to the applied cyclic stress. Due to this reason the fatigue failures seem occur so suddenly that the bulk of the changes in the material are not visible. Also, it seems that the unreinforced base alloy and AMCs do not have a fatigue limit because of external factors (such as: the internal structure of material, the alignment of sample, the general shape the sample test, the surface roughness of the sample under stress), in addition to the external factors (fabricating and specifications).

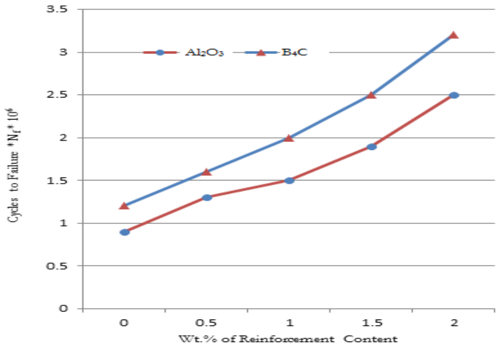

Fig. (8): Cycles to failure versus ceramic particles weight fraction wt% under 50 MPa

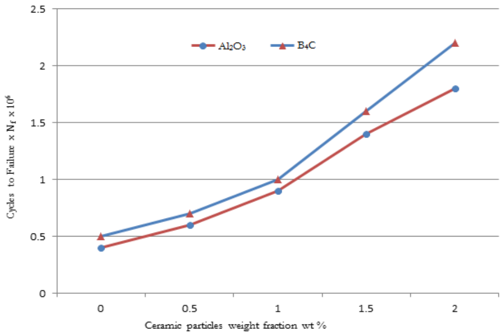

Fig. (9): Cycles to failure versus ceramic particles weight fraction wt% under 250

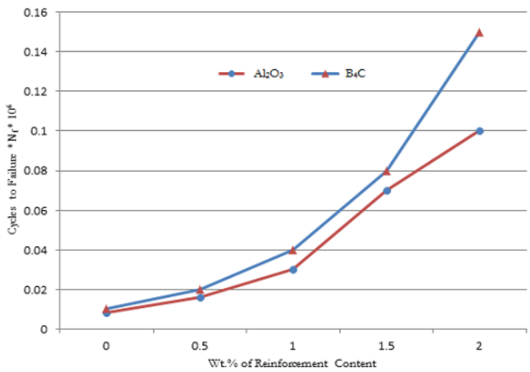

Fig. (10): Cycles to failure versus Ceramic particles weight fraction wt% under 400 MPa

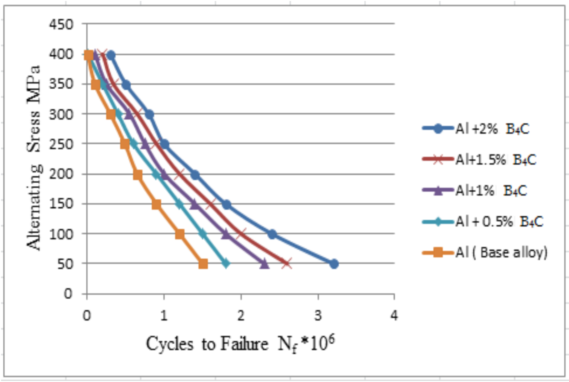

Fig (11): Alternating stress versus cycles to failure for AMCs strengthened with B_4C particles

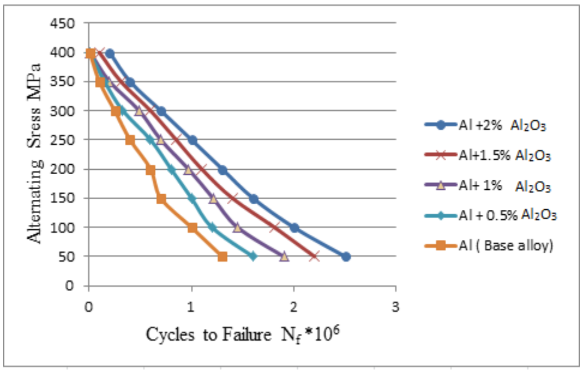

Fig (12): Alternating stress versus cycles to failure for AMCs strengthened with Al_2O_3 particles

5. Conclusions

In this investigation, the impact of addition 0.5%,1%,1.5%,2% B_4C and Al_2O_3 nano-scaled ceramic on mechanical properties and fatigue behavior of AA6061 alloy were studied. The ceramic inclusion had shown noticeable improvements in mechanical behaviors (i.e., hardness and maximum tensile stress). and fatigue behavior.

- The hardness value of AMCs increased with increasing of wt% of ceramic particles.
- The maximum tensile stress of AMCs increased up to 303 MPa.
- The hardness value and maximum tensile stress of AMCs reinforced with nano-scaled B_4C is a little bit higher than nano-scaled Al_2O_3
- The addition of 0.5%,1%,1.5%,2% B_4C and Al_2O_3 nano-scaled ceramic cause improvement in the fatigue life of the AA6061.

6. References

[1] K. Subramanian, S. Murugesan, D. G. Mohan, and J. Tomków, "Study on dry sliding wear and friction behaviour of al7068/si3n4/bn hybrid composites," *Materials (Basel).*, vol. 14, no. 21, pp. 1–14, 2021, doi: 10.3390/ma14216560.

[2] J. Singh and A. Chauhan, "A review on sliding wear behaviour of aluminium matrix composites with hybrid reinforcements for automotive applications," *Tribol. Online*, vol. 9, no. 3, pp. 121–134, 2014, doi: 10.2474/trol.9.121.

[3] I. P. Fesenko, P. S. Kisly, M. A. Kuzenkova, T. O. Prikhna, V. K. Sulzhenko, and S. N. Dub, "Properties of AIN-TiN composite ceramics," *Br. Ceram. Trans.*, vol. 99, no. 6, pp. 278–279, 2000, doi: 10.1179/096797800681090.

[4] N. K. Bhoi, H. Singh, and S. Pratap, "Developments in the aluminum metal matrix composites reinforced by micro/nano particles – A review," *J. Compos. Mater.*, vol. 54, no. 6, pp. 813–833, 2020, doi: 10.1177/0021998319865307.

[5] Y. Yang, Z. Zhang, and X. Zhang, "Processing map of Al 2O 3 particulate reinforced Al alloy matrix composites," *Mater. Sci. Eng. A*, vol. 558, pp. 112–118, 2012, doi: 10.1016/j.msea.2012.07.092.

[6] V. Umasankar, "Experimental evaluation of the influence of processing parameters on the mechanical properties of SiC particle reinforced AA6061 aluminium alloy matrix composite by powder processing," *J. Alloys Compd.*, vol. 582, pp. 380–386, 2014, doi: 10.1016/j.jallcom.2013.07.129.

[7] R. Liu, W. Wang, H. Chen, M. Tan, and Y. Zhang, "Microstructure evolution and mechanical properties of micro-/nano-bimodal size B4C particles reinforced aluminum matrix composites prepared by SPS followed by HER," *Vacuum*, vol. 151, pp. 39–50, 2018, doi: 10.1016/j.vacuum.2018.01.052.

[8] H. Ahamed and V. Senthilkumar, "Role of nano-size reinforcement and milling on the synthesis of nano-crystalline aluminium alloy composites by mechanical alloying," *J. Alloys Compd.*, vol. 505, no. 2, pp. 772–782, 2010, doi: 10.1016/j.jallcom.2010.06.139.

[9] K. N. Antin and K. Jalava, "Mechanical properties of cast aluminium matrix composites reinforced with SiC and Al2O3 particles," *ICCM Int. Conf. Compos.*, pp. 19–24, 2015.

[10] R. Taherzadeh Mousavian, R. Azari Khosroshahi, S. Yazdani, D. Brabazon, and A. F. Boostani, "Fabrication of aluminum matrix composites reinforced with nano- to micrometer-sized SiC particles," *Mater. Des.*, vol. 89, pp. 58–70, 2016, doi: 10.1016/j.matdes.2015.09.130.

[11] A. E. Nassar and E. E. Nassar, "Properties of aluminum matrix Nano composites prepared by powder metallurgy processing," *J. King Saud Univ. - Eng. Sci.*, vol. 29, no. 3, pp. 295–299, 2017, doi: 10.1016/j.jksues.2015.11.001.

[12] F. Pelayo, A. Skafte, M. L. Aenlle, and R. Brincker, "Modal Analysis Based Stress Estimation for Structural Elements Subjected to Operational Dynamic Loadings," *Exp. Mech.*, vol. 55, no. 9, pp. 1791–1802, 2015, doi: 10.1007/s11340-015-0073-6.

[13] T. Dawson, V. Johnson, P. Miller, M. Morabito, M. Schultz, and G. W. Swain, "Chapter 12 - Fatigue," *EN380 Navel Mater. Sci. Eng. Course Notes*, pp. 1–13.

[14] H. J. M. Alalkawi, A. A. Hamdany, and A. A. Alasadi, "Influence of Nanoreinforced Particles (Al_2O_3) on Fatigue Life and Strength of Aluminium Based Metal Matrix Composite," *Al-Khwarizmi Eng. J.*, vol. 13, no. 3, pp. 91–99, 2017, doi: 10.22153/kej.2017.03.005.

[15] N. Faisal and K. Kumar, "Mechanical and tribological behaviour of nano scaled silicon carbide reinforced aluminium composites," *J. Exp. Nanosci.*, vol. 13, pp. S1–S13, 2018, doi: 10.1080/17458080.2018.1431846.

[16] V. S. S. Venkatesh and A. B. Deoghare, "Fabrication and mechanical behaviour of Al-Kaoline metal matrix composite fabricated through powder metallurgy technique," *Mater. Today Proc.*, vol. 38, no. November 2020, pp. 3291–3296, 2020, doi: 10.1016/j.matpr.2020.10.021.

[17] P. D. Srivyas and M. S. Charoo, "Role of Reinforcements on the Mechanical and Tribological Behavior of Aluminum Metal Matrix Composites - A Review," *Mater. Today Proc.*, vol. 5, no. 9, pp. 20041–20053, 2018, doi: 10.1016/j.matpr.2018.06.371.

[18] M. O. Bodunrin, K. K. Alaneme, and L. H. Chown, "Aluminium matrix hybrid composites: A review of reinforcement philosophies; Mechanical, corrosion and tribological characteristics," *J. Mater. Res. Technol.*, vol. 4, no. 4, pp. 434–445, 2015, doi: 10.1016/j.jmrt.2015.05.003.

[19] A. Sharma, V. M. Sharma, B. Sahoo, J. Joseph, and J. Paul, "Study of nano-mechanical, electrochemical and raman spectroscopic behavior of al6061-sic-graphite hybrid surface composite fabricated through friction stir processing," *J. Compos. Sci.*, vol. 2, no. 2, pp. 1–17, 2018, doi: 10.3390/jcs2020032.

[20] X. N. Zhang, L. Geng, and G. S. Wang, "Fabrication of Al-based hybrid composites reinforced with SiC whiskers and SiC nanoparticles by squeeze casting," *J. Mater. Process. Technol.*, vol. 176, no. 1–3, pp. 146–151, 2006, doi: 10.1016/j.jmatprotec.2006.03.125.

[21] A. Sangghaleh and M. Halali, "Applied Surface Science Effect of magnesium addition on the wetting of alumina by aluminium," vol. 255, pp. 8202–8206, 2009, doi: 10.1016/j.apsusc.2009.05.044.

[22] R. Casati and M. Vedani, "Metal matrix composites reinforced by Nano-Particles—A review," *Metals (Basel).*, vol. 4, no. 1, pp. 65–83, 2014, doi: 10.3390/met4010065.

[23] I. Dinaharan, "Influence of ceramic particulate type on microstructure and tensile strength of aluminum matrix composites produced using friction stir processing," *Integr. Med. Res.*, 2016, doi: 10.1016/j.jascer.2016.04.002.

[24] S. T. Advisors and M. Science, "Tention and fatigue behavior of Al-2124/SiC Particulate Matrix Composites," 2019.