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Studying on the fatigue behavior of Al- Al_2O_3 metal matrix nano composites processed through powder metallurgy

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ABSTRACT

Excellent mechanical properties and fatigue performance of Al/Al_2O_3 metal-based nanocomposites caused to introduce this material as a good candidate for various applications. In this regard, the preparation and characterization of this composite can be considered as a hot issue for research. The study was carried out in several steps including: (i) preparation of Al/Al_2O_3 metal-based nanocomposites at various Al_2O_3 content as reinforcement (4, 6 and 8 wt.%) using wet attrition milling; (ii) hot forward extrusion process of prepared samples; (iii) determination of mechanical properties of prepared composite by tensile test; (iv) usage of rotating-bending fatigue test for determination of the fatigue performance of prepared composite and (v) analysis of the fracture surfaces of fatigue tests specimens to determine the mechanism/s of failure based on scanning electron microscope analysis. The results showed that the presence of Al_2O_3 nanoparticles up to 6 wt.% enhanced the fatigue strength of Al/Al_2O_3 nanocomposites while the higher amount of reinforcement has a detrimental effect on the fatigue strength. Also, the statistical nature of fatigue data confirmed the higher coherency as well as homogeneity of prepared composites by 6 wt.% of reinforcement. The EDX spectrum confirmed the presence of Al_2O_3 at the origin of crack. As a consequence, the most probable mechanisms for crack initiation through the cyclic loading can be considered as the fracture and/or detachment of reinforcement particles.

Keywords: *Aluminum; Nanocomposite; Powder metallurgy; Extrusion; Fatigue strength*

1. Introduction

Unique characteristics of metal matrix composites combined with simple production process proposed these materials as good candidates for production at industrial scale. According to the literature [1-10], the type, size, shape, distribution, volume fraction and coherency of reinforcement to the matrix have administrated effects on the fatigue performance of prepared composites. Aluminum matrix nano-composites (Al MMNCs) are a wide category of engineering material that uses Al_2O_3 nanoparticles (with the size lower than 100 nm) as reinforcement and considering as a hot issue for many researches [11-15].

Fatigue failure during the cyclic loading in many engineering instruments is inevitable. In this regards, investigation of fatigue behavior of Al MMNCs during the dynamic loading plays a key role in design, material selection, forecasting the life of components and its durability [16-20].

It is worth to note that, the mechanical properties (using tensile test) and tribological characteristics of

Al MMNCs were the subjects of various researches [21-25] while, in spite of the importance of fatigue behavior of such components, little investigations were carried out in these categories [26]. There are various techniques for the production of metal matrix nanocomposites (MMNCs) including solid-state processes (e.g., high energy ball mill and powder metallurgy techniques) [27]; liquid-state (e.g., casting processes, stir casting, ultrasonic-assisted casting) [28]; semi-solid processing (e.g., a combination of rheo-casting, squeeze casting and semi-solid route stir casting) [29]. Outstanding specifications of hot extrusion including excellent preferential axial alignment of discontinuous fibers and large compressive hydrostatic state of stress [30-33] caused to evolve this technique as the most promising approach for the preparation of MMNCs [34-36]. Senthilkumar et al. [37] fabricated Al/Al_2O_3 composites using hot extrusion process. They used nano and micron size of Al_2O_3 particles as reinforcement. Analysis of low cycle fatigue data of prepared samples revealed that the usage of reinforcement in nano scale showed better fatigue performance respect to the samples that used Al_2O_3 with micron size. The main contributions of the current study can be considered as the investigation of the effect of the presence of various amounts of reinforcement, i.e., Al_2O_3 nanoparticle, on the fatigue behavior of prepared Al/Al_2O_3 nanocomposites and illustration of a comperhensive study on the fatigue behavior (low cycle fatigue and high cycle fatigue) of prepared composites.

2. Materials and Methods

Air atomized commercial pure aluminum powder (powder size of 45 μm) and α- Al_2O_3 powder (the average powder size of 35 nm, Nanostructured& Amorphous Materials, Inc.) were used as raw materials. The samples were prepared using the powder metallurgy technique. Before starting the milling process, the agglomeration of reinforcement, viz. Al_2O_3 nanoparticles, was inhibited by utilization of ultrasonic vibration in ethanol slurry for 60 min. As the next step, the prepared Al_2O_3 solution was added to the Al powder and milled for 8 hr by attrition ball mill. This study used hardened steel balls with a diameter of 5 mm, the ball to powder ratio of 15/1 and rotational speed of 480 rpm. Various samples including pure aluminum and nanocomposites with 4, 6 and 8 wt.% of Al_2O_3 nano-particles were prepared. The consolidation process was carried out as follows: (1) drying of prepared samples for 90 min at 150 °C; (2) production of billets using uniaxial single action compaction at the pressure of 140 MPa; (3) final densification process to provide a dense rod with the diameter of 10 mm by employment of hot forward extrusion technique at 600 °C with reduction ratio equal 2.7/1; (4) the surfaces of prepared samples were polished by sandpaper # 600, 1200 and 3000, respectively to remove all surface defects including scratches and key defects. Scanning electron microscope (SEM, Leica Cambridge S360) was employed to investigate the fracture surfaces of prepared samples. The theoretical densities of prepared composites were calculated by mixture rule. The mechanical properties were determined by uniaxial tensile test and micro-hardness test. The load and dwell time of microhardness were supposed as 25 g and 15 sec, respectively. It was worth to note that, the uniaxial tensile tests were done parallel to the extrusion direction according to ASTM E8 using a gauge length of 20 mm. Fig. 1 schematically showed the geometry of the tensile test. Instron 8802 testing machine with a crosshead speed of 0.05 cm/min was used at the room temperature. The fracture surfaces of specimens were investigated by SEM. The relative density of prepared samples determined using Archimedes water immersion method. The fatigue behavior of prepared samples was investigated by the rotating-bending fatigue test based on ASTM E466. Fig. 2 illustrates the geometry of the fatigue test sample. The rotating fatigue machine (HSM19D, P.A. Hilton Ltd) with high-speed testing 6000 rpm was used at room temperature.

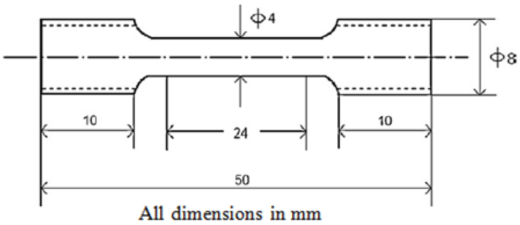

Fig. 1- Schematically representation of tensile test specimens according to ASTM E8.

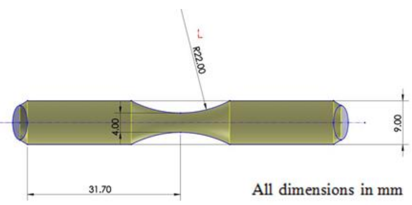

Fig. 2- Schematically representation of fatigue test specimens on the base of ASTM E466.

3. Results and discussion

The relative density of consolidated samples as a function of wt.% of reinforcement was shown in Fig. 3. Accordingly, the relative density showed an increasing trend where the Al_2O_3 wt.% changed from zero to 6 wt.%, while this trend was inverted at following up to 8 wt.%. It was worth to note that, the metallic bonding of Al as matrix has higher tendency for cold work respect to the combination of ionic-covalent bonding of Al_2O_3 as reinforcement. The lower content of Al_2O_3 (up to 6 wt.% Al_2O_3) enhanced the possibility of filling pores of prepared composites. As a consequence, the relative density in these composites enhanced. Since, the agglomeration of nanoparticles is an effective physical process for the reduction of its surface energy, it seems that in the case of 8 wt.% Al_2O_3, agglomeration of reinforcement was intensified and decreased the relative density of prepared samples. Also, the lower range of error bare of the prepared sample with 6 wt.% Al_2O_3 respect to the other samples can be considered as an evidence of higher uniformity of this sample. Fig. 4 shows the micro-hardness of various prepared composites. Accordingly, the presence of Al_2O_3 (up to 8 wt.%) dramatically enhanced the micro-hardness of prepared samples [38-40]. It seems that Al_2O_3 nanoparticles decrease the dislocation motion in prepared samples. Comparison of yield strengths and ultimate tensile strengths in Fig. 4 revealed that the presence of reinforcement effectively enhanced the strength of prepared composites. According to the Orowan bowing mechanism, the tensile strength of metal matrix composites strongly dependent on the interaction between the dislocation and reinforcement particles. Eqs. 1 and 2 showed the correlation between the strength and dislocation characteristics. In which, G is shear modulus, L, b, d, and V are the interparticle spacing, Burger's vector, grain diameter of the reinforcements and volume fraction of particles, respectively. Since, the matrix and reinforcement of composites have various thermal expansions, enhanced the density of dislocation in the structure. If ρ, ΔC, ΔT defined as dislocation density, thermal mismatch, and temperature changes, respectively, then dislocation density can be calculated using Eq. 3. The strength of prepared composites can be calculated using Eq. 4 in which G and b are the shear modulus of composite and Burgers vector, respectively. Also, α is a constant between 0.5 and 1.

$$\Delta\sigma = 2Gb/L \quad \text{(eq. 1)}$$

$$L = 0.6d(\frac{2\pi}{V})^{0.5} \quad \text{(eq. 2)}$$

$$\rho = 12\Delta T\Delta CV/bd \quad \text{(eq. 3)}$$

$$\sigma_d = \alpha Gb\rho^{\frac{1}{2}} \quad \text{(eq. 4)}$$

By consideration of the thermal mismatch among the structural component of MMNCs and Orowan bowing mechanism can be concluded that lowering the particle size induced higher strength to the prepared composites. It was necessary to note that, due to the lower particle size of reinforcement, the occurrence of the Orowan bowing mechanism was more probable. On the other hand, large enough variation between the processing and test temperature-induced considerably thermal expansion coefficient mismatch in the prepared composites.

Figure 5 shows the S-N curves of product samples. As can be seen, there is not any clear fatigue limit in all prepared composites. Accordingly, the fatigue strength of prepared samples in 10^7 cycles

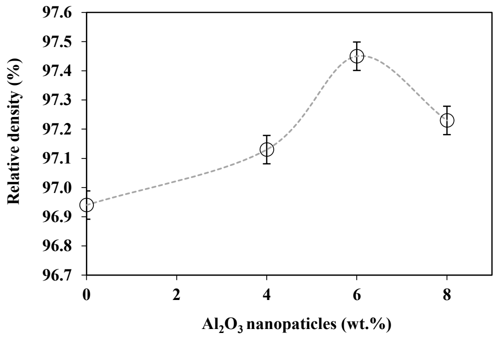

Fig. 3- Relative density of various Al/Al_2O_3 prepared nanocomposites.

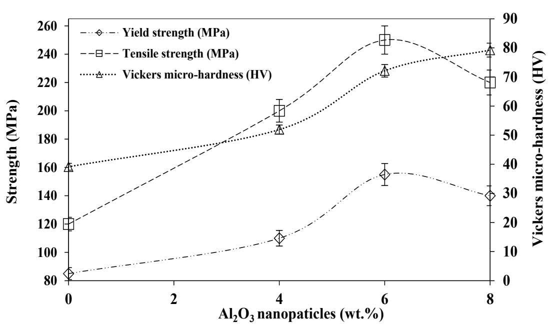

Fig. 4- The changes of strength and Vickers micro-hardness of Al/Al_2O_3 prepared nanocomposites as a function of wt.% of Al_2O_3 as reinforcement.

considered as fatigue strength. The absence of institutional atoms including C, H, N, and O is the main reason for the absence of a sharp fatigue limit. Similar behaviors have been reported in Al alloys [41, 42]. Boxplot used to illustrate the distribution of S-N data for low cycle fatigue (LCF) and high cycle fatigue (HCF) as shown in Fig. 5. As a general trend, at the constant stress levels, all samples showed the wider distribution in HCF respect to LCF. This behavior can be related to the higher effect of microstructure on fatigue behavior in the HCF regime. In these regards, the wider distribution of fatigue data in HCF of Al- 8 wt.% Al_2O_3 can be related to the higher possibility of agglomeration in this sample respect to the Al- 6 wt.% Al_2O_3. Also, the average number of cycles to the fracture of Al- 6 wt.% Al_2O_3 was nearly the same as the median and confirmed the uniformity of these samples. It was worth to note that, similar to Al- 8 wt.% Al_2O_3, the median of pure Al and Al- 4 wt.% Al_2O_3 were significantly different from the average and can be considered as inhomogeneity of these samples.

Table 1 abbreviated various mechanical properties of prepared composites obtained from tensile and fatigue tests. Accordingly, the presence of Al_2O_3 up to 6 wt.% enhanced the strength and ductility of prepared samples, effectively. Also, the comparison of fatigue strength in 10^7 cycles showed

Table 1- Mechanical propeties of prepared composites

Sample	Yield strength (MPa)	Tensile strength (MPa)	%Elongation	σ_a(MPa)	Fatigue strength at 10^7 cycles (MPa)
Al -0 wt.% Al_2O_3	85	120	35	80	32
Al- 4 wt.% Al_2O_3	110	200	31	130	48
Al-6 wt.% Al_2O_3	155	250	28	165	72
Al-8 wt.% Al_2O_3	140	220	25	145	67

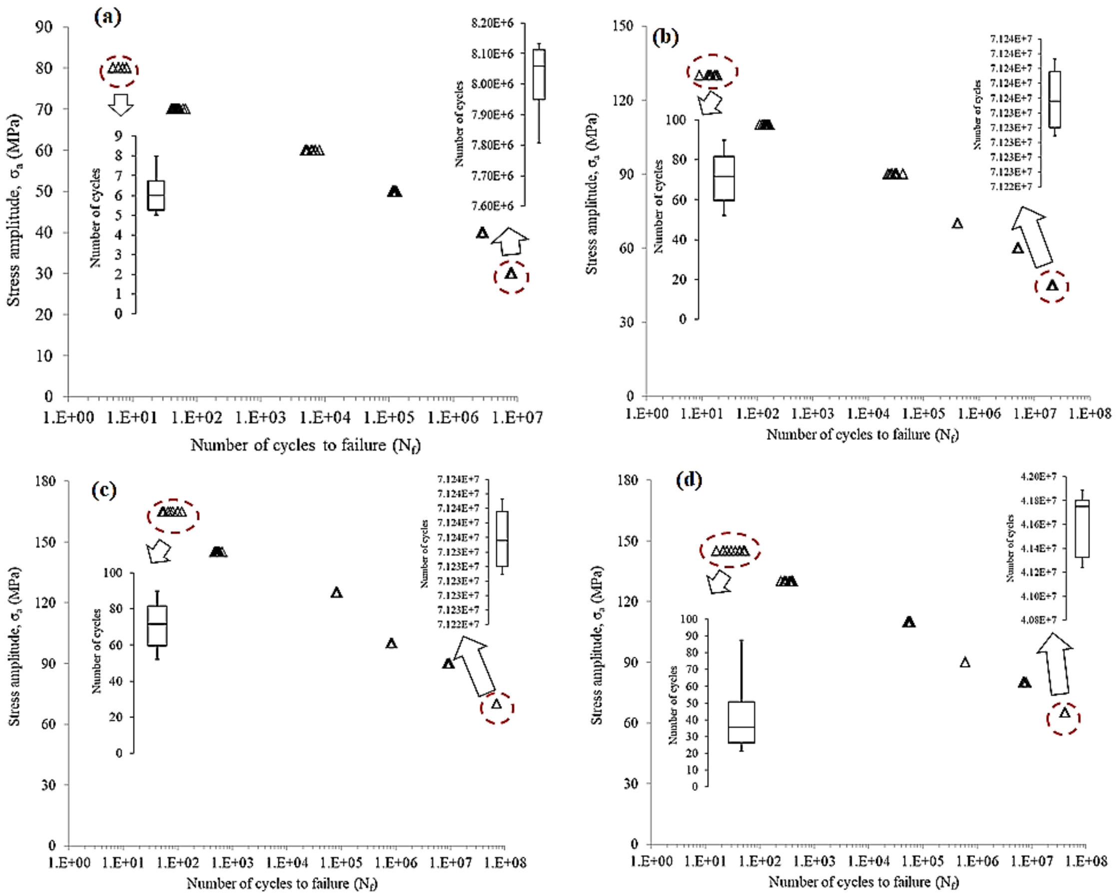

Fig. 5- S-N curves for (a) Al, (b) Al- 4 wt.% Al_2O_3, (c) Al- 6 wt.% Al_2O_3 and (d) Al- 8 wt.% Al_2O_3.

that using 6 wt. % Al_2O_3 as reinforcement can be enhanced the fatigue strength to be about 125% respect to the pure sample. Since, all engineering materials inherently have the micro-cracks, the main part of fatigue life related to the crack propagation respect to the crack initiation. There are three different mechanisms for the control of fracture in metal matrix composites including (i) nucleation of voids and growth, (ii) fracture of reinforcement particles and (iii) interfacial decohesion.

As shown in Fig. 6, all of fatigue cracks initiated from the surface defects and extended to the core of sample. Also, higher values of reinforcement enhanced the possibility of agglomeration as well as the creation of a continuous Al_2O_3 brittle phase through the grain boundary.

According to the literature [43-50], there are four major sources for crack initiation as follows:

i) Through the first period of cyclic loading, due to the intrinsic brittleness of reinforcement particles, micro cracks were initiated due to the fracture of reinforcement particles. The high rate of strain concentration as a consequence of incoherency between the surrounding matrix and reinforcement particles intensified this behavior;

ii) The detachment of reinforcement from matrix especially at the interface between the reinforcement and matrix can be considered as the second possible mechanism for the crack initiation through the cyclic loading. In this case, the cluster of particles can act as single large particles that effectively prevented from the plastic flow through the loading and enhanced the possibility of crack initiation;

iii) Fracture of large foreign particles, e.g. inclusion and/or intermetallic, rather than reinforcement, are the other responsible for the crack initiation. From one hand, the large size of these phases (about 20 to 100 μm) and from the other hand their brittle nature enhanced the possibility of crack initiation in this mechanism;

iv) Crack initiation can be formed due to the aggregation of cavities and porosities through prolonged cyclic loading. These defects were formed typically from incomplete penetration of the matrix material into the particle clusters.

As shown in Fig. 7, the size of dimples that formed in fractured surfaces decreased by the amount of reinforcement. Fig. 7(d), confirmed the formation of micro-cracks in Al- 8 wt.% Al_2O_3 samples. Consequently, due to the presence of Al_2O_3

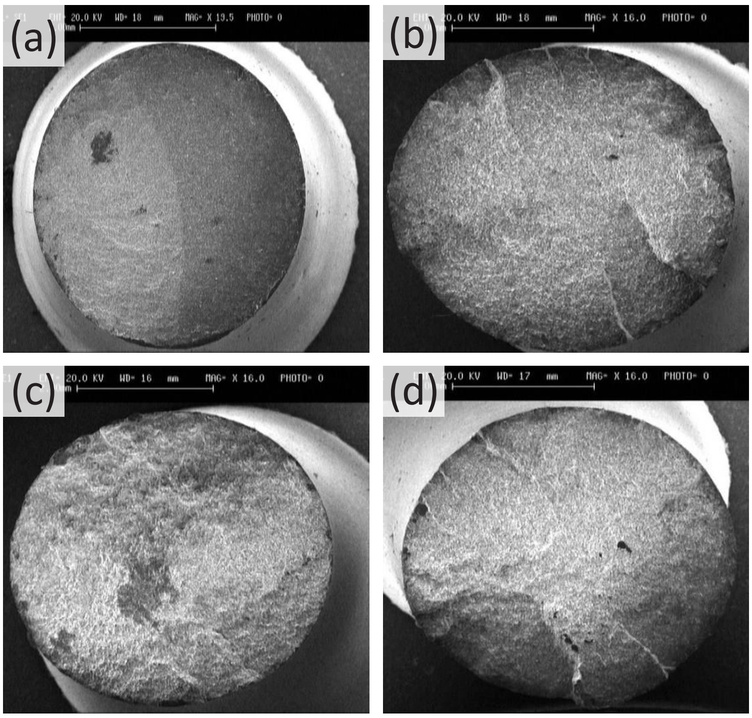

Fig. 6- Fracture surface of the specimens: (a) Al, (b) Al- 4 wt.% Al_2O_3, (c) Al- 6 wt.% Al_2O_3 and (d) Al- 8 wt.% Al_2O_3.

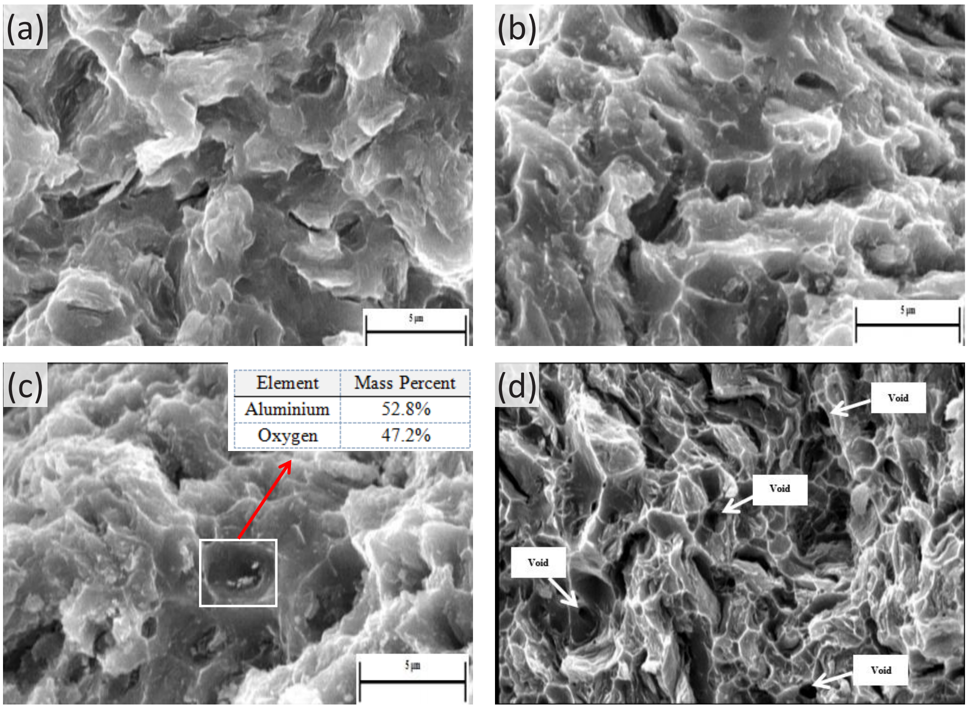

Fig. 7- Fracture surface of the specimens: (a) Al, (b) Al- 4 wt.% Al_2O_3, (c) Al- 6 wt.% Al_2O_3 and (d) Al- 8 wt. % Al_2O_3.

phase in the formed micro-cracks that confirmed by EDX spectrum confirmed that the occurrence of the fracture or detachment of reinforcement particles were the most administrated mechanism for the crack initiation through the cyclic loading.

4. Conclusion

Al matrix composites reinforced by Al_2O_3 fabricated using wet attrition milling followed by hot forward extrusion process. The results confirmed that, increasing the amount of nano-sized particulates, induced higher relative density at first (until to 6 wt.% of Al_2O_3) and then decreased the relative density for samples prepared at 8 wt.% of Al_2O_3. Moreover, the microhardness of composites by increasing the amount of reinforcement enhanced. Similar trend especially observed for the strength of prepared samples until 6 wt.%. The results showed the possibility of the employment of the Orowan bowing mechanism as well as the thermal mismatch between the matrix and reinforcement for the explanation of the behavior of prepared composites. In summary, the presence of higher Al_2O_3 nanoparticles up to 6 wt.%, enhanced the fatigue life of prepared composites. While the higher amount of nanoparticles to 8 wt.% showed adverse behavior. This trend can be related to the agglomeration of Al_2O_3 nanoparticles as well as the generation of continuous brittle phases within the grain boundaries. The results confirmed the higher size of dimples that formed at the surface of fractured specimens with a higher amount of reinforcement. Accordingly, the Al- 6 wt.% Al_2O_3 proposed as appropriate composite for the construction of structure used in cyclic loading.

References

1. Raju PRM, Rajesh S, Raju KSR, Raju VR. Evaluation of Fatigue Life of Al2024/Al 2 O 3 Particulate Nano Composite Fabricated Using Stir Casting Technique. Materials Today: Proceedings. 2017;4(2):3188-96.
2. He T, Ertuğrul O, Ciftci N, Uhlenwinkel V, Nielsch K, Scudino S. Effect of particle size ratio on microstructure and mechanical properties of aluminum matrix composites reinforced with Zr48Cu36Ag8Al8 metallic glass particles. Materials Science and Engineering: A. 2019;742:517-25.
3. Hwa P. Fatigue behaviour of 6061 aluminium alloy and its composite: Dublin City University; 2001.
4. Huang J, Spowart JE, Jones JW. The role of microstructural variability on the very high-cycle fatigue behavior of discontinuously-reinforced aluminum metal matrix composites using ultrasonic fatigue. International Journal of Fatigue. 2010;32(8):1243-54.
5. Ramesh CS, Keshavamurthy R, Madhusudhan J. Fatigue Behavior of Ni-P Coated Si 3 N 4 Reinforced Al6061 Composites. Procedia Materials Science. 2014;6:1444-54.

6. Paknia A, Pramanik A, Dixit AR, Chattopadhyaya S. Effect of Size, Content and Shape of Reinforcements on the Behavior of Metal Matrix Composites (MMCs) Under Tension. Journal of Materials Engineering and Performance. 2016;25(10):4444-59.

7. Cerit A, Karamis M, Nair F, Yildizli K. Effect of reinforcement particle size and volume fraction on wear behaviour of metal matrix composites. Journal of Balkan Tribological Association. 2008;12(4):482-9.

8. Li W, Liang H, Chen J, Zhu SQ, Chen YL. Effect of SiC Particles on Fatigue Crack Growth Behavior of SiC Particulate-reinforced Al-Si Alloy Composites Produced by Spray Forming. Procedia Materials Science. 2014;3:1694-9.

9. Barzegar Vishlaghi M, Ataei A. Characterization of the metastable Cu-Fe nanoparticles prepared by the mechanical alloying route. Journal of Ultrafine Grained and Nanostructured Materials. 2014;47(2):57-61.

10. Amiri Talischi L, Samadi A. Structural characterization and ordering transformation of mechanically alloyed nanocrystalline Fe-28Al powder. Journal of Ultrafine Grained and Nanostructured Materials. 2016;49(2):112-9.

11. Mazahery A, Alizadeh M, Shabani MO. Study of Tribological and Mechanical Properties of A356–Nano SiC Composites. Transactions of the Indian Institute of Metals. 2012;65(4):393-8.

12. Bodunrin MO, Alaneme KK, Chown LH. Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics. Journal of Materials Research and Technology. 2015;4(4):434-45.

13. Shin SE, Bae DH. Fatigue behavior of Al2024 alloy-matrix nanocomposites reinforced with multi-walled carbon nanotubes. Composites Part B: Engineering. 2018;134:61-8.

14. Cavaliere P, Jahantigh F, Shabani A, Sadeghi B. Influence of SiO2 nanoparticles on the microstructure and mechanical properties of Al matrix nanocomposites fabricated by spark plasma sintering. Composites Part B: Engineering. 2018;146:60-8.

15. Boostani AF, Yazdani S, Khosroshahi RA, Jiang ZY, Wei D. A novel graphene-stimulated semi-solid processing to fabricate advanced aluminium matrix nanocomposites. Materials Science and Engineering: A. 2018;736:316-22.

16. Ding HZ, Biermann H, Hartmann O. Low cycle fatigue crack growth and life prediction of short-fibre reinforced aluminium matrix composites. International Journal of Fatigue. 2003;25(3):209-20.

17. Fouret C. Experimental and numerical study of the low-cycle fatigue behaviour of a cast metal matrix composite Al?SiCp. International Journal of Fatigue. 2002;24(2-4):223-32.

18. Luk MJ, Mirza FA, Chen DL, Ni DR, Xiao BL, Ma ZY. Low cycle fatigue of SiCp reinforced AA2009 composites. Materials & Design (1980-2015). 2015;66:274-83.

19. Harik V. Low-cycle fatigue of unidirectional composites:Bi-linear S?N curves. International Journal of Fatigue. 2002;24(2-4):455-62.

20. Bekheet NE, Gadelrab RM, Salah MF, Abd El-Azim AN. The effects of aging on the hardness and fatigue behavior of 2024 Al alloy/SiC composites. Materials & Design. 2002;23(2):153-9.

21. Hima Gireesh C, Durga Prasad K, Ramji K. Experimental Investigation on Mechanical Properties of an Al6061 Hybrid Metal Matrix Composite. Journal of Composites Science. 2018;2(3):49.

22. Manikandan P, Sieh R, Elayaperumal A, Le HR, Basu S. Micro/Nanostructure and Tribological Characteristics of Pressureless Sintered Carbon Nanotubes Reinforced Aluminium Matrix Composites. Journal of Nanomaterials. 2016;2016:1-10.

23. Senthilkumar R, Arunkumar N, Hussian MM, Vijayaraj R. Studies on Mechanical Properties and Microstructure of Al₂O₃ Reinforced AA5083 Matrix Composite . Applied Mechanics and Materials. 2014;592-594:749-54.

24. B. S. Arasukumar and K. C. Bendigeri, "Studies on Mechanical Properties and Tribological Characteristics of LM25- Graphite- Silicon Carbide and LM25-Flyash- Silicon Carbide - Hybrid MMC ' s," Int. J. Innov. Res. Sci. Eng. Technol., 2012;1(1):107-12.

25. Ts S, N DM. ALUMINUM BASED HYBRID NANO COMPOSITES: A REVIEW ON REINFORCEMENT, MECHANICAL AND TRIBOLOGICAL CHARACTERISTICS. International Journal of Advanced Research. 2016;4(10):167-75.

26. Divagar S, Vigneshwar M, Selvamani ST. Impacts of Nano Particles on Fatigue Strength of Aluminum Based Metal Matrix Composites for Aerospace. Materials Today: Proceedings. 2016;3(10):3734-9.

27. Casati R, Vedani M. Metal Matrix Composites Reinforced by Nano-Particles—A Review. Metals. 2014;4(1):65-83.

28. Pramanik A, Littlefair G. Fabrication of Nano-Particle Reinforced Metal Matrix Composites. Advanced Materials Research. 2013;651:289-94.

29. Dhanashekar M, Kumar VSS. Squeeze Casting of Aluminium Metal Matrix Composites-An Overview. Procedia Engineering. 2014;97:412-20.

30. Ramesh C, Hirianiah A, Harishanad K, Noronha NP. A review on hot extrusion of Metal Matrix Composites (MMC's). International Journal of Engineering and Science. 2012;1(10):30-5.

31. Pakdel A, Farhangi H, Emamy M. Influence of Hot Extrusion Process on the Mechanical Behavior of AA6061/SIC Composites. Advanced Materials Research. 2011;264-265:141-8.

32. Lee J-C, Ahn J-P, Shim J-H, Shi Z, Lee H-I. Control of the interface in SiC/Al composites. Scripta Materialia. 1999;41(8):895-900.

33. Kim NH, Kang CG, Kim BM. Die design optimization for axisymmetric hot extrusion of metal matrix composites. International Journal of Mechanical Sciences. 2001;43(6):1507-20.

34. El-Kady O, Fathy A. Effect of SiC particle size on the physical and mechanical properties of extruded Al matrix nanocomposites. Materials & Design (1980-2015). 2014;54:348-53.

35. Abdollahi A, Alizadeh A, Baharvandi HR. Dry sliding tribological behavior and mechanical properties of Al2024–5wt.%B4C nanocomposite produced by mechanical milling and hot extrusion. Materials & Design. 2014;55:471-81.

36. Rizaneh S, Borhani GH, Tavoosi M. Synthesis and characterization of Al (Al2O3–TiB2/Fe) nanocomposite by means of mechanical alloying and hot extrusion processes. Advanced Powder Technology. 2014;25(6):1693-8.

37. Senthilkumar R, Arunkumar N, Manzoor Hussian M. A comparative study on low cycle fatigue behaviour of nano and micro Al 2 O 3 reinforced AA2014 particulate hybrid composites. Results in Physics. 2015;5:273-80.

38. Shehata F, Abdelhameed M, Fathy A, Elmahdy M. Preparation and characteristics of Cu-Al2O3 nanocomposite. Open Journal of Metal. 2011;1(02):25.

39. Ma P, Jia Y, Konda Gokuldoss P, Yu Z, Yang S, Zhao J, et al. Effect of Al2O3 Nanoparticles as Reinforcement on the Tensile Behavior of Al-12Si Composites. Metals. 2017;7(9):359.

40. Mazahery A, Ostadshabani M. Investigation on mechanical properties of nano-Al2O3-reinforced aluminum matrix composites. Journal of Composite Materials. 2011;45(24):2579-86.

41. Sakin R. Investigation of bending fatigue-life of aluminum

sheets based on rolling direction. Alexandria Engineering Journal. 2018;57(1):35-47.
42. Bauri R, Yadav D. Introduction to Metal Matrix Composites. Metal Matrix Composites by Friction Stir Processing: Elsevier; 2018. p. 1-16.
43. ASM International. Handbook Committee., ASM Handbook Volume 21: Composites.
44. Kumai S, King JE, Knott JF. SHORT AND LONG FATIGUE CRACK GROWTH IN A SiC REINFORCED ALUMINIUM ALLOY. Fatigue & Fracture of Engineering Materials and Structures. 1990;13(5):511-24.
45. Hall JN, Wayne Jones J, Sachdev AK. Particle size, volume fraction and matrix strength effects on fatigue behavior and particle fracture in 2124 aluminum-SiCp composites. Materials Science and Engineering: A. 1994;183(1-2):69-80.
46. Chawla N, Andres C, Davis L, Jones J, Allison J. The interactive role of inclusions and SiC reinforcement on the high-cycle fatigue resistance of particle reinforced metal matrix composites. Metallurgical and Materials Transactions A. 2000;31(13):951-7.
47. Park BG, Crosky AG, Hellier AK. High cycle fatigue behaviour of microsphere Al2O3–Al particulate metal matrix composites. Composites Part B: Engineering. 2008;39(7-8):1257-69.
48. Li W, Chen ZH, Chen D, Teng J, Fan C. Low-cycle fatigue behavior of SiCp/Al–Si composites produced by spray deposition. Materials Science and Engineering: A. 2010;527(29-30):7631-7.
49. Rohatgi PK, Alaraj S, Thakkar RB, Daoud A. Variation in fatigue properties of cast A359-SiC composites under total strain controlled conditions: Effects of porosity and inclusions. Composites Part A: Applied Science and Manufacturing. 2007;38(8):1829-41.
50. Tu ST, Zhang XC. Fatigue Crack Initiation Mechanisms. Reference Module in Materials Science and Materials Engineering: Elsevier; 2016.