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Influence of Nanoreinforced Particles (Al_2O_3) on Fatigue Life and Strength of Aluminium Based Metal Matrix Composite

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Abstract

In this investigation, Al_2O_3 nano material of 50nm particles size were added to the 6061 Al aluminium alloy by using the stir casting technique to fabricate the nanocomposite of 10wt% Al_2O_3. The experimental results observed that the addition of 10wt% Al_2O_3 improved the fatigue life and strength of constant and cumulative fatigue. Comparison between the S-N curves behaviour of metal matrix (AA6061) and the nanocomposite 10wt% Al_2O_3 has been made. The comparison revealed that 12.8% enhancement in fatigue strength at 10^7cycles due to 10wt% nano reinforcement. Also cumulative fatigue life of 10wt% nanocomposite was found to be increased by 33.37% and 39.58% for low-high and high-low loading sequences, respectively, compared to the metal-matrix cumulative life.

Keywords: *Al_2O_3 nanoparticles, AA6061/10wt%, constant and cumulative fatigue, MMCs.*

1. Introduction

Fatigue life and strength are the most important parameters in which the stress failure occurs less than the allowable stresses because of combined loading; prediction of its value can avoid catastrophic in machines at the service [1].

Metal matrix composites have been studied and are widely used in an industry for several applications in aerospace, automotive and others [2-5]. Estimating fatigue life is an important parameter to design equipment with safety.

A full fatigue fracture behaviour have been studied for Al-SiC nano-metal composite MMCs with 50 nm particles size, different vol.% up to 6 nanocomposites have been fabricated to find optimum fatigue behaviour, it was examined the internal fracture surface of the same nano-metal composite, a ductile-brittle fracture with an increase in the ductile fracture at higher nano-particles within higher fractions [2].

The fatigue behaviour of aluminium (AA2014) alloy reinforced with micro and nano-sized alumina particles Al_2O_3 have studied for their structural applications. Microscope examinations by high resolution (TEM) images were used to evaluate the fatigue behaviour of the composite samples. It was found improving in the mechanical and fatigue properties by the nano-alumina reinforced Al-composites. Compared to the micron sized alumina reinforced composites. The failure cycle was observed to be higher for the nano alumina reinforced composites in comparison with micron sized alumina composites due to a lower order of induced plastic strain [3].

Fatigue parameters have studied on Al reinforced with (SiC) particulates. Comparison have mode based on the matrix aluminium alloy containing Si. The different weight percentages of SiC particulates in the size range of some different μm were used. Fatigue tests indicated that the nanocomposite fatigue resistance increased with increasing content of SiC particulates. SiC particulates improved fatigue resistance which acting as barriers to cracks deflecting the growth plane of cracks resulting in decreased crack propagation rates [4].

Experimental work carried out to find the fatigue properties of Al-matrix nanocomposites using friction stir processing technique (FSP). Aluminium alloy (AA5052) with different amounts of nanoparticles up to 6 stages were fabricated to get homogenous dispersion of nano-particles inclusions. Microstructural studies of high resolution techniques showed that nano-metric Al_3Ti with different nano-particles in size were scattered throughout a fine-grained Al matrix (<2 μm) an improvement in the tensile strength and hardness was attained. Uniaxial stress-controlled tension– tension fatigue testing (R = 0.1) were applied to estimate the fatigue characterization of the nanocomposites alloy. The results were compared with the un-processed (annealed) and FSPed alloy without pre-placing TiO_2 particles. It was found that FSP of the aluminum alloy increased the fatigue strength (at 10^7 cycles) for about 28% and 32% compared with the annealed specimen when the concentration of the reinforcing particles was 2 and 3.5 vol. %, respectively [5].

The aim of the present work is to investigate the fatigue properties (life and strength) under interaction of nanomaterial as reinforcement with the AA 6061 Al alloy as metal-matrix. 10wt% Al_2O_3 nanoparticles were added to Al 6061 metal-matrix for manufactured the nanocomposite and tested under fatigue condition to determine the life and strength of nanocomposite.

2. Experimental Work

This section focuses on the materials used and its chemical composition, mechanical properties in addition of nanocomposite manufacturing and the tensile testing.

2.1. Selection of Materials

The matrix metal used for the present work is 6061 Al alloy. It is widely used the alloy easy to manufacture, preparation and available. Table (1) gives the chemical composition in wt% of the matrix used.

Table 1,
Chemical analysis of 6061 Al. alloy examined at state company for inspection and engineering (SIER) wt. % in comparison with Ref [6].

Elements wt.%	Cr	Zn	Co	Si	Ti	Mn	Mg	Fe	others	Al
Standard [6]	0.04-0.35	Max 0.25	0.15-0.4	0.4-0.8	Max0.15	0.8-1.2	Max 0.15	Max 0.7	0.05	Balance
Experimental according to SIER	0.18	0.13	0.28	0.61	0.08	0.96	0.11	0.54	-	Balance

The mechanical properties of 6061 Al. alloy compared with Ref [6] are summarized in Table (2).

Table 2,
Mechanical properties of 6061 Al. alloy tested at SIER compared with the findings of Ref [6].

6061 Al properties	Hardness HB	Strength σu (MPa)	Yield stress σy (MPa)	Modules of elasticity (GPa)
Ref.[6]	30	149.76	138.06	70-80
Experimental SIER	32	154	140	74

2.2. The Reinforced Material

Hard particles like Al_2O_3 are usually used as reinforced material in the (MMCs) metal-matrix composites (MMCs).The above particle is commonly used with aluminium as reinforcement and the application of the Al_2O_3/Al composites in the aircraft industries, automotive where the tribological characterization is very important [7].

For present work the adopted reinforced material used in manufacturing the nanocomposite is Al_2O_3 with the particle size of 50nm. The chemical analysis of the reinforced material can be shown in table (3).

Table 3,
Chemical analysis of Al_2O_3 wt%.[8].

Element	Cao	TiO_2	Fe_2O_3	others	Alumina
Wt.%	1.1	1.8	0.8	0.02	97

2.3. Composites Preparation

The stir casting method used for preparation the 6061Al/Al_2O_3 composites. The reinforced particles were preheated to 200°C before putting into the melt. The stirrer speed of 450 rpm and the casting temperature was 850°C. More details of the test rig which used to prepare the nanocomposite can be seen elsewhere [9]. Thus, the nanocomposite of 10%Al_2O_3 was obtained in the form of rod of diameter 12 mm and length of about 100mm. The reason of selection 10wt% Al_2O_3 based on the findings of Ref [10] who found that the maximum improvement in mechanical properties was occurred at 10wt% Al_2O_3 reinforcement.

2.4. Fatigue Specimen Geometry

The material was received from the casting moulds as 12 mm in diameter and 100mm length. 12 specimens with nano and 12 specimens as received were manufactured using programmable CNC lathing machine by writing a suitable programme. Then all specimens were machined. Careful attention was done to produce good surface finish and to reduce the tensile residual stresses. The surface of all specimens were polished using 260, 300, 400, 600, 800, and 1000 silicon carbide papers and after that three different diamond laps, course 3/2 micron, fine 1 micron and finally extra-fine 1/4 micron. The last stage was cleaning by distilled water then washing the specimens for polishing with alcohol. The specimens were numbered and tested for measuring the roughness of selected specimens.

Table 4,
Selective surface roughness results of 8 specimens.

Specimens No	**1**	**3**	**5**	**7**	**9**	**11**	**13**	**15**
Ra μm	0.4	0.28	0.5	0.44	0.6	0.66	0.36	0.49
Rt μm	1.2	0.9	1.32	1.07	1.4	1.44	0.96	1.02

The fatigue test specimen can be illustrated in Fig. (1).

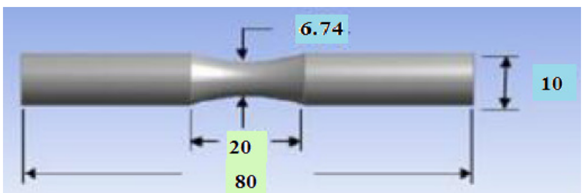


Fig. 1. The specimen dimensions in mm according to (DIN 50113) standard values.

2.5. Fatigue Test Machine

A rotating bending machine fatigue–testing Schenck product type was used to implement all fatigue tests, with constant and variable amplitude. The fatigue specimen which is shown in Fig. (1) Has a round cross section and is subjected to an applied load form the right side of the perpendicular to the axis of specimen, developing a bending moment. Therefore the surface of the specimen is under tension and compression stress when it rotates. The value of the load (P) is measured by Newton (N), applied to the specimen for a known value of stress (σ) measured by (N/mm^2) and used from applying the relation below:

$$\sigma(MPa) = \frac{32 \times 125.7 \times P(N)}{\pi \times d^3}$$

Where d (mm) is the minimum diameter of the specimen, and force arm is equal to 125.7mm, and [11]. The fatigue test rig is shown in Fig (2).

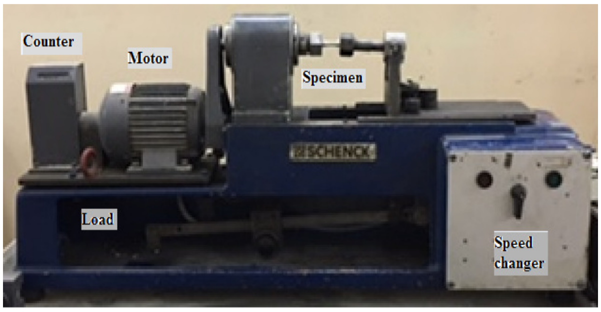


Fig. 2. Fatigue bending machine test.

3. Results and Discussions
3.1. Constant Fatigue Results

The specimens were tested under constant amplitude fatigue, stress at room temperature (RT), to estimate the S-N curves .The results of this series are illustrated in Table (5) and Figure (3).

Table 5,
S-N curve results of Al6061 and Al6061/10 wt. % nanocomposite.

Al6061 metal-matrix							**Al6061-10 wt% nanocomposite**						
Specimen No.			**Applied stress(MPa)**	***N_f* cycles**			**Specimen No.**			**Applied stress(MPa)**	***N_f* cycles**		
1	2	3	140	6500	12000	8000	16	17	18	140	8800	11000	12500
4	5	6	120	18600	22600	25000	19	20	21	120	24600	30000	26000
7	8	9	100	43200	48000	40000	22	23	24	100	72000	66000	74200
10	11	12	80	118000	135000	127000	25	26	27	80	205000	217600	225000
13	14	15	60	380000	405600	422000	28	29	30	60	510000	525000	49800

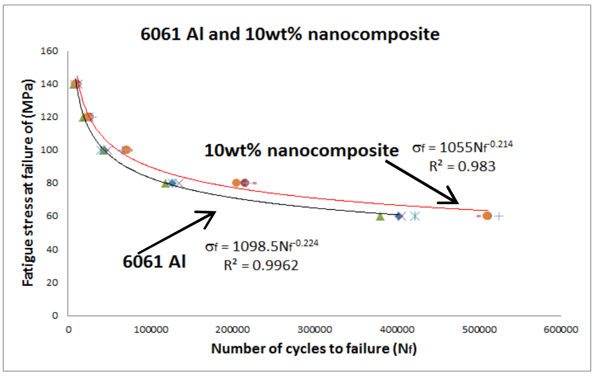


Fig. 3. S-N curves for both 6061 Al and 10wt% nanocomposite.

From table (5), the best fit equation which accurately describe the behaviour of the metal and the nanocomposite is the Basquin formula which can be written in the form.

$$\sigma_f = aN_f^b \qquad \ldots(1)$$

Where a, b are material constants. These constants can be obtained by the equations

$$b = \frac{h\sum_{i=1}^{h}\log\sigma_{fi}\log N_{fi} - \sum_{i=1}^{h}\log\sigma_{fi}\sum_{i=}^{h}\log N_{fi}}{h\sum_{i=1}^{h}(\log N_{fi})^2 - [\sum_{i=1}^{h}\log N_{fi}]^2} \qquad \ldots(2)$$

And

$$\log a = \frac{\sum_{i=1}^{h}\log\sigma_{fi} - b\sum_{i=1}^{h}\log N_{fi}}{h} \qquad \ldots(3)$$

Where h is the number of test specimens

Applying the above equations to the experimental data in table (5), the Basquin equations with their correlation coefficient (R^2) can be seen in table (6).

Table 6,
Basquin equations with correlation factor for metal and composite.

6061 Al alloy	**6061 Al /10wt% nanocomposite**	**Improvement factor (IF) for fatigue endurance limit**
$\sigma_f = 1099N_f^{-0.224}$ R^2=0.9962	$\sigma_f = 1055N_f^{-0.214}$ R^2 =0.983	12.28%

IF is calculated from the equation,

$$IF = \frac{\sigma_{E.L(nano)} - \sigma_{E.L(metal)}}{\sigma_{E.L(nano)}} * 100$$

Where $\sigma_{E.L}$ is endurance limit stress (MPa). The $\sigma_{E.L}$ was calculated from the Basquin equation at 10^7 cycles. The results revealed that $\sigma_{E.L(metal)} = 87.3$ MPa and $\sigma_{E.L(nano)} = 99.53$ MPa. IF (improvement factor was found to be 12.28% due to nanomaterial addition. Many workers focused on the fatigue properties such as Akio et.al. [12] and Mussert et.al.[13]. They tested nanocomposite under fatigue cycling and they concluded that the nano reinforced work to strengthen the metal matrix and to enhance the fatigue strength of nanocomposites.

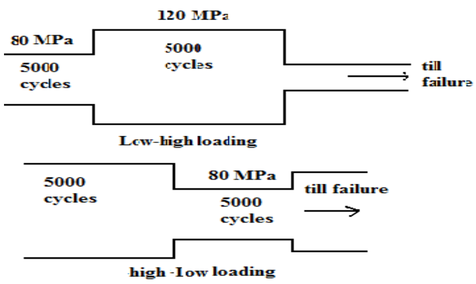
Hafeez and Senthil [14] found that the ceramic particles strengthen the metal-matrix composite fatigue properties (fatigue strength), maintaining good ductility at high temperature creep resistance.

3.2. Cumulative Fatigue Results

Cumulative fatigue tests were carried out at the same conditions for S-N curve i-e room temperature (RT) and stress ratio (R=-1).
Table (7) gives the experimental results obtained for materials, metal-matrix and nanocomposite (MMCs).

Table 7,
Cumulative fatigue results for metal-matrix and nanocomposite (MMCs).

Specimen No	Loading sequences (MPa)	Metal-matrix 6061 Al	Nanocomposite 6061 Al/10wt% Al_2O_3	Loading programme
31	80-120	34600	51000	
32		38000	60000	
33		44000	64000	
34	120-80	30000	42000	
35		31000	48000	
35		26000	54000	



The improvement in cumulative fatigue lives due to 10wt% nanomaterial Al_2O_3 can be illustrated in table (8).

Table 8,
Shows the improvement factor in cumulative fatigue live due to 10wt% Al_2O_3.

Loading sequences (MPa)	N_f average metal-matrix	N_f average nanocomposite	IF
80-120	38867	58333	33.37%
120-80	29000	48000	39.58%

The results of table (8) are plotted in Fig. (4). Fig (4) shows the enhancement of cumulative fatigue lifes.

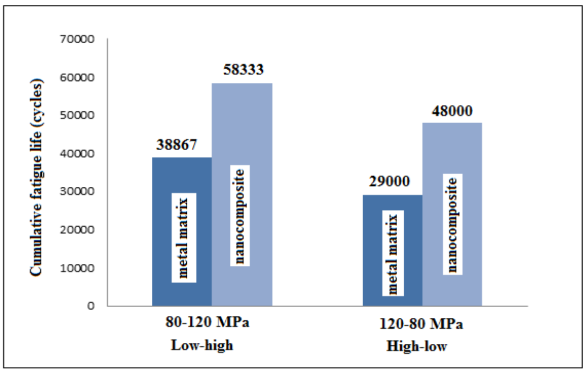


Fig. 4. Improvement of cumulative fatigue life due to 10wt% Al_2O_3.

The applications of nanocomposites based on aluminium alloy as a metal-matrix and Al_2O_3 nano-reinforced material are commonly used in aircraft industries, space applications and automotive where the fatigue and tribological properties are required [15].

Comparison has been made between the MMCs and metal matrix and the comparison revealed that the MMCs have better fatigue resistance [16].
It is observed from the constant and cumulative fatigue testing; tables (5), (7) that the nanocomposite of 10wt% Al_2O_3 achieved higher fatigue strength and life. The reasons may be the followings:

1. Uniform dispersion of Al_2O_3 particles in the nanocomposite [17].
2. Less porosity and homogeneous dispersion of Al2O3 which in turn increased the mechanical

and fatigue properties .Porosity should be kept to minimum level [18].

3. Al2O3 addition increases brittleness in which the mechanical and fatigue properties increased [19].
4. The fine size of the particles leads to improve the mechanical and fatigue properties.
5. Good thermal bounding between the 6061 Al. alloy and the reinforced material the attribute to enhance fatigue behaviour [2].
6. The high mechanical properties of Al2O3 itself leads to enhance the fatigue strength and life [6].

4. Conclusions

A fundamental understanding of the mechanism which provides the enhancement in fatigue properties is required and the following remarks derived from this work are concluded.

1. The fatigue strength of 10wt% Al_2O_3 nanocomposite at 10^7cycles was improved by 12.28% compared to as cast Al 6061 alloy.
2. The cumulative fatigue lives of the 10wt% Al2O3 nanocomposite were enhanced by 33.37% for low-high loading and 39.58% for high-low loading
3. The above improvements of the nanocomposite may be due to uniform distribution, less porosity , high bounding between Al2O3 and 6061 Al. alloy, high dislocation density, high mechanical properties of Al2O3 itself.

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تاثير حبيبات المادة النانوية المقواة (Al_2O_3) على عمر ومقاومة الكلال لمركب ذي الاساس المعدني

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الخلاصة

في هذا البحث تم اضافة المادة النانوية Al_2O_3 ذات حجم حبيبات 50 نانوميتر الى سبيكة الالمنيوم AA6061 باستخدام تقنية السباكة بالتحريك لتصنيع المركب النانوي ذو 10wt% من المادة النانوية Al_2O_3.النتائج المستخرجة عمليا اوضحت ان اضافة Al_2O_3 10wt% بوصفه نسبة وزنية حسنت من عمر مقاومة الكلال الثابت والمتراكم .تمت مقارنة بين سلوك منحنيات S-N للمعدن الاساس AA6061 والمركب النانوي Al_2O_3 10wt% .واوضحت المقارنة تحسن بمقدار 12.8% في مقاومة الكلال عند 10^7 دورة نتيجة 10w% للمادة المقواة. كذلك وجد ايضا ان عمر الكلال التراكمي ازداد نسبة 33.37% و% 39.58 للتحميل المتتابع من واطئ-عالٍ ومن عالٍ-واطئ على التوالي مقارنة مع العمر التراكمي للمعدن الاساس.