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Fatigue Strength of Nanocomposite Under High Temperature

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Abstract: The influence of reinforced ratio 6 wt.% of alumina particles of Al_2O_3 size with aluminum alloy 7100 metal matrix on constant fatigue strength and life at 200°C was studied. The experimental results revealed that the fatigue strength improvement factor FSIF for the composite was obtained to be from 0.84-4.84. The FSIF for the nanocomposite tested at 200°C exhibited for 10^3 and 10^5 cycles, respectively, at Room Temperature (RT) and the net FSIF was recorded as 4, the value of 7.29-7.4% at 10^3 and 10^5 cycles, respectively with 0.11 net FSIF. The addition of nanoreinforced material resulted to rais the fatigue endurance limit at 10^7 cycles from 47-51.8 MPa and from 46-50.86 MPa at RT and 200°C, respectively.

Key words: Aluminum alloy 7100, alumina, stir casting, high temperature fatigue behavior, matrix, fatigue endurance

INTRODUCTION

Aluminum alloys have high corrosion resistance, high thermal conductivity, sufficient strength characteristics, recyclability, ductility, durability and especially, low density. Therefore, it can be widely used in many areas of industry such as aerospace, architectural construction, marine industries and particularly in the automotive applications. Now a days, especially in the automotive industry, demands are increasing day by day and aluminum does not satisfy some case. So that, production industry has begun to look for alternative engineering materials. One of the engineering materials is composite. Composite materials consist of two or more materials. One of these materials is called reinforcement and other one is called matrix. Fibers, particulates or whiskers are examples of reinforcements and metals, plastics or ceramics are examples of matrix material. In metal matrix composites systems, aluminum and its alloys have been drawn attention, especially for last 20 years. Silicon Carbide (SiC) and Aluminum Oxide (Al_2O_3) are the most commonly used reinforcements (Aybarc *et al*., 2018). So that, this study deals with aluminum metal matrix composites in which Al_2O_3 were used as reinforcements materials with average size (20-30 nm) tested under fatigue and thermal fatigue to understand the effect of nanomaterial on the improvement of the thermal fatigue properties. Fatigue of metals reduced under elevated temperature. The 2024-T4 aluminum alloy was subjected to 150°C under constant fatigue tests and compared to the Room Temperature (RT). The experimental results revealed that a decrease in fatigue life of about 80% and significantly reduction was observed in fatigue strength (Majeed *et al*., 2010).

Stocker *et al*. (2009) studied the fatigue of super alloy RR1000 at 650°C. They concluded that a major reduction in fatigue strength and life was observed when compared to the fatigue at dry condition (RT). Mege-Revil *et al*. (2010) studied TiSin and TiSin AlN nanocomposites coatings and thermomechanical properties and compared these properties with the thermal fatigue. The fatigue resistance was studied in isothermal, dynamic as well as cycling (10 cycles rms 25-800-25°C) conditions. Thermal cycling observed high resistance of nanocomposites while the metal without nano showed reduction in fatigue resistance.

Zhang *et al*. (2006) studied the performance of thermal fatigue and creep resistance of nanocomposite solder in microelectronic/optoelectronic packaging. A comparison between the performance of thermal fatigue and the traditional solder was made. The results revealed that the nano-composite solder was much better fatigue resistance and creep resistance due to the uniformly distributed nanosized through the grain boundary and provided effective impediment to dislocation movement. In the current work, the constant fatigue behavior of 7100 Al. alloy/6 wt.% Al_2O_3 nanocomposite reinforced by 6wt.% alumina was investigated. A comparison between the fatigue strength and life for the above composite with the base metal (matrix) was made.

MATERIALS AND METHODS

Experimental investigation

Material selection: The matrix used in the present research is the aluminum alloy 7100 in the composite material which is used in different applications. Table 1 states chemical composition of 7100 aluminum alloy. While the mechanical properties are presented in Table 2.

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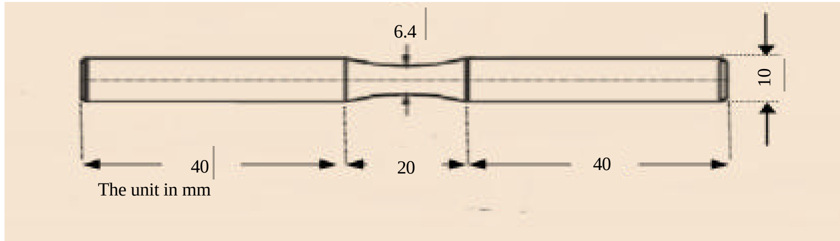

Fig. 1: Rotating bending fatigue specimen (cantilever beam) according to the American Society for testing and materials (AST81-8)

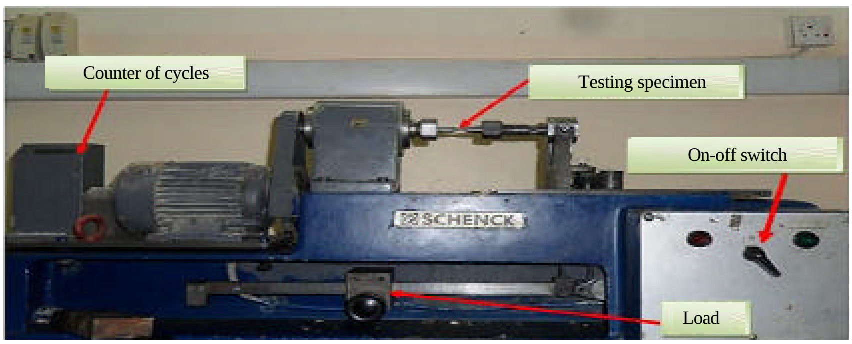

Fig. 2: Rotating bending testing machine

Fabrication of 7100 Al. alloy Al_2O_3 composite stir casting route: The method used to manufacture the nanocomposite is the stir casting method. This method includes several steps as follows:

- 7100 Al. alloy is cutting into cubes (1-2) cm^3 then washed with alcohol and followed by water several times
- Dry the parts that were washed with steam of hot air at a temperature 100°C
- Then this parts heated by an electric heater at 200°C
- Lift the oven covers and carry the resulting parts of the heating process then close the oven cover tightly. Then, withdrawn air from the oven using vacuum
- The oven pumped with the argon gas then heated into 800°C
- The Alumina (Al_2O_3) are heated to 200°C
- The nanoparticles are added to the molten 7100Al.alloy through the gas pump
- First, the temperature of furnace is raised over the liquid temperature of Al about 850°C after that cool it less from 650°C
- Four minutes are designed for stirring and with stirring speed 450 rpm
- The mixing are heated to 850±10°C
- At last, the liquid is poured into molds to obtain an aluminum rod

Table 1: Chemical composition of 7100 Al. alloy

Chemical compositions	Element wt.% of Al 7100	Chemical composition	Element wt.% of Al 7100
Zn	2.0	Cr	0.0402
Mg	1.5.	Pb	0.1550
Si	0.764	Sn	0.1140
Cu	0.441	Ca	0.0200
Fe	1.0	V	0.0121
Ti	0.0404	Others	0.1350
Mn	0.391	Rem. Al	93.4194

Table 2: Mechanical properties of 7100 Al. alloy

Variables	----------------Values------------------	
Wt.%	0	6
σu (MPa)	115	165
σy (MPa)	82	126
E (GPa)	67	72.3
G (GPa)	26.2	27.59
μ	0.28	0.31
HV (kgf/mm²)	74	90
∈ (%)	16.72	14.2

Fatigue test: The specimens of the fatigue test were prepared according to the machines manual as shown in Fig. 1. The specimens were manufactured and tested to generate the S-N curve by an alternating bending specification of fatigue test machine (rotating bending fatigue testing machine) shown in Fig. 2. The application stress is calculated from the applied moment according to the simple theory of a cantilever beam as:

Fig. 3: Furnace attached to fatigue machine with control board

$$\sigma = (1281\ P)/d^3 \quad (1)$$

Where:

- σ = The bending stress in (Mpa)
- P = The force in (N.)
- d = The minimum diameter of the specimen (mm)

Constant fatigue tests are performed in laboratory with rotary fatigue bending rig at a stress ratio of R = -1. The failure is defined as the fatigue specimen becomes into two pieces. When specimen fails the fatigue testing automatically stops. The number of cycles until failure of the specimens are recorded by a mechanical counter which is coupled directly to the drive shaft of the d.c motor which records the number of stress cycles. This test is performed in the University of Technology/ Department of Electromechanical Engineering in Baghdad.

Thermal device: Fatigue at elevated temperature requires a thermal device for heating the environment of the specimens to a known elevated temperature. An electric furnace is manufactured with suitable dimensions of (100×120×140 mm). The furnace can be attached to the testing machine with a digital thermal control unit board. The walls of the furnace are made of two layers of steel plate with 3mm thickness for each layer. An electrical heater of (2000 W) is fastened inside the furnace with a K-type thermocouple for the sake of controlling heating temperature inside the furnace. The furnace and digital thermal control unit board are illustrated in Fig. 3.

RESULTS AND DISCUSSION

Constant amplitude fatigue results: The specimens were tested under constant amplitude fatigue stress rotating bending with a stress ratio R = -1 at room temperature and for high temperatures 200°C to estimate the S-N curves. The results of aluminum alloy 7100 are given in Table (3-6) and plotted in Fig. 4.

Table 3: S-N curve results of Al7100 without heating

Al. 7100 best zero

Applied stress (σ_f) MP_a	No. of average cycle to Failure, Nf_{av}	Basquin equation	R^2
100	3600	$\sigma_f = 236(N_f)^{-0.10}$	0.997
90	11000		
80	35000		
70	110000		

Table 4: S-N curve results of Al7100 wt.6% nanocomposite without heating

Al. 7100 best nano 6% alpha Al_2O_3

Applied stress (σ_f) MP_a	No. of average cycle to failure, Nf_{av}	Basquin equation	R^2
100	4460	$\sigma_f = 221(N_f)^{-0.09}$	0.981
90	22000		
80	67800		
70	215000		

Table 5: S-N curve results of Al7100 at 200°C

Al.7100 zero nano

Applied stress (σ_f) MP_a	No. of average cycle to failure, Nf_{av}	Basquin equation	R^2
100	1200	$\sigma_f = 201(N_f)^{-0.09}$	0.926
90	8000		
80	21000		
70	44000		

Table 6: S-N curve results of Al7100 wt.6% nanocomposite at 200°C

Al7100 best nano 6% Alpha Al_2O_3

Applied stress (σ_f) MP_a	No. of average cycle to failure, Nf_{av}	Basquin equation	R^2
100	3000	$\sigma_f = 217\ (N_f)^{-0.09}$	0.966
90	16000		
80	48000		
70	125600		

S-N curves behavior: From the Basquin equations obtained from the experimental results and calculated according to $\sigma_f = \alpha\ (N_f)^b$ where a and b are material constants. It is clear that, the above equations have good (R^2) correlation coefficient which proved that the experimental recorded data can be explained well using Basquin equation. Table 7 gives how the fatigue strength improved at 10^3 and 10^5 cycles due to addition the nanomaterial reinforcement. Relating to Table 7, the difference in the FSIF are apparent. The above

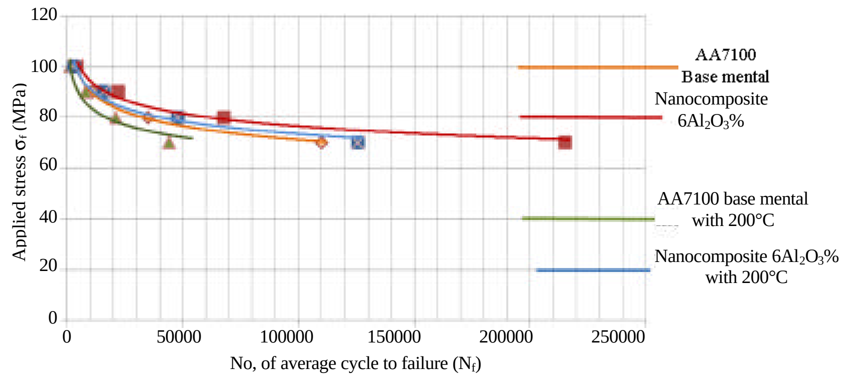

Fig. 4: S-N curves behaviors for four cases of testing

Tabe 7: S-N fatigue behaviours under 10^3 and 10^5 cycles

Dry fatigue without and with 6 wt.% Al_2O_3				Thermal fatigue at 200C without and with 6wt.% Al_2O_3			
10^3 cycles		10^5 cycles		10^3 cycles		10^5 cycles	
Without nano (MPa)	With nano (MPa)	Without nano (MPa)	With nano (MPa)	Fatigue strength with nano (MPa)	Fatigue strength with nano (MPa)	Fatigue strength with nano (MPa)	Fatiguestrength withnano(MPa)
118	119	74.6	78.4	108	116.5	71.3	77
Fatigue Strength Improvement Factor FSIF = $\frac{\sigma_{nano} - \sigma_{unreinforced}}{\sigma_{nano}} * 100\%$ (Asmaa *et al*., 2014)							
0.84		4.84		7.29		7.4	

Table 8: Mechanical properties of nanoreinforced material of Al_2O_3

Hardness HB500	Tensile strength (MPa)	Elastic module E (GPa)	Ref.
1175	2100 Compression	300	(Mazahery *et al*., 2009)

Table 9: Endurance fatigue limit of base metal and composites at room temperature and at 200°C

Room temp.25°C without nano	Room temp. 25°C with nanomaterial	200°C without nano	200°C with nano material
47 MPa	51.8 MPa	46 MPa	50.86 MPa

improvement is due to the hard nanoreinforced material of Al_2O_3 which has high hardness and mechanical properties as given in Table 8 according to (Mazahery *et al*., 2009).

According to, Table 7 when the fatigue life increased from 10^3-10^5 the FSIF raised from 0.84-4.84% i.e. Increasing the fatigue life leads to increase the FSIF. For this reason the low cycle fatigue has little effect on the FSIF. In the thermal fatigue case, the FSIF improved from 7.29-7.4%. Reducing the applied fatigue stress resulting in increase of FSIF for both dry and thermal fatigue.

Endurance fatigue limit at 10^7 cycles: The 6 wt.% of Al_2O_3 nanoreinforced material has improved the fatigue property is most pronounced under conditions of high cycle fatigue (Low applied stress) but has little effect at low-cycle fatigue region (High applied stress). The reason for this case is that probably because the grain size generated with 6 wt.% Al_2O_3 reduced to small grain size and this will retard fatigue cracks resulted long life. Table 9 gives the endurance fatigue limit at 10^7 cycles.

Elevated temperature has a deleterious effect on the mechanical and fatigue properties of composite. Which can result in additional degradation of endurance fatigue resulted a degradation in fatigue life (Mars and Fatemi, 2004). According to the obtained experimental results given in Table 9, many workers reported that the fatigue life decreases with increasing testing temperature (Al-Alkawi *et al*., 2015). It is clear that, Table 9 gives best endurance fatigue limit of 51.8 MPa for the composite tested at room temperature while the worst endurance fatigue limit is 46 MPa for the base metal tested at 200°C. The addition of nano reinforcement raised the value for fatigue strength at 10^7 cycle from 47-51.8 MPa and from 46-50.86 MPa for room and elevated temperature 200°C. The high hardness and mechanical properties of alumina could be the main reason for enhancing the fatigue strength and endurance fatigue of the composite (Bharath *et al*., 2014).

CONCLUSION

The constant S-N curves fatigue strength and life of 7100 Al.alloy reinforced by 6 wt.% of α-Al_2O_3 under rotating bending loading are investigated. The following conclusions may be derived from this research. The effect of 6 wt.% Al_2O_3 on the fatigue strength improvement factor FSIF was obtained to be 0.84 and 4.84 for 10^3 and 10^5 cycles, respectively, at Room Temperature (RT). Increasing the fatigue life from 10^3 and 10^5 cycles resulted in an increase of 4 in FSIF. While the effect of nano reinforced material 6 wt.% Al_2O_3 on the FSIF at 200°C was recorded to be 0.11. FSIF reduced from 4 at (RT) to 0.11 at 200°C due to the heating condition. The endurance fatigue limit at 10^7 cycles of nano composite increased from 47-51.8 MPa at (RT) showing an improvement of 10.2%. While this value increased from 46-50.86 MPa at 200°C giving 10.56% improvement.

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