Investigation and improvement the Properties of 7075 AL/T6 Alloy using TiO₂ Nanomaterials

Nisreen Mizher Rahma¹, Khalid Mershed Eweed ¹ and Mohammed Ali A¹

¹Material Engineering Department, Al-Mustansiriyah University, Baghdad, Iraq.

Abstract. Aluminium based metal matrix composites had drawn most attraction because of enhanced properties in structural applications for the past two decades; therefore fatigue and tensile properties of composite materials should be studied for their structural applications. In the present research nanoparticles TiO₂ were added with different weight percentage (1,3,5,7, and 9wt.%) and average particles size (10-20nm) to the 7075/T6 Al-alloy by stir casting technique. The results indicated that the tensile and fatigue properties increase with increasing the wt. % of TiO₂ nanoparticle. The optical micrographs of 7075 Al-alloy with 1,3,5,7, and 9wt.%) TiO₂ particles were shown uniform distribution of TiO₂ and less level of porosity of microstructure compared to 7075/T6 Al-alloy and the optimum improvement in tensile and fatigue properties is occurred at 9 wt.% of TiO₂.

Keywords: metal matrix, alumina, Microstructure, Fatigue.

1. Introduction

In current, aluminium metal matrix composites (AMMCs) attract a much attention caused by their machinability, light weight property, weldability, low coefficient of thermal expansion, corrosion resistance and greater mechanical properties due to these advantages AMMCs use in many applications like the automotive industries, cam shafts, cylinder liners, connecting rods, brake rotors, main bearings, calipers, electronic components, engine pistons, aerospace and aircraft etc. [1, 2]. Nanotechnology is one of the leading scientific fields today because it combines knowledge in the fields of chemistry, physics, informatics, biology, engineering and medicine. The 7075/T6 – TiO₂ aluminum composites are suitable for automobile, aircraft and aerospace application [3]. Khorramie, et al, (2013) [4] fabricated a 356 Al-alloy with various volume fraction (0.75, 1.5 and 2.5 vol. %) of Al₂ZrO₅ nanoparticles reinforcement (particle size about 38 nm) by stir casting method. They observed the compressive strength improvement to 900 MPa and hardness improvement to maximum values of BHN 61, the compressive strength and hardness of the sample contain 1.5vol. % Al₂ZrO₅ improvement compared with other sample. Divagar, et al. (2016) [5] fabricate 7075-T651 Al-alloy with various weight percentages of SiC nanoparticles 5, 10 & 15 wt. % and a constant (5 wt. %) of Al₂O₃ nanoparticles as reinforcements by stir casting process. They found fatigue strength of MMNCs were have a direct proportional relationship with percentage of nano particle, the composite contain (7075-T651 + SiC-10 % + Al₂O₃ -5 % ) exhibits 12.13% highest fatigue strength than other composites and base metal, and the fatigue life increased when volume fraction of reinforcement increased. Rama Murty Raju , et al. (2017) [6] fabricated Al 2024 alloy with various weight percentage (0, 0.5, 1, 1.5, 2 ) of nano alumina with partial size 13 nm by stir casting method. They founded that the tensile strength increased with increasing the weight percentage of nano Al₂O₃ of the
composites and highest value tensile strength observed in 1.5 weight percentage of nano alumina reinforcement, and then tested fatigue life for 1.5 wt. % of nano alumina used five different stress (90, 80, 70, 60, 50 MPa) and draw the S-N curve for the this sample and unreinforced sample. They observed fatigue life for nano sample contain 1.5 wt. % of nano alumina was superior compared than of unreinforced sample. Gopalakannan & Senthivelan (2015) [7] manufactured 7075 Al-alloy reinforced with nanoparticle (particle size about 50 nm) of 0.5 wt.% SiC and manufactured 7075 Al-alloy reinforced with nanoparticle of 0.5 wt.% B₄C by ultrasonic cavitation process. They observed the hardness and tensile strength of sample 7075 Al-alloy reinforcement with 0.5 wt.% of SiC and B₄C nano size improved than sample without reinforcement and the results of B₄C better than SiC. Dinesh & Ravindran (2016) [8] studied hardness and tensile behavior of 7075 aluminum alloy when reinforcement by Cr nano particles of different weight (2, 3, 4, 5, 6) wt. % and zinc nano particle of 1 wt. % by stir casting route. They found the tensile and hardness value of the composite were higher than the composite unreinforced with nanoparticles, the stir casting was suitable technique for manufacture of this type of composite and the composite Cr-4%Zn-1% showed enhanced properties such as hardness and tensile compared to another specimens. This paper presents the effect of various wt.% reinforced material on the tensile and fatigue properties of aluminum 7075 based metal matrix composite through stir casting method.

2. Experimental Work

2.1. Material and nanomaterial selection
The metal matrix used for the present work is 7075 Al/T6 alloy with chemical composition in wt. % and mechanical properties as shown in table (1) and table (2).

| Table 1. chemical composition of 7075 aluminum alloy in wt. % |
|-----------------|--------|-------|-------|-------|------|-------|-------|-------|
| Zn   | Fe    | Si    | Mn    | Cu    | Cr   | Mg    | Ti    | Al    |
| wt.% | wt.%  | wt.%  | wt.%  | wt.%  | wt.% | wt.%  | wt.%  | wt.%  |
| Standard [9] | 5.1-6.1 | Max 0.5 | Max 0.4 | 0.3 | 1.2-2 | 0.18-2.1 | 0.28 | Max 0.2 | Bal. |
| Measured | 5.3 | 0.31 | 0.21 | 0.23 | 1.49 | 0.25 | 2.8 | 0.16 | Bal. |

| Table 2. Mechanical properties of 7075 aluminum T6 alloy compared to the standard [10] |
|-----------------|--------|--------|--------|--------|
|                | ultimate tensile strength (MPa) | yield strength (MPa) | elongation % | modulus of elasticity (GPa) |
| Standard [10]   | 228    | 103    | 17     | 71.7   |
| Measured        | 231    | 113    | 17     | 71.6   |

The TiO₂ nano particles is chosen because it is one of the most widely used particle reinforcement with various grades of aluminum alloys and available in the markets with low cost. In addition have good properties like wear resistance, hardness and thermal stability [9]. In the current work TiO₂ with (10-20 nm) particle size was used. The properties of nano-TiO₂ are shown in table (3) after.
Table 3. The properties of nano-TiO$_2$ [12].

| Chemical composition | Particle size (nm) | pH  | Appearance | Specific surface area (m$^2$/g) | Purity       |
|----------------------|-------------------|-----|------------|---------------------------------|--------------|
| TiO$_2$              | 10-20             | 7.6 | White powder | 20-30                           | $>99.9\%$    |

2.2. Preparation of the composite

The manufacturing composite material by using stir casting method, in the first stage melting the 7075/T6 aluminium alloy inside crucible (made of silicon carbide capacity 1 Kg) by using electric furnace at the temperature 850°C for 20 minute after that nano alumina with particle size (10-20 nm) is preheated to 230 °C and added to the melt of Al alloy by the following percentage (1,3,5,7,9) wt. % at stirring speed 500 rpm. for 6 min. by using electric mixer to obtain good homogeneity in a protected atmosphere (argon gas to avoid oxidation).

The used mold (cast iron) is heating before used it to 300 °C which has the diameter 16 mm and the length 160 mm and then the final mixture will be pour in the mold. This process is reiterated to get the specimens which contain different weight percentage of nano. The stirring speed, time and temperature of the manufacturing process used according to Ref.[10].

2.3. Tensile specimen and testing

After manufacturing the specimen is prepared using computer programs CNC Milling machine (C-test), during manufacturing careful attention must be taken into considerations to produce a good surface finish and to reduce residual stresses.

2.4. Fatigue Properties

2.4.1. Fatigue specimen preparation

The fatigue samples are manufactured according to standard ASTM (E8/E8M-09). The results of the surface roughness for 10 specimens have been selected randomly are given in table (4).

Table 4. The results of surface roughness for 10 specimen

| Specimen No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|--------------|---|---|---|---|---|---|---|---|---|----|
| Ra (µm)      | 0.8 | 0.63 | 0.61 | 0.9 | 0.74 | 0.9 | 0.87 | 0.46 | 0.47 | 0.41 |
| Rt (µm)      | 1.91 | 1.35 | 1.61 | 1.7 | 1.71 | 1.4 | 2.02 | 1.6 | 1.63 | 1.25 |

2.4.2. Fatigue testing machine

The fatigue machine of type Schench rotating bending was used for all fatigue samples with a constant and a variable loading. The sample has a rod Cross Section and the load is applied in the right side which is perpendicular on the axis of sample, to develop a bending moment; so that the surface of the sample is subjected to Tension and Compression stress when it rotate.

The applied stress is calculated from the applied moment according to the simple theory of a cantilever beam as:

$$
\sigma_b = \frac{125.7 \cdot 32 \cdot P}{\pi \cdot d^3}
$$

Where:
P : the load which is measured by Newton (N).
σb : applied stress which is measured (MPa).
d: the minimum diameter of the specimen (mm).
The force arm is equal to 125.7mm and the rate of cycle is (1420) rpm . equal to 23.67 Hz [11].

3. Results and Discussions

3.1. Tensile results
The tensile specimen studied in the current work contain different weight percentage (2, 4, 6) wt.% of nano alumina which are manufactured by stir casting method. The size of Al₂O₃ nano particles is about (20-30 nm). The results of tensile test for 7075/T6 AL-alloy (metal matrix) and 7075/T6 AL-alloy with different wt.% of nano TiO₂ are listed in table (5). The figure (1) shows the variation of ultimate tensile strength and yield strength of composites.

| Property                  | Standard | ASTM B-211 [10] |
|---------------------------|----------|-----------------|
| As received               | 1wt. %   | 3wt. %          |
| 1wt. % TiO₂              | 228      | 225             |
| 3wt. % TiO₂              | 262      | 267             |
| 5wt. % TiO₂              | 271      | 276             |
| 7wt. % TiO₂              | 276      |                 |
| 9wt. % TiO₂              |          |                 |

Figure 1. Variation of tensile strength against TiO₂ wt.% σu(MPa)
3.2. The constant amplitude fatigue results

The constant amplitude fatigue tests was carried out to obtain S-N curves by using 26 specimens (without nano material and with different wt.% of nano alumina) at room temperature. The results are illustrated in table (6) and figure (2).

Table 6. S-N curves of 7075 Al alloy without and with different wt. % of nano TiO₂

| Specimen No | Applied stress MPa | Nf Cycles |
|-------------|--------------------|-----------|
| 7075/T6 AL - alloy with zero nano TiO₂ |
| 1           | 120                | 19150     |
| 2           | 110                | 115625    |
| 3           | 100                | 270256    |
| 4           | 90                 | 1303245   |
| 5           | 80                 | 1720541   |
| 7075/T6 Al alloy with 1 wt.% nano TiO₂ |
| 6           | 120                | 24256     |
| 7           | 110                | 200548    |
| 8           | 100                | 340265    |
| 9           | 90                 | 1492654   |
| 10          | 80                 | 1985235   |
| 7075/T6 AL - alloy with 3 wt. % nano TiO₂ |
| 11          | 120                | 28256     |
| 12          | 110                | 180326    |
| 13          | 100                | 360258    |
| 14          | 90                 | 1768246   |
| 15          | 80                 | 2325842   |
| 7075/T6 AL - alloy with 5 wt. % nano TiO₂ |
| 16          | 120                | 32512     |
| 17          | 110                | 215658    |
|   |   |   |
|---|---|---|
| 18 | 100 | 380251 |
| 19 | 90  | 1856802 |
| 20 | 80  | 2568025 |

7075/T6 AL - alloy with 7 wt. % nano TiO₂

|   |   |   |
|---|---|---|
| 21 | 120 | 36215 |
| 22 | 110 | 225124 |
| 23 | 100 | 402568 |
| 24 | 90  | 1956832 |
| 25 | 80  | 2754231 |

7075/T6 AL - alloy with 7 wt. % nano TiO₂

|   |   |   |
|---|---|---|
| 26 | 120 | 39254 |
| 27 | 110 | 248652 |
| 28 | 100 | 450235 |
| 29 | 90  | 2154235 |
| 30 | 80  | 2905254 |
Figure 2. S- N curve results for metal without and with different weight percentage of nano Al₂O₃. The fatigue curve can be presented by the following equation (based on Basquin equation).

\[
\sigma_f = A \left( N_f \right)^\alpha
\]  \hspace{1cm} (2)

Where:

- \( \sigma_f \) : the applied stress (MPa).
- \( N_f \) : the fatigue life at failure (cycles).
- \( A \) and \( \alpha \) are material constants and these constants can be calculated from the equations:

\[
\alpha = \frac{h \sum \log \sigma f \log N_f - \sum \log \sigma f \sum \log N_f}{h \Sigma (\log N_f)^2 - \left[ \Sigma \log N_f \right]^2}
\]  \hspace{1cm} (3)

\[
\log A = \frac{\Sigma \log \sigma f - \alpha \Sigma \log N_f}{h}
\]  \hspace{1cm} (4)

Where \( h \) is the number of average test specimens [12]. The details of S-N curves equation can be tabulated in table 7.
Table 7. The S-N curves equation

| Wt.% TiO₂ | A   | α     | S-N curve equation | R²  |
|-----------|-----|-------|--------------------|-----|
| 0         | 282.35 | -0.084 | σ_f = 282.35 Nf⁻⁰.⁰⁸⁴ | 0.9337 |
| 1         | 294.6 | -0.086 | σ_f = 294.6 Nf⁻⁰.⁰⁸⁶ | 0.9294 |
| 3         | 297.77 | -0.086 | σ_f = 297.77 Nf⁻⁰.⁰⁸⁶ | 0.9285 |
| 5         | 306.62 | -0.087 | σ_f = 306.62 Nf⁻⁰.⁰⁸⁷ | 0.9279 |
| 7         | 312.3 | -0.088 | σ_f = 312.3 Nf⁻⁰.⁰⁸⁸ | 0.9331 |
| 9         | 315.01 | -0.088 | σ_f = 315.01 Nf⁻⁰.⁰⁸⁸ | 0.9281 |

From the table above, S-N curve equations which were calculated according to the Basquin equation of the form \( \sigma_f = A N_f^\alpha \). It is noted that the S-N curve equations have good correlation coefficient \( R^2 \) which proved that the experimental data can be described well using Basquin equation. The strength improvement factor (SIF%) can be obtained from the equation [5].

\[
SIF\% = \left( \frac{\sigma_{nano} - \sigma_{unreinforced}}{\sigma_{nano}} \right) \times 100 \quad (5)
\]

The \( \sigma_{E.L.} \) (endurance fatigue limit stress) for 7075/T6 Al-alloy with different weight percentage of nano TiO₂ and SIF% (strength improvement factor) for \( 10^8 \) cycles can be shown in the table (8).

Table 8. The endurance limit stress and SIF% for 7075/T6 Al-alloy with different wt.% of nano TiO₂

| N_c | Fatigue strength unreinforced (MPa) | Fatigue strength reinforced with nano TiO₂ (MPa) | SIF% |
|-----|-----------------------------------|-------------------------------------------------|------|
| \( 10^8 \) | \( 70.3 \)                        | \( 74.5 \)                                       | \( 5.637 \) |
| \( 10^8 \) | \( 71.6 \)                        | \( 76.3 \)                                       | \( 6.159 \) |

7075/T6 Al-alloy with 1 wt.% nano TiO₂

7075/T6 Al-alloy with 3 wt.% nano TiO₂
It is clear from the above data the fatigue strength and life improved with increase in wt. % of nano material. The maximum fatigue strength occurred when added 9 wt. % nano TiO$_2$ is 81.7 MPa compared with Al - alloy is 73.9 MPa and the strength improvement factor is 7.800 %. This enhancement in the fatigue life and strength due to the uniform distribution of nano TiO$_2$ and less porosity in the composite. Divagar, et al. [5] tested 7075-T651 Al- alloy with different wt.% of SiC nanoparticles 5, 10 & 15 wt. % and a constant ( 5 wt. %) of Al$_2$O$_3$ nanoparticles as reinforcements by stir casting process. They found the composite contain (7075-T651 + SiC-10 % + Al$_2$O$_3$-5 %) exhibits 12.13% highest fatigue strength than other composites and base metal, and the fatigue life increased when volume fraction of reinforcement increased.

3.3. Microstructure Results
The resulting images of SEM shown in figure (3) . It is clear from figure (3) that the TiO$_2$ nano particles exhibits uniform distribution in metal matrix composite compare to base metal and the microstructure of MMNC (metal matrix nano composite) 9wt.% have high uniformly distribution of alumina in composite. The less porosity and uniform distribution of nano alumina causes to improve hardness, yield, ultimate strength and ductility of MMNCS compared with base metal. Shabani et al. [9] tested the microstructure of 356 Al- alloy with different volume percentage of nano TiO$_2$. They concluded that more uniformly distributed of TiO2 and minimal porosity. That an incorporation of the nanoparticles for improving the mechanical properties of the composites.

|          | 73.2 | 78.5 | 6.752 |
|----------|------|------|-------|
| 7075/T6 Al - alloy with 7 wt. % nano TiO$_2$ |

|          | 74.5 | 80.3 | 7.222 |
|----------|------|------|-------|
| 7075/T6 Al - alloy with 9 wt. % nano TiO$_2$ |

|          | 73.9 | 81.7 | 7.800 |
|----------|------|------|-------|
| 7075/T6 Al - alloy with 11 wt. % nano TiO$_2$ |

a. Microstructure for 7075/T6 AL alloy
b. Microstructure for 7075/T6 AL alloy with 9% wt. TiO$_2$

Figure 3. Microstructure test for 7075/T6 Al- Alloy and 7075/T6 Al- Alloy 9% wt. of nano TiO$_2$

4. Conclusions

The tensile and fatigue properties of aluminum metal matrix composite have been improved by using the nano TiO$_2$, the Ultimate Tensile Strength and yield Strength increased with the increasing weight percentage of TiO$_2$ nanoparticles. The maximum increase in $\sigma_u$ and $\sigma_y$ is occurred at 9 wt. % TiO$_2$ and the improvement percentage (IP) of $\sigma_u$ is 18.5 % while IP for $\sigma_y$ is 15.3 %, for constant fatigue that the maximum fatigue strength and life occurred when added 9wt. % of nano TiO$_2$. The fatigue strength for 9wt. % nano TiO$_2$ at $10^8$ cycle is 81.7 MPa while 7075/T6 Al-alloy exhibited 73.9 MPa resulting 7.800% strength improvement factor and the microstructure of nanocomposite showed fairly uniform distribution of TiO$_2$ in metal matrix resulting in improvement of mechanical properties.

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