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IDENTIFYING REGULARITIES OF HIGH TEMPERATURE ON CONSTANT AND VARIABLE FATIGUE LIFE OF AA7075-Al_2O_3 NANOCOMPOSITE FABRICATED BY STIR CASTING METHOD

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This study aims to determine the effect of high temperature on the fatigue life of AA7075-Al_2O_3 nanocomposites (6 wt % Al_2O_3) fabricated by stir casting. The research problem is to determine the durability, fatigue resistance, and mechanical properties of the nanocomposite under constant and variable loading conditions at elevated temperatures, as well as to identify changes in its behavior due to exposure to high temperatures. The results show that higher temperatures have a big effect on the nanocomposite's fatigue performance under both loading conditions. When the material was tested at a high temperature (150 °C) with an extra 6 wt % Al_2O_3, the ultimate tensile strength and yield stress both went up by 16 % and 15.7 %, respectively. Its fatigue life was also successfully tested under both variable and constant amplitude load conditions. The interpretation of the results suggests that the changes in the microstructure of the nanocomposite material at elevated temperatures lead to an increase in dislocation density and grain size, resulting in an improvement in its mechanical properties. The findings can be utilized to optimize the nanocomposite fabrication process and enhance its fatigue resistance at high temperatures. In addition, the results can be used to enhance the design of aerospace components and high-temperature engines that require materials with excellent fatigue resistance at elevated temperatures. In summary, the investigation of the effect of high temperature on the constant and variable fatigue lives of AA7075-Al_2O_3 nanocomposite provides valuable insight into the material's mechanical properties. The findings contribute to the development of materials that can withstand high-temperature conditions, which has implications for a variety of industries

***Keywords:** AA7075, ceramic particles Al_2O_3, mechanical properties, fatigue characterizations, high temperature*

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1. Introduction

Metal matrix composites (MMCs) are becoming increasingly popular in a wide range of engineering applications, particularly in the aerospace and automotive industries, due to their improved mechanical and physical properties. Among MMCs, aluminum-based composites reinforced with ceramic particles such as Al_2O_3 have garnered considerable interest due to their enhanced mechanical properties, such as strength, hardness, and wear resistance [1]. However, the effect of high temperature on the fatigue life of these composites remains a complex issue that requires additional research. Several studies have been conducted to examine the mechanical properties and fatigue behavior of stir-cast aluminum-based composites reinforced with ceramic particles such as Al_2O_3. The effect of high temperature on the fatigue behavior of these composites, particularly under constant and variable amplitude loading conditions, requires further investigation. In addition, accurate fatigue life prediction models for these composites under high temperature conditions are required.

2. Literature review and problem statement

The paper [1] discussed the processing techniques and mechanical properties of aluminum matrix composites. Powder metallurgy, stir casting, and in-situ techniques, among others, were analyzed in the context of the production of aluminum matrix composites. The article also discussed the mechanical properties of aluminum matrix composites, such as tensile strength, compressive strength, and hardness, and how they are affected by a number of variables, such as the type and quantity of reinforcement used and the fabrication method employed. The study concluded that excellent mechanical properties can be designed into aluminum matrix composites, making them desirable for a variety of applications, including aerospace, automotive, and sporting goods. The article does not explore the effects of high temperature on constant and variable fatigue life of aluminum matrix composites.

Using an analytical approach, the paper [2] investigated the effect of temperature on the fatigue behavior of aluminum alloy AA6061. It was discovered that increasing the temperature decreased the alloy's fatigue life due to an increase in the rate of crack growth and a decrease in fracture toughness. However, other factors such as material microstructure, surface finish, and loading frequency were not considered in the study. To validate the analytical approach and provide more accurate and reliable predictions of fatigue life, experimental studies are required. The study focused only on the AA6061 aluminum alloy, and it did not explore the fatigue behavior of other aluminum alloys. Additionally, the study did not investigate the impact of other variables, such as the presence of nanocomposites, on the fatigue life behavior of aluminum alloys.

The paper [3] examined the influence of alumina and silicon carbide reinforcements on the mechanical and wear properties of Al7075 alloy. The study evaluated the hybrid composite's mechanical properties, including tensile strength and hardness, as well as its wear behavior, using a stir casting technique to produce it. The addition of alumina and silicon carbide reinforcements significantly improves the mechanical and wear properties of the Al7075 alloy, as demonstrated by the results. The research indicates that hybrid composites can be utilized in applications requiring high mechanical strength and wear resistance. However, the study did not investigate the impact of high temperature on the fatigue life behavior of the Al7075/Al_2O_3/SiC hybrid composite.

The effect of stirring temperature (ST) on the mechanical and fatigue properties of AA6061/AL_2O_3 nanocomposites was investigated by the paper [4]. They fabricated the composites using stir casting and conducted mechanical tests. The authors discovered that increasing the stirring temperature enhanced the mechanical properties, such as the tensile strength, yield strength, and hardness. However, the study did not take into account the impact of other processing parameters, such as stirring time and speed, on the composites' properties.

The papers [5–7] focus on the use of ceramic particles, namely SiC and Al_2O_3, as reinforcement in aluminum alloys. These studies investigate the effect of particle size and temperature on the behavior and mechanical properties of high-cycle fatigue. However, the precise effects of Al_2O_3 nanoparticles on the fatigue behavior of AA7075 at elevated temperatures are not completely understood. The paper [5] examined the impact of temperature and particle size on the high cycle fatigue behavior of SiC-reinforced 2124 aluminum alloy. The composites were fabricated using a powder metallurgical technique, and high cycle fatigue tests were conducted at various temperatures and particle sizes. The researchers discovered that an increase in temperature led to a decrease in fatigue life and an increase in crack initiation and propagation rates, whereas a decrease in the particle size of the reinforcement led to an increase in fatigue strength. The paper [7] investigated the effect of varying alumina reinforcement particle sizes. The research used stir casting to create composites with varying particle sizes. The mechanical properties of the composites, such as hardness, tensile strength, and compressive strength, as well as their wear properties, are evaluated. The particle size has a significant effect on the composite, with smaller particle sizes exhibiting superior mechanical and wear resistance properties. The study emphasizes the significance of particle size distribution in determining the properties of particulate composites and offers insight into the design and optimization of such materials for a variety of applications.

The paper [8] examined the fatigue properties of metal alloys at a variety of temperatures and discovered that at room temperature, UTS, YS, and E were lower, but ductility increased by 28.27 %. They investigated the influence of elevated temperatures on the fatigue and tensile properties of 7001-T6 aluminum alloy. They discovered that as the load increased, the material's creep-fatigue life decreased, with the material's maximum stress level being the primary factor in its failure. However, the effect of temperature was not addressed in the study. The paper [9] presented the outcomes of experimental research on the mechanical properties of a stir-cast Al7075-Al_2O_3-B4C composite material. The study examined the effects of varying percentages of alumina and boron carbide reinforcements on the composite's mechanical properties. The study evaluated the composite's mechanical properties, such as hardness, tensile strength, and compressive strength, and identified the optimal reinforcement percentage for achieving the best mechanical properties. The results indicate that both alumina and boron carbide reinforcements significantly improve the mechanical properties of the Al7075 alloy, with the optimal reinforcement percentage varying depending on the mechanical property being evaluated. The study concluded that the stir-cast Al7075-Al_2O_3-B4C composite is a promising material for applications requiring high mechanical strength and hardness. The papers [10, 11] shed light on the mechanical properties of aluminum alloys and nanocomposites, such as the effect of nanomaterials and elevated temperatures on fatigue behavior, creep-fatigue life and strength, and swarm-intelligence optimization of microstructure and mechanical properties. These studies demonstrated the significance of comprehending the microstructure of materials and their response to various loading conditions, as well as the role of nanomaterials in enhancing mechanical properties. Nonetheless, the specific challenges associated with the fatigue behavior of AA7075-Al_2O_3 nanocomposites at elevated temperatures remain unanswered.

The paper [12] proposes a safe fatigue life model for AA2024-T4 and AA2024-T361 under combined high temperature and shot peening in their article. This study does not focus on the same material as the present study, but it emphasizes the significance of developing reliable models for predicting the fatigue behavior of materials under different loading conditions. To be addressed, however, are the specific challenges associated with modeling the fatigue behavior of AA7075-Al_2O_3 nanocomposites at high temperatures.

The paper [13 studied the effect of particle size of TiO_2 reinforced aluminum alloy composites using AA 7075 as a base metal on the fatigue life under room temperate. The experimental results revaled that the increase in particle size of the nonreinforcement gives low fatigue life and strength. Also, the less particle size showed high strength and fatigue life. However, the researchers did not investigate the effect of high temperatures on the fatigue life of the composites, which is a limitation of the study.

In summary, the relevant articles provide valuable insights into the mechanical properties of aluminum alloys and nanocomposites, the role of ceramic particles as reinforcement, the effects of fabrication methods, and the development of accurate models for predicting fatigue behavior. However, the specific challenges associated with the fatigue behavior of AA7075-Al_2O_3 nanocomposites at elevated temperatures remain unresolved, emphasizing the need for additional research in this area. This information is essential for the development of advanced materials that can withstand harsh operating conditions in a variety of industries, including the aerospace, automotive, and marine sectors.

3. The aim and objectives of the study

The aim of the study identifying is to examine the influence of high temperature on the fatigue behavior and mechanical properties of AA7075 under variable and constant load under four cases: room temperature, 150 degrees Celsius, nanocomposite (6 wt % Al_2O_3) at room temperature, and nanocomposite at 150 °C.

To achieve this aim, the following objectives are accomplished:

– to calculate mechanical properties such as ultimate tensile strength (UTS) and yield stress (YS);

– to calculate of the stress-fatigue interaction S-N curve, which shows the applied stress and number of cycles to failure for four different testing scenarios;

– to determine the fatigue life under variable amplitude loading.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of this study is the AA7075-Al_2O_3 nanocomposite produced through stir casting. The purpose of this study is to determine how high temperatures affect the fatigue life of nanocomposites under constant and variable loading conditions.

The main hypothesis of this study is that high temperature has a significant impact on the fatigue performance of the AA7075-Al_2O_3 nanocomposites. The study hypothesizes that exposure to high temperatures alters the nanocomposite's microstructure, leading to an increase in dislocation density and grain size, which enhances its mechanical properties.

The study assumes that the addition of 6 wt % Al_2O_3 nanoparticles to the AA7075 alloy enhances the nanocomposite's mechanical properties and fatigue resistance. The study also assumes that the nanocomposite manufactured by stir casting is appropriate for investigating the effect of high temperature on its fatigue performance.

Utilizing constant and variable loading conditions, the study simplifies the investigation of the effect of high temperature on the fatigue life of the nanocomposite. The study also simplifies the interpretation of the results by focusing on changes in the nanocomposite's microstructure as a result of exposure to high temperatures rather than investigating other factors that may affect the material's fatigue performance.

4. 2. Materials selection

AA7075 metal was chosen due to good toughness, high wear resistance and medium strength, this alloy is widely employed in missile components, aircraft and automobile [1] Al_2O_3 nanoreinforced material particle size with (average 30 nm) is selected due to good properties such as wear resistance tensile and hardness and it widely available in the markets [2].

4. 3. Chemical analysis

The AA7075 base metal was tested for chemical analysis at SIRE in Iraq and compared to standard [14] while the properties of nano reinforced material are taken from [14]. The results are illustrated in Tables 1, 2 respectively.

The mechanical tensile properties were obtained using the tensile-high temperature testing after [16]. Fig. 1 shows the tensile test specimen at (RT) and the tensile high temperature test rig.

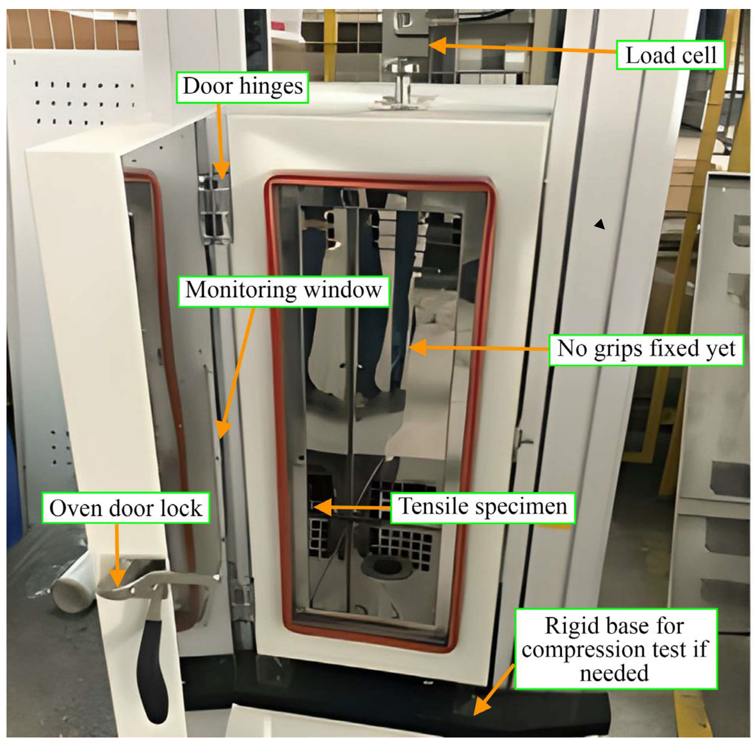

Fig. 1. Thermal tensile test device [15]

Table 1

Chemical analysis of AA7075 in wt % [14]

Mg	Ti	Mn	Cu	Cr	Fe	Si	Zn	Al	Test type
2.7	0.13	0.21	1.52	0.22	0.23	0.17	5.5	Bal	Experimental
2.1–2.9	0.2 max	0.3 max	1.2–2	0.18–0.28	0.5 max	0.4 max	5.1–6.1	Bal	Standard

Table 2

Al_2O_3 chemical composition [15]

Component	CaO	TiO_2	Fe_2O_3	α-alumina	Other
wt %	1.10	1.80	0.80	93	0.02

The capacity of application of temperatures is about 500 °C. The max load which can be applied is 800 MPa.

4. 4. Nanocomposite preparation using stir casting process

The preparation and manufacturing of nanocomposite can be presented by the following steps:

– melting the matrix AA7075 inside the crucible using electric furnace to 850 °C for 20 minutes;

– alumina (Al_2O_3) nano material to 200 °C and added to the melt. The amount of Al_2O_3 is 6 wt %;

– applied 450 rpm stirring speed for 4 minutes by means of mixer;

– pushing argon gas to the solution in order to avoid oxidation.

The device of the manufacturing method can be seen in Fig. 2. More details of the above steps can be found in [10].

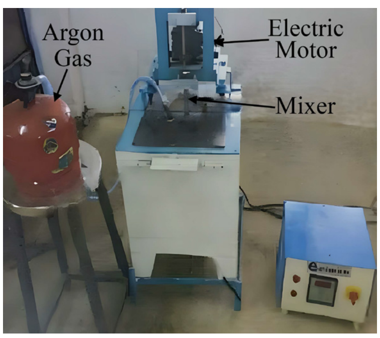

Fig. 2. Manufacturing process of nanocomposite materials [10]

This process is reiterated to get the specimens which contain different weight percentage of nanoparticles.

4. 5. Fatigue test

All the fatigue tests (constant and variable) were done using the fatigue test type PUNN. The shape of the specimens is hourglass type in order to obtain stress concentration in the center of the sample. For all the tests, crack began and fracking took place at the middle of sample [16].

5. Results of fatigue behavior and mechanical properties of AA7075-Al_2O_3 nanocomposite under varying loads and temperature

5. 1. Results of Mechanical properties

The tensile mechanical properties of matrix and nanocomposite 6 wt % Al_2O_3 with high temperature (150 °C) can be presented in Table 3.

The high temperature reduced the mechanical properties, the (UTS) reduced from 233 MPa to198 MPa showing 15 % reduction percentage while the Al_2O_3 improved (UTS) from 198 MPa to 236 MPa showing 16 % improvement and 15.7 % enhancement for (YS) at (150 °C), The same results were found by [6, 8]. The improvement in the mechanical properties of the 6 wt % nanocomposite may be related to the less amount of porosity and uniformly distributed of nanocomposite into the matrix [8].

Table 3

Experimental mechanical properties results

Property	AA7075 (RT)	AA7075 (150 °C)	Nanocomposite (RT)	Nanocomposite (150 °C)
UTS, MPa	233	198	272	236
YS, MPa	120	102	135	121

5. 2. Results of S-N curve

Table 4 presents the applied stress (σ_f) in MPa and No. of cycles to failure for four cases of testing i-e (RT) 150 °C, 6 wt % Al_2O_3 nanocomposite at (RT) and 6 wt % Al_2O_3 nanocomposite at 150 °C. The results are tabulated in Table 4. The Basquin equation of the four cases can be seen in Table 5. The S-N curve of the four tests can be presented in Fig. 3.

Table 4

S-N curve results for four cases of testing

Specimen. No.	Test description	Applied stress (σ_f), MPa	N_f cycles	N_f ave.
1–3	S-N curve at (RT)	125	11800, 16000, 18600	15467
4–6		100	116200, 98800, 124000	113000
7–9		75	1265000, 926760, 1626000	1272587
10–12	S-N curve at 150 °C	125	8200, 10600, 11200	10000
13–15		100	88400, 90000, 1062400	91533
16–18		75	870600, 916200, 1062400	949733
19–21	S-N curve 6 wt % Al_2O_3 at (RT)	125	14200, 20600, 16800	17200
22–24		100	132600, 118000, 127800	126133
25–27		75	1362000, 1526000, 1396200	1428067
28–30	S-N curve for 6 wt % Al_2O_3 at150 °C	125	10200, 12800, 14600	12533
31–33		100	114200, 96600, 101200	104000
34–36		75	1025000, 1162000, 962600	1049867

Table 5

Basquin equations for S-N curve at four cases of testing

Test description	S-N curve equation	R^2
Matrix S-N curve at (RT)	$\sigma_f = 394N_f^{-0.116}$	0.9997
Matrix S-N curve at 150 °C	$\sigma_f = 354N_f^{-0.118}$	0.9968
S-N curve for 6 wt % Al_2O_3 at (RT)	$\sigma_f = 387N_f^{-0.107}$	0.9997
S-N curve for 6 wt % Al_2O_3 at 150 °C	$\sigma_f = 374N_f^{-0.116}$	0.9968

From the above Basquin equations, it is clear that these equations have good correlations coefficient (R^2) which proved that the experimental data can be described well using Basquin formula.

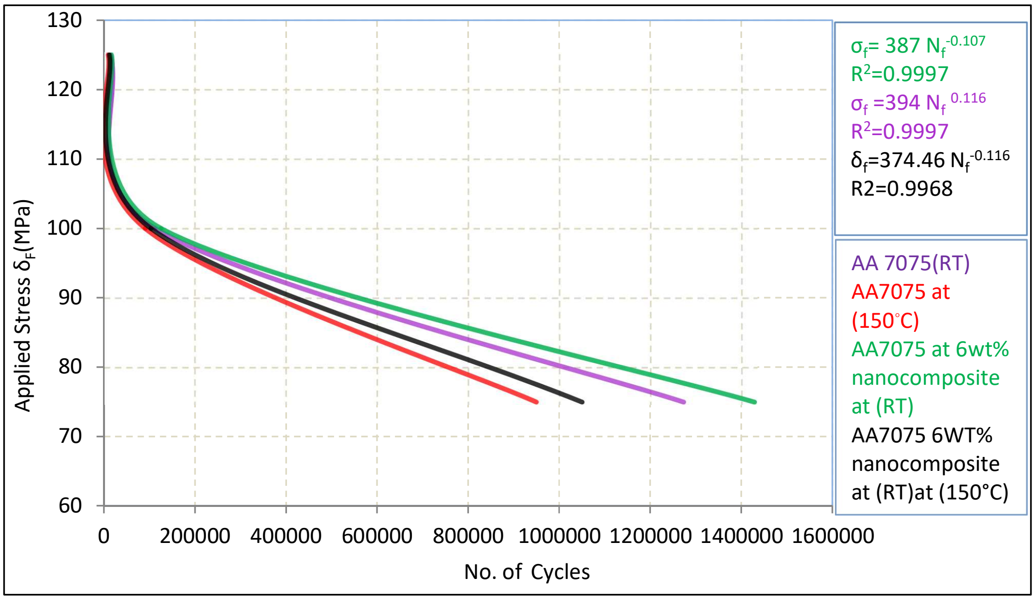

Fig. 3. Constant S-N curve at four cases of testing

As shown in Table 6 fatigue strength of AA7075/6wt %. Al_2O_3 nanocomposite at (RT) has the highest value of endurance fatigue limit of 68.97 MPa and it reduced to 57.65 MPa due to the application of 150 °C high temperature. The amount of reduction in fatigue strength is 11.32 MPa. Therefore, both mechanical and microstructure behaviors of 7075/6 wt %. Al_2O_3 contribute significantly in evolution of fatigue strength. For matrix AA7075 the reduction percentage in fatigue strength due to 150 °C temperature was 13 %. A comparison between base metal (AA7075) and nanocomposite at 150 °C is illustrated in Table 7.

Table 6

The fatigue strength of the four cases at 10^7

Test description	Fatigue strength at 10^7
S-N curve at (RT)	60.74 MPa
S-N curve at 150 °C	52.84 MPa
S-N curve for 6wt%Al_2O_3 at (RT)	68.97 MPa
S-N curve for 6wt%Al_2O_3 at150 °C	57.65 MPa

Table 7

Effect of addition Al_2O_3 on fatigue strength at 150 °C

Fatigue strength at 10^7 cycles	
Matrix	Nanocomposite
52.84	57.65
Improvement percentage (IP)	8.34 %

The addition of 6vwt % Al_2O_3 to the base metal improved the fatigue strength by 8.34 % at 150 °C. The use of nano reinforcement material is aimed at minimizing the grain size and the porosity and maximizing the tensile, hardness properties of AA7075 based metal nanocomposite. [10] tested aluminum alloy with various volume friction of Al_2O_3 using stir casting route. They found that increasing the amount of Al_2O_3 lead to reduce the grain size. At zero Al_2O_3, grain size was 44 μm and at 5 volume friction the grain size was 24 μm. Increase in wt % of nanoparticles enhanced the mechanical properties of AA7075 when added Al_2O_3 using stir casting method. The reduction in porosity, grain size and increase in mechanical properties contribute for improvement the fatigue strength and life [6].

The behavior of constant S-N curve at four cases of testing observed that the application of temperature reduces the fatigue life and strength. Comparison between 17 lowered by 43.963 % at stress level of 540 MPa [11]. Fatigue life experimental results showed that an increase of 17.4 % when addition 9 wt % of Al_2O_3 to AA6061 compared to matrix fatigue results [4]. The following factors may contribute to improve the fatigue life and strength [10, 12]:

1. The uniform distribution of Al_2O_3 into matrix.
2. Homogenous dispersion of nanoparticles.
3. The improvement in mechanical properties.
4. High thermal boundary between the matrix and the nanoparticles.

5. 3. Results of variable loading test

From the Table 8 it is observed that the fatigue life for low-high loading is greater than that at high – low loading. Starting with high load leads to accelerate the crack speed and then failure occurs at low fatigue life [13] Fatigue life for variable loading of 10 wt % nanocomposite AA6061/10 wt % Al_2O_3 exhibited high fatigue life when the composite tested at low-high loading compared to high–low loading fatigue life. Also, a comparison between variable loading with 10 wt %. Al_2O_3 and based metal was made. The experimental results revealed that the 10 wt %. Al_2O_3 composite exhibits 33.37 % and 39.58 % increase in fatigue life when they compared to the matrix for low-high and high-low loading sequence respectively [10].

It is clear that the addition of nanomaterial to matrix leads to high improvement in fatigue life and Strength.

The experimental results are an average of three samples. It is clear that the addition of 6 wt % Al_2O_3 to the matrix raised the variable fatigue life at 150 °C from 72400 cycles resulting to 169800 cycles leading to an improvement percentage of 57.36 % while at high – low loading an improvement percentage (IP) of 65.5 % is recorded as shown in Fig. 4.

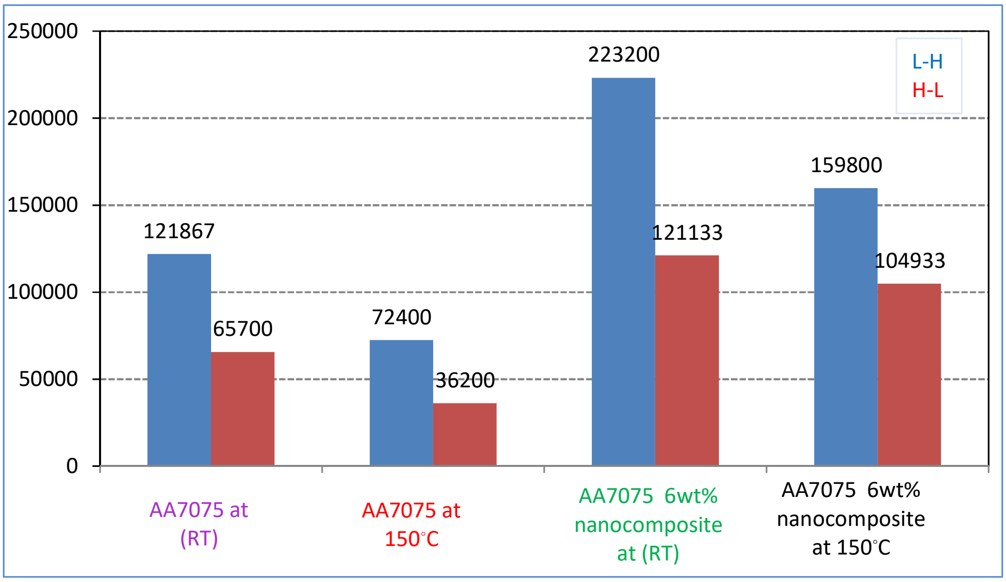

Fig. 4. Variable fatigue loading fatigue result at (RT) and (150 °C)

Table 8

Variable loading fatigue results at (150 °C) without and with addition the 6 wt % Al_2O_3

Matrix at 150 °C		Nanocomposite at 150 °C	
Low-high	High-low	Low-high	High-low
72400 cycles	36200 cycles	169800 cycles	104933 cycles
Improvement percentage (IP)			
Low-high (57.36 %)		High-low (65.5 %)	

Fig. 4 explains how the nonreinforced material enhances the cumulative fatigue life for both loadings (Low high and high-low).

6. Discussion of experimental results of high temperature fatigue performance of AA7075-AL_2O_3 nanocomposite

The obtained results of this study indicated that the tensile mechanical and fatigue properties of aluminum metal matrix composites have been improved by using Al_2O_3 nanomaterial. The UTS and YS increased by 6 wt % of Al_2O_3 as given in (Table 3). For constant fatigue results, life and strength are improved at 6 wt % Al_2O_3 compared to matrix. For cumulative fatigue, the addition of 6 wt % Al_2O_3 to the base metal showed a high improvement in fatigue properties. These improvements of AA 7075 with 6 wt % Al_2O_3 may be due to the uniform distribution of Al_2O_3 into the matrix, less porosity, high mechanical properties of Al_2O_3 itself, and high binding between Al_2O_3 and matrix (Table 3). These notes are in good agreement with Ref [10], who used the same matrix and nonreinforced material but without room temperature (RT).

The peculiarities of the proposed method include the use of the stir casting method to manufacture the AA7075-Al_2O_3 nanocomposite and the examination of the fatigue behavior and mechanical properties of the nanocomposite at high temperatures. Stir casting produced a more uniform distribution of nanoparticles in the matrix than previous studies, which improved the mechanical properties of the composite as shown in (Table 3). The obtained results are consistent with the existing literature, which suggests that high temperatures can reduce the fatigue life of the nanocomposite.

The addition of Al_2O_3 to the matrix raised the mechanical properties, which clearly outweighed the matrix, and the mechanical properties of Al_2O_3 are higher than the matrix. The mechanical and fatigue properties, which still stand, are affected more by these factors. The effect of high temperatures 50 nanomaterials improve the characterization of composites when exposed to high temperatures as presented in (Table 6).

The limitations inherent in this study include the use of only one high temperature and the examination of only one nanocomposite composition. The results may not be representative of other levels of temperature or other nanocomposite compositions. Furthermore, the study did not examine the changes in the microstructure that occurred during the manufacturing process.

The disadvantages of the study include the lack of examination of the microstructure of the nanocomposite and the lack of comparison with other manufacturing methods for the nanocomposite. To eliminate these disadvantages, future studies could include examining the microstructure using techniques such as scanning electron microscopy and comparing the fatigue behavior and mechanical properties of the stir casting method with those of other manufacturing methods.

One of the difficulties that is encountered along the way is the variability in the properties of the nanocomposite due to the manufacturing process, which can affect the accuracy and reproducibility of the results. Future research could look into how different nanoparticle weight fractions affect composite fatigue life and how advanced characterization techniques can be used to examine microstructural changes that occur during the manufacturing process.

7. Conclusions

1. There is obvious effect of the Al_2O_3 content addition on strength of AA7075.The addition amount of 6 wt %

Al_2O_3 improved the (UTS) and (YS) by 16 % and 15.7 % at (150 °C) respectively.

2. The application of nanocomposite technique is aimed at maximizing the mechanical properties, Fatigue strength and life at constant amplitude and fatigue strength and life at available amplitude loading. Fatigue strength of AA7075 at high temperature (150 °C) was improved by 8.34 % when 6 wt % Al_2O_3 addition to the base metal.

3. The fatigue life of available loading was improved by 57.36 % and 65.5 % for low-high and high-low loading sequences under the application of 6 wt % Al_2O_3 respectively.

Conflict of interest

The authors state that there is no conflict of interest regarding this study, whether it be financial, personal, authorship, or any other nature that could affect the research and its results as they are presented in this article. The authors declare that there is no conflict of interest regarding this study.

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Data availability

The manuscript has no associated data.

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