Numerical Analysis of Fatigue Life and Strength of AA5052 Aluminum Alloy Reinforced with ZrO₂, TiO₂ and Al₂O₃ Nanoparticles

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ARTICLE INFO	ABSTRACT
  	In this study, the finite element method using ANSYS workbench 16.1 has been successfully used to predict the fatigue life, fatigue strength, and the factors of safety for the as cast AA5052 as arrow matrix and its composites: AA5052/7 wt% ZrO_2, AA5052/7 wt% TiO_2 and AA5052/7 wt% Al_2O_3. The Finite Element Analysis (FEA) model was building according to dimensions of the experimental fatigue specimen. The total number of elements was 504 elements with a total number of nodes of 2572 nodes. The numerical fatigue test was processed under static structural analysis, and it has been analyzed using fatigue tool on ANSYS, Goodman theory was used for the prediction of life. The FEM using ANSYS.16.1 workbench simulation showed a good agreement with the experimental results for all the stress life curves and the highest difference in fatigue life was 17% and the lowest was 1.4%, for ZrO_2 composite, while the maximum overall average error was 2.031% for AA5052 and the lowest was 0.378%, for Al_2O_3 composite. The maximum difference about 4.14 % between the experimental and numerical fatigue strength at 10^7 cycles for the row matrix and less than for the composites, also the minimum factor of safety for the AA5052 alloy is 0.8327 and for AA5052/7 wt% ZrO_2 composite is 1.0709 while for both AA5052/7wt%TiO_2 and AA5052/7 wt% Al_2O_3 composites are 1.0707 at specific design life.

1. Introduction

The phenomenon of the degradation of mechanical properties of a material due to the application of loads that fluctuate over time is called fatigue and the resulting failure is called fatigue failure [1]. Fatigue has been widely recognized by engineers as an important element in mechanical design, most machine parts are subjected to variable loads, and a few are subjected to static loading. Fatigue failure is caused by cyclic loading at loads well below the yield strength of materials, [2]. Composite materials are the combination of two or more distinct materials to form new materials that have quite different properties, and they do not dissolve or blend into each other, the different materials in the composite work together to give the composite its unique properties [3]. Many studies have been analysed the behaviour of fatigue (strength and life) of materials and composites.

Yahya Ali Fageehi, (2021),[4] presented computational modeling of a crack growth path under mixed-mode and investigated the influence of a hole on both fatigue crack propagation and fatigue life when subjected to constant amplitude loading conditions the simulation specified the crack propagation path such that the critical structure domain was not exceeded. ANSYS Mechanical APDL 19.2 was introduced with the aid of a new feature in ANSYS: Smart Crack growth technology. It

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predicts the propagation direction and subsequent fatigue life for structural components using the extended finite element method (XFEM). The validation of the software results was revealed by consistent comparisons with the numerical results of crack propagation by ANSYS and the experimental results.

A. Mamoon et al (2020), [5]: studied fatigue properties of AA6061 as a master Aluminum alloy reinforced with (0.5, 1.0, 1.5, 2.0 and 2.5) wt.% and 10nm size of silicon carbide, (SiC). The Nano composite was fabricated using stir casting method. For fatigue testing the type of load is rotating bending and stress ratio (R= -1), they found that the highest fatigue strength and life were occurred at 2.0 wt. % of SiC Nano particles at (10^7) cycles, about 11.48% compared to as cast AA6061 alloy. Also, the study say that the enhancement of the Nano composite may be occurs because of: the less porosity, uniform distribution and high bounding between SiC and AA6061 matrix and high mechanical properties of SiC dislocation density.

M. Vaghari et al (2019), [6]: fabricated Al matrix composites reinforced by Al_2O_3 of 35nm in size and (4, 6 and 8) wt.% using wet attrition milling followed by hot forward extrusion process, the study shows that the increasing of Al_2O_3 weight percentage up to 6 wt.% enhanced the fatigue life of the composites and adverse behavior at 8%wt.

S. Arivukkarasan, et al (2013), [7]: fabricated four types of specimens: Al-alloy matrix without alumina silicate particulates and Al-alloy matrix with 5, 15 and 20 Vol. % Alumina silicate particulates to study the behavior of materials under cyclical loading.

ANSYS work bench has been used for the fatigue strength analysis. The results showed that the minimum value of factor of safety for 5% reinforcement composites is 1.0131, while for the composite with 15% and 20% volume fraction of particle reinforcement has the value nearest to one. So, that indicates failure before the design life is reached, also the study showed that the fatigue life for the 20% reinforcement is high, when compared to the remaining volume fraction of the particle reinforcement and the

fatigue strength analysis using the software has good agreement with the experimental results.

N. Sinan Koksal, et al (2013), [8]. studied fatigue life estimation of a notched structural steel beam. The fatigue analysis is performed using ansys Workbench and the Stress life type analysis is used which based on stress-cycle curves. The maximum damage and the equivalent alternating stress, and minimum factor of safety occurred at the tip of the notch. Two notch angles (45° and 90°) and various notch depths are considered. On the other hand, the fatigue life decreased slightly up to a certain notch size (20 mm) and considerably after that value.

There are two methods that can be used to predict fatigue life, i.e., conducting experiment tests and using Finite Element Method (FEM)-based simulation. FEM has the advantage that it is possible to identify stress distribution, capable to visualize the failure mechanisms in certain areas, can reduce development time and development cost, facilitate shape optimization, and improve product quality. Nevertheless, FEM needs to be validated to maintain its accuracy in analyzing fatigue phenomena. The finite element method is a numerical simulation approach that may be used to solve mechanical engineering problems such as stress-strain problems influenced by cyclic or other loads. In the study of fatigue life materials, the finite element method divides material bodies into elements and nodes. Every node should have physical properties such as stress-strain, the value of which is determined by the amount of energy applied to the materials.

The aim of present work is is to verify the experimental results of fatigue properties of Aluminum alloy AA5052 Nano composites that obtained from experimental work and simulate the experimental results using FEM in ANSYS.16.1 workbench and compare the results and to present reliable validation reference by considering stress life approach in calculation.

2. Finite element method

Discretization domain able to analysis using the finite element method, the values among of

node should be approximate using interpolation function [9]. Mathematically this function:

$$\bar{u}(x) = \sum_{i=1}^{n+1} uiNi(x) \qquad (1)$$

$$L\left[\bar{u}(x)\right] - f(x) = R \qquad (2)$$

where $\bar{u}(x)$ is a solution in x direction, ui is node, and Ni is element or linear function, and $L[\bar{u}(x)]$ linear differential operator. Equation 1 and equation (2) can be written to be differential equation in one dimension:

$$\frac{d^2u}{dx^2} - u = 0 \; (0 \le x \le 1) \qquad (3)$$

Using the Galerkin method, equation (3) can be writing into the matrix equation:

$$[Kij]\{uj\} = \{fi\} \qquad (4)$$

Linear algebra in equation (4) is the formulation to solve mechanical properties of materials such as strain, stress, and deformation materials, etc., so the fatigue life of material can be calculated.

3. Numerical procedure

The using of numerical software is to determine an approximate solution to the specific problem. When the experimental results are available, any numerical results can be verified. In the present work, the finite element analysis (FEA) model was built according to the dimensions of the experimental fatigue specimen. The procedure for building the model geometry in ANSYS Workbench 16.1 starts by using (new spaceclaim geometry) to sketch a circle shape of diameter 9 mm, and pull it for a length of 21 mm, to produce solid geometry, then, select other circle with 4mm in diameter to complete the required shape and obtain the complete body. The complete 3D model such as shown in Figure (1), the model was saved for the ease of importing from ANSYS Workbench 16.1.

The mechanical properties such as yield strength, ultimate tensile strength, mean stress, alternating stress and fatigue life (the average of three specimens), acquired from experimental tests were assigned in the engineering data of the software. The material properties can be fed to the model using the following command sequence: "Engineering Data" "General Material" "Add Material" "Input Properties" "Save Data". Moreover, the meshing process was done by choosing automatic method, and then generates mesh option to generate mesh. The number of elements and nods for the model were generated automatically as shown in Figure (2). The total number of elements was 504 elements with a total number of nodes of 2572 nodes. The boundary conditions shown in Figures (3and 4), the applied load can be change to obtain the equivalent alternating stress, (applied stress level) and corresponding fatigue life. The fixed support indicates the specimen end was clamped with all degrees of freedom fixed and at the other end the load was applied.
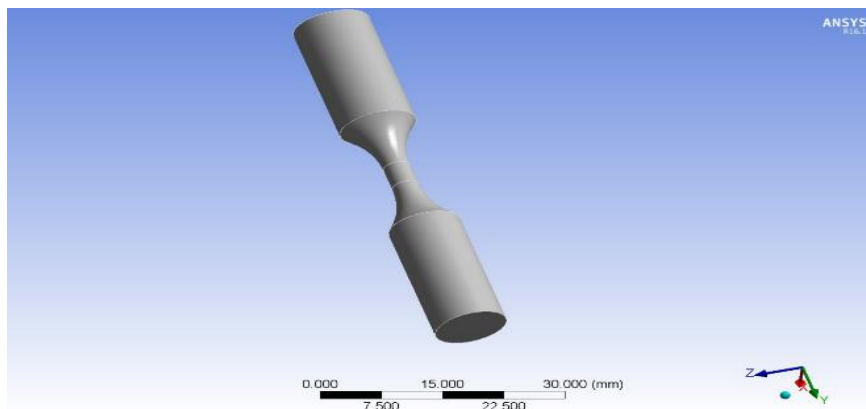

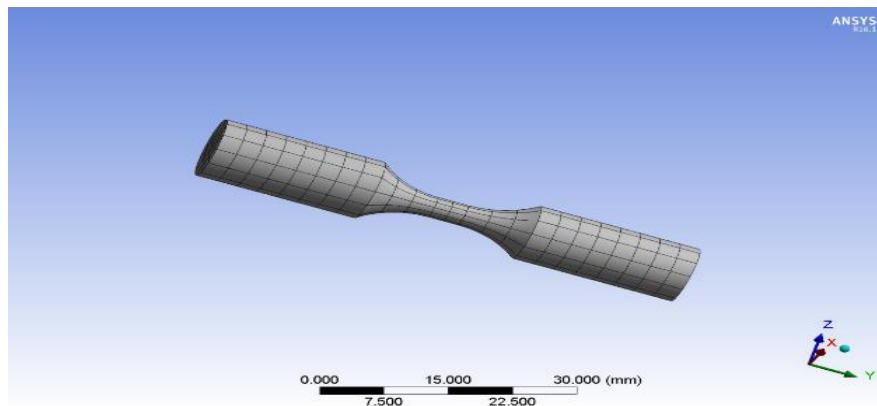
Figure 1. ANSYS model used for fatigue analysis
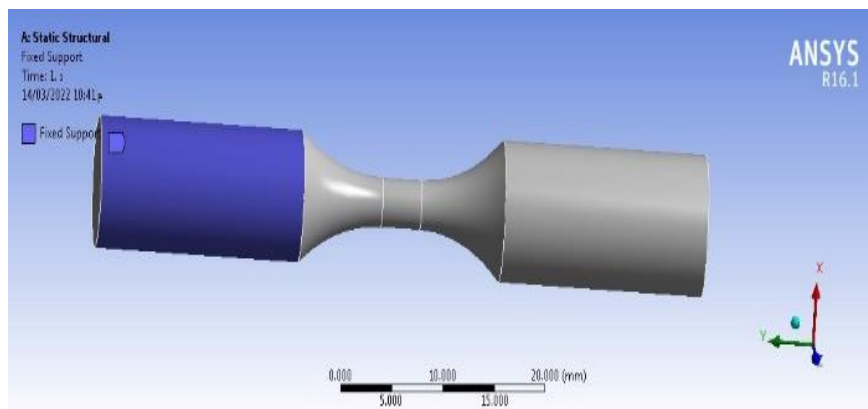
Figure 2. The model with mesh

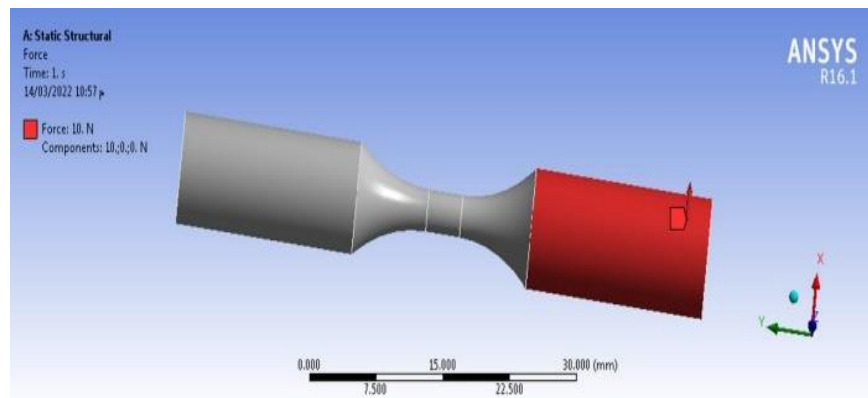**Figure 3.** The model with a fixed support

Figure 4. The model with applied load

4. Results and discussion

4.1. Experimental results

The experimental results of mechanical and fatigue properties for the AA5052 Metal matrix and for the composites: AA5052/7wt%ZrO$_2$, AA5052/7wt%TiO$_2$ and AA5052/7wt%Al$_2$O$_3$ were obtained from the reference [9]. The mechanical properties such as shown in Table (1) and fatigue testing results under constant amplitude loading with stress ratio R= -1 for the metal matrix and composites can be seen in Table (2).

where:

UTS: ultimate tensile strength, (MPa).

YS: tensile yield strength, (MPa).

σ_a: applied stress level, (MPa).

N_f: number of cycles to failure.

(Nf). avg: the average cycles to failure of three specimens.

Table 1: Mechanical properties of AA5052 alloy and composites with 7 wt. % of Al_2O_3, TiO_2 and ZrO_2, [10]

Types of material	UTS MPa	YS MPa
AA5052	87.65	65
A5052/7wt%ZrO_2	135	87
A5052/7wt%TiO_2	119	75
A5052/7wt%Al_2O_3	99	69

Table 2: Experimental fatigue testing results under constant amplitude loading for AA5052 and for the Composites, [10]

Description of Specimens	Specimen No.	Applied Stress σ_a (MPa)	Number of cycles to failure (N_f) cycles			(N_f) avg
AA5052 Metal matrix	1,2, 3	60	32500	36100		32616
	4, 5, 6	50	29250			153351
	7, 8, 9	45	137250	180340		466307
	10,11, 12	40	142465			554299
			462660	450661		
			485600			
			571314	556474		
			535110			
AA5052/7 wt% ZrO	13,14,15	70	9986	8749	9573	9436
	16,17,18	60	55104	49312		54872
	19,20,21	50	60200			657432
	22,23,24	45	766523	670333		996518
			535441			
			950123	1150200		
			889232			
AA5052/7 wt% TiO_2	25,26,27	70	6850	11523		9015
	28,29,30	60	8672			42190
	31,32,33	50	39400	42370		214273
	34,35,36	45	44800			638474
			186700	210000		
			246119			
			666474	727322		
			521113			
AA5052/7 wt% Al_2O_3	37,38,39	70	7869	10236	11487	9864
	40,41,42	60	37687	39262		42171
	43,44,45	50	49565			194354
	46,47,48	45	197866	200715		502543
			184482			
			549927	485921		
			471782			

4.2 Numerical results

In ANSYS.16.1 workbench we can change the applied load on the specimen until the part will fail due to fatigue load, to change its fatigue life, so for every load, the fatigue life can be found numerically and consequently, the numerical S-N curve can be obtained for every material or, composite materials which is used in this work. The fatigue test was processed under static structural analysis with fully reversed applied stress (stress ratio R= -1), Goodman theory has been used for the prediction of life. Figures (5) and (6) shows the example of numerical results from the software ANSYS. The maximum Stress is located at the mid area of the specimen, at this area the failure occurs and the fatigue life is the minimum.
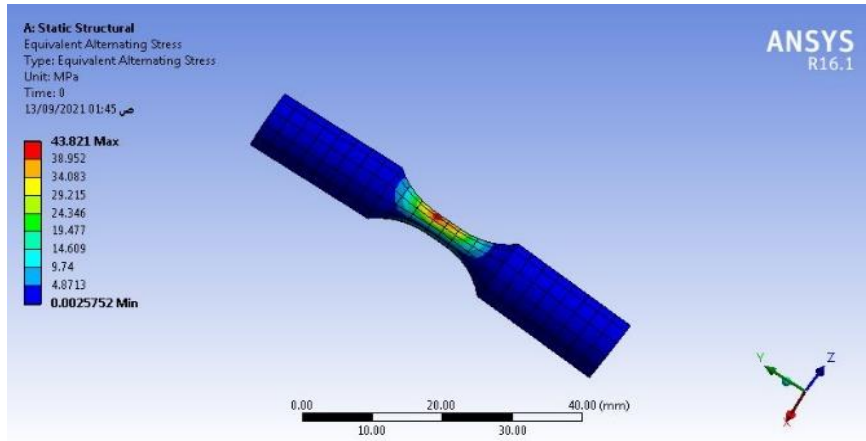

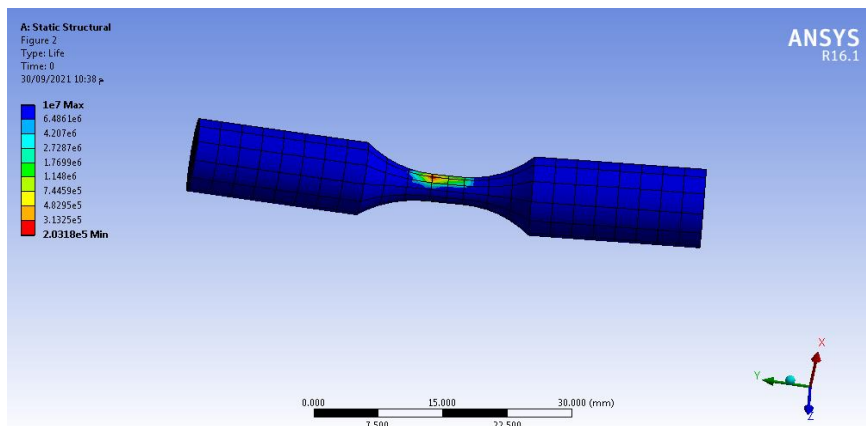**Figure 5.** Example of applied alternating stress result

Figure 6. Example of numerical fatigue life result

The fatigue life is the most essential factor that can be obtained from the numerical analysis based on basquin equation:

$$\sigma_f = a*(N_f)^b \tag{5}$$

where:

σ_f: applied stress, (fatigue strength at N_f), (MPa).

N_f: fatigue life at failure, (cycles).

(a) & (b) are material constants.

Figures (7, 8, 9, and 10), shows the numerical behavior of fatigue life, (S-N) curves for the as cast AA5052 aluminum alloy and for the composites: 55052/7 wt% ZrO_2, AA5052/7 wt% TiO_2, AA5052/7 wt% Al_2O_3 respectively, comparing with experimental fatigue life behavior. The experimental data were compared with the numerical ones by using the overall average error calculations which can be expressed as in the following equation [11].

Overall average error =
$$\frac{\sum_{j=1}^{n} |\log Ni(\exp) - \log Ni(num)|}{\sum_{j=1}^{n} \log Ni(\exp)} \times 100\% \tag{6}$$

where
N: is the number of cycles to failure,
n: is the number of specimens in each curve.

The stress-life in Figure (7) shows the comparison of experimental and numerical results of AA5052 row matrix. The highest difference was 14% at (60MPa) applied stress level. In terms of numbers, the experiment displayed (35472) cycles and numerical (41282) cycles. The lowest difference was at (50MP) applied stress with only a 3%, while the difference at (45MPa) is 4% only. And overall error was 2.323%.
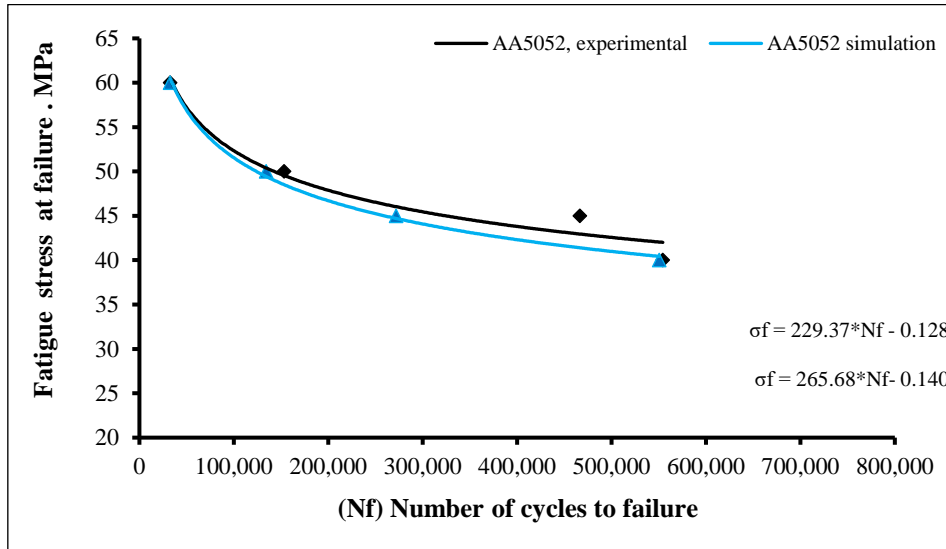

Figure 7. S-N curves of experimental and numerical data of the as cast AA5052 aluminum alloy

The comparison between experimental and numerical results of AA5052/7wt. % ZrO_2 composite is presented by the stress-life curves in Figure (8). The results showed the fatigue life of (55865) cycles and (56679) cycles for the experimental and numerical work, respectively, at 60MPa applied stress, there was only a small difference of about 1.4%. While the difference increased to 14.8% and 17% between the two methods, at 50 and 45 MPa, respectively. And overall error was 2.031%.
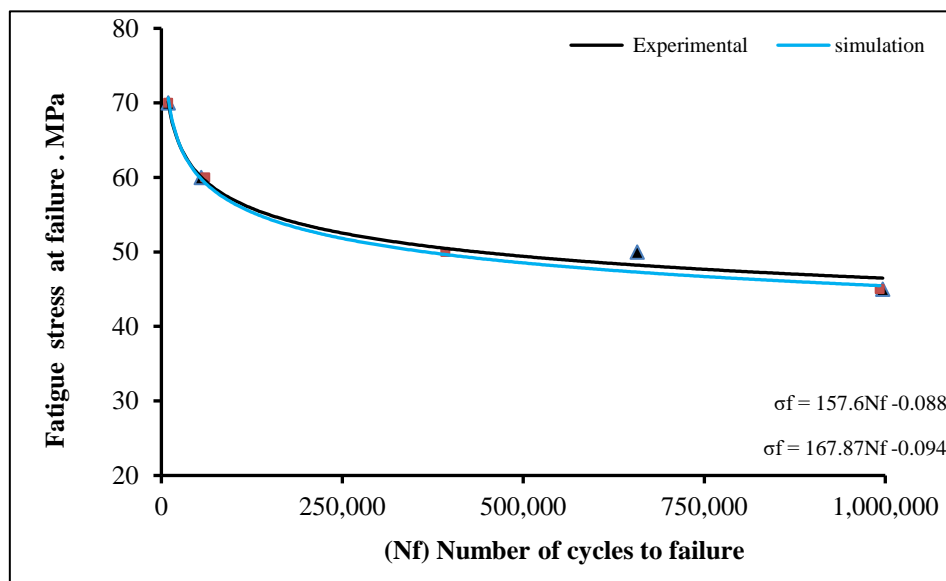

Figure 8. S-N curves of experimental and numerical data of AA5052/7% ZrO_2 composite

Figure (9) shows the comparison of the stress-life curves for the AA5052/7wt% TiO_2 composite at room temperature. At applied stress 60MPa, the experimental fatigue life was 43402 cycles and the numerical value was 45,443 cycles, with only a small difference of about 4.5%, while increased to 6% and 7.8% at 50 and 45MPa, respectively. And overall error was 0.914%.
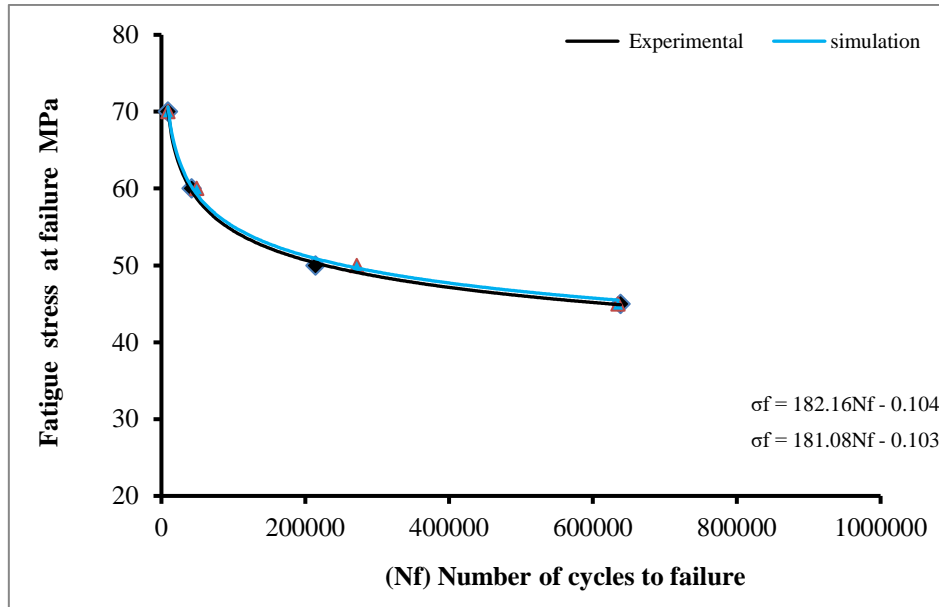

Figure 9. S-N curves of experimental and numerical data of AA5052/7% TiO_2 composite

The stress-life in Figure (10) shows the comparison of experimental and numerical results of AA5052/7 wt%. Al_2O_3, lowest difference was at (60MP) applied stress with only a 2.19%. In terms of numbers, the experiment displayed is (40476) cycles and numerical is (41384) cycles. The highest difference was 4.4% at (45MPa) applied stress; while the difference at (50MPa) is 3.6% only, and overall error was 0.378%.
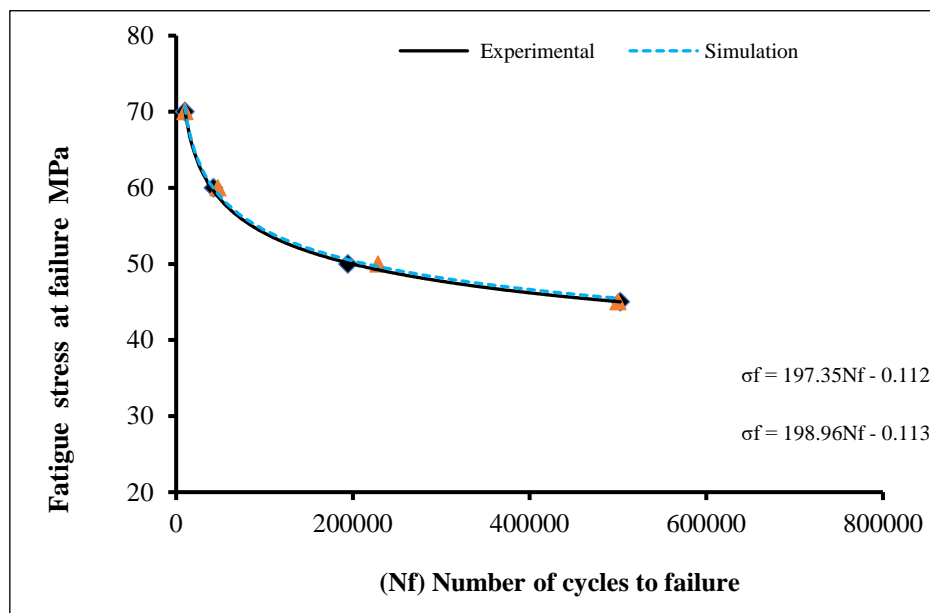

Figure 10. S-N curves of experimental and numerical data for AA5052/7% Al_2O_3 composite

Also, the numerical fatigue strength can be obtained from the S-N curves equation at 10^7 cycles as given in Table (3). The percentage difference between experimental and numerical fatigue strength at 10^7 cycles for the base material AA5052 and the composites, also listed. The percentage difference, (error) was calculated by the following equation:

$$percentage\ error = \frac{\sigma fnum - \sigma fexp}{\sigma fnum} \times 100 \qquad (7)$$

where:

$\sigma_{f \cdot num}$: the numerical fatigue strength at 10^7 cycles

$\sigma_{f \cdot exp}$: the experimental fatigue strength at 10^7 cycles

Table 3: Numerical and experimental fatigue strength at 10^7 cycles, with the percentage error

Composite material	Numerical fatigue strength (MPa)	Experimental fatigue strength (MPa)	Percentage error%
AA5052	27.8	29	4.13
AA5052/ ZrO$_2$	36.9	38	2.9
AA5052/ TiO$_2$	34.4	34	1.16
AA5052/ Al$_2$O$_3$	32.45	32	1.38

The experimental and numerical S-N curves are clearly too convergent, as seen in the comparative Figures. As a result of the comparison, the experimental work and numerical data behaved similarly. In all cases, the highest percentage difference (error) of fatigue strength between experimental and numerical values doesn't exceed 4.14 percent. The difference of experimental results is due to several factors such as scratches and micro-structural behavior; therefore, all the results show a good trend line comparison which proves a good agreement and the fatigue life for the 7 wt. % ZrO$_2$ reinforcement is high, when compared to the remaining types of the particle reinforcement.

The fatigue strength of the alloy and composites was further analyzed with the aid of ANSYS software to determine the factor of safety. Figures (11, 12 and 13) display the contours graph of the factors of safety, it is seen clearly that the maximum factor of safety obtained in this study was 15 and the minimum factors of safety for the alloy was 0.8327 and for the composites AA5052/7 wt% ZrO$_2$, AA5052/7 wt% TiO$_2$ and AA5052/7 wt% Al$_2$O$_3$ were 1.0709 and 1.0707 at specific design life respectively, The result shows that the fatigue failure of the alloy occurred before the design life was reached since the minimum value obtained less than one. This result can help the user of the developed material to know the idea of the stress state.
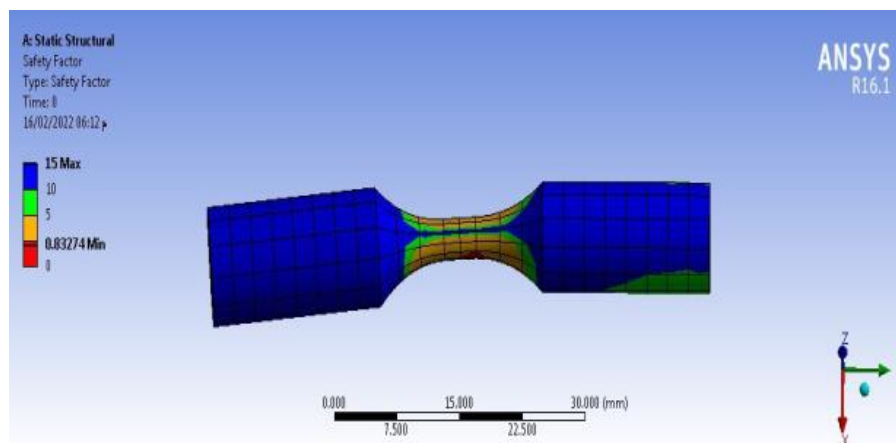

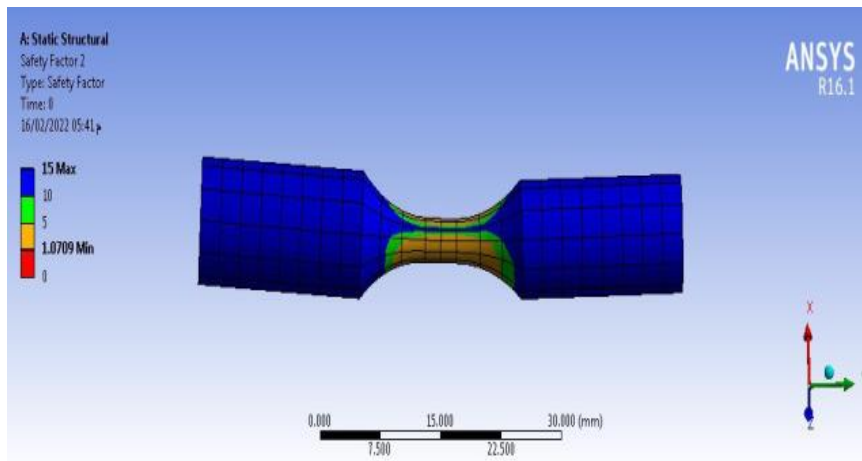**Figure 11.** Fatigue factor of safety for the AA5052 alloy

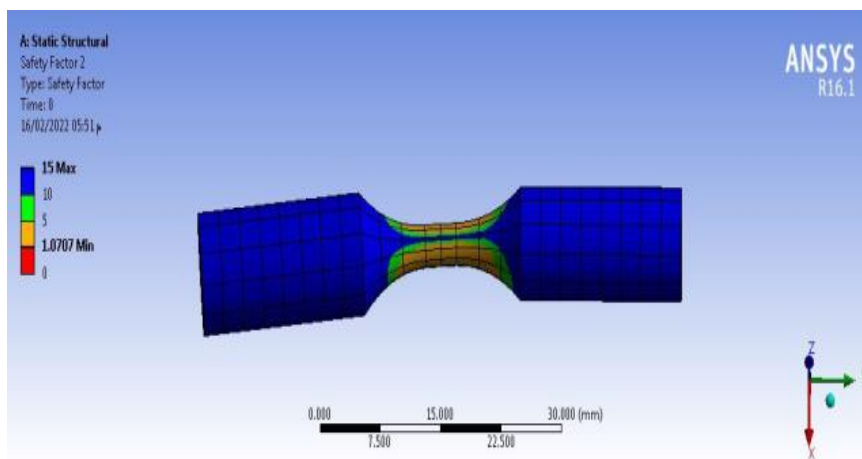**Figure 12.** Factor of safety for the 7 wt% ZrO_2 composites

Fatigue 13. Factor of safety for the 7 wt% Al_2O_3 composites

4. Conclusions

1. Finite element method by using ANSYS.16.1 workbench is a good tool for fatigue. The numerical results showed a good agreement with the experimental results for all stress life curves. The comparison of the experimental and numerical results at room temperature showed that the highest difference in fatigue life was 17% and the lowest was 1.4%, for ZrO_2 composite, while, the maximum overall average error was 2.031% for AA5052 and the lowest was 0.378%, for Al_2O_3 composite.

2. The experimental and numerical fatigue strength under constant amplitude loading of the ZrO_2 Nano composite showed highest value such as (38 MPa) and (36.9MPa) respectively, at 10^7 cycles, and less than for TiO_2 and Al_2O_3 Nano composite compared to the matrix.

3. The maximum difference about 4.14 % between the experimental and numerical fatigue strength at 10^7 cycles was for the row matrix and less than for the composites.

4. The minimum factors of safety for the alloy are 0.8327 and for AA5052/7 wt% ZrO_2 composite is 1.0709 while for both AA5052/7 wt% TiO_2 and AA5052/7 wt% Al_2O_3 composite are 1.0707.

5. Based on the results on the fatigue strength, it was concluded that AA5052 alloy/7 wt. % ZrO_2. Composite can be used for application where cycling loading is vital.

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