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Cumulative Fatigue Life Estimation Under Combined Shot Peening and Elevated Temperature for AA7001-T6

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ABSTRACT

The fatigue life of aluminum alloys (7001–T6) and shot peening at various temperatures are predicted in this study. Shot peening (SP) steel balls is a surface treatment technique that can help minimize damage. This study set out to conduct an experimental investigation in order to ascertain the amount of damage caused by fatigue buildup for AA7001-T6 under rotating bending loading and a stress ratio R = -1. RT (room temperature), 330 °C, and SP + 330 °C were the temperatures used in the testing. To predict the fatigue life under high temperatures, it was suggested to use a modified damage stress model that had been established to take damage at different load levels into account. To determine the most damage (Miner's rule), the output of the current model was compared to experimental findings and the output from the fatigue damage model. The comparison showed that the current model had a respectable level of safety, whereas the miners' model had two models: one for low-high loading and the other for high-low loading, and the results were suitable for extending fatigue life. Despite the fact that H-L loading has a longer fatigue life (19477) cycles than the experimental (16433 cycles), L-H loading is conservative (Nf is 19477 cycles less than the experimental (24733 cycles) (non-conservative).

1. Introduction

Fatigue is the term for the degradation that can happen to a structure or component after it has been subjected to a dynamic load, such as cracking or other damage. Damage is defined as localized plastic distortion that leads to the development of cracks. Practically speaking, 90% of mechanical failures result from fatigue [1]. Fatigue failure happens when a material is subjected to different loads. The fracture surface lengthens and experiences catastrophic failure when there is less failure stress than yield stress [2]. Due to its great strength, low weight, outstanding thermal and electrical conductivity, ease of recycling, and other beneficial properties, aluminum is commonly used in vehicles, airplanes, and a number of other applications [3]. Fatigue failure is one of the most prevalent problems with industrial components. The stress levels at which fatigue does not happen are either lower than the component's ultimate strength or lower than its yield strength [4]. Commercial heat-treatable aluminum alloys, such as the wrought aluminum alloys in the 7XXX series, have the highest strength and are the strongest forging alloys. It also has a decent amount of corrosion resistance. This alloy is in high demand among aircraft

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manufacturing businesses for structural components and other highly stressed applications. It has long been understood that different heat-treating techniques may enhance the mechanical characteristics of metals at room temperature [5]. "Miner's rule," which assumes that damage to the material is directly proportional to the number of cycles at a given stress, is the most basic and widely accepted hypothesis used to explain cumulative fatigue damage. The rule also assumes that the stress level is unimportant and that the rate at which damage accumulates at a given stress level is unrelated to the stress history [6]. Although machines and structural components may experience varying levels of reversed stress cycles or randomly fluctuating stress levels, the majority of data on fatigue failure is acquired from tests with constant amplitude loading. Simple load histories, block load histories, and random service-simulating load histories are the three main divisions of variable amplitude (V.A.) loading. Block loadings might be high-low, low-high, or mixtures of these patterns [7].

The main goal of this study is to obtain experimentally the fatigue life of the selected alloy under different conditions.

2. Literature review

An experimental inuestgation was conducted by Zainab K. H, 2012 [8] An experimental investigation was conducted to determine the fatigue accumulation damage for the aluminum alloy 2024-T4 under rotating bending loading and stress ratio R = -1. The studies were conducted at RT (room temperature), 25°C, and 200°C. A modified damage stress model was proposed to forecast the fatigue life under high temperatures and to account for damage at various load levels. The results of the current model were contrasted with those obtained from experiments and those estimated using the fatigue damage model that is most commonly used (Miner's rule). The comparison revealed that the current model offers a fair factor of safety, while the Miner model occasionally provided a factor of safety close to unity.

An experimental investigation was conducted by Zakariaa K. A.et al, 2013 [9] In this study, the standard S-N curve was used to predict the S-N curve of an aluminum alloy at higher temperatures. It was shown that the enhanced temperature test for AA6061 and the temperature sensitivity, are related. The S-N curve can be predicted using this relationship. The AA6061's fatigue life was significantly reduced when the temperature was increased from 27°C to 250°C, reducing it from roughly 75% to 83%. The S-N curve at high temperatures changed as a result, indicating a lower fatigue life. Another finding from the study was the load sequence effect. The low-to-high sequence loading produced the longest fatigue life, whereas CAL produced the shortest fatigue life at both lower and higher temperatures. However, the impact of the load sequence was greater than that of high temperatures.

An experimental investigation was conducted by Asmaa Abdulqasim,.et al 2015 [10] The behavior of the aluminum alloy AA7349 under cumulative and continual creep-fatigue interaction has been examined utilizing an electrical system that was created and designed to look into creep-fatigue interaction at various temperatures and stress levels. A continuous and varied creep-fatigue test was conducted on an hourglass-shaped specimen of the aluminum alloy AA7349 under rotating bending loads and stress control at stress ratio R=-1. The creep-fatigue life's outcomes have been examined by Miner's rule and contrasted with both the suggested and experimental approaches. It was established that the Miner rule and suggested model produce findings that are realistic and well-consistent with experimental fatigue lifetimes.

An experimental investigation was conducted by Ali, A. J. H,.2016 [11] With the use of the laser shock peening (LSP) technique, which has two energies of 250 mJ and 500 mJ, the work's objective is to investigate how to extend the fatigue life of AA-7075 under constant and varied loads. The outcomes demonstrate that the fatigue life has been enhanced to varying degrees at various constant stress amplitude loads. For specimens treated, the improvement in life factor was roughly (1.534) and (1.157) under constant amplitude stress in the range (0.3-0.8). The experimental results of cumulative fatigue damage under two-step programs of Low-High stress (156-312 MPa) and High-Low stress (312-156 MPa) stress tests have also demonstrated improvements in life factors of 1.61 and 1.54 compared to those of untreated specimens.

An experimental investigation was conducted by Mohammed J. Kadhim, et al 2018[12] Experimental studies were conducted in this work to estimate the lifetime of aluminum alloy thermal fatigue. Under different temperatures and a stress ratio of R = -1, fatigue-temperature interactions on the aluminum alloy 6063-T6 have been studied. It was discovered that a power law relationship existed between temperature and the number of cycles that would fail and the fatigue strength, both of which dropped with temperature. High temperatures result in temperature and fatigue service interactions, which significantly reduce the number of cyclists. The decreasing life ratio (Nf evaluated temperature/Nf room temperature) has been established to increase with temperature.

(Chen S., Abderrahim,et al .2020)[13] A novel cumulative damage strategy is examined for various loading routes in a finite life regime based on the damage stress model parameter. The damage stress model parameter and equivalent stress determined by Sines, Dang Van, and Robert fatigue criteria, respectively, are coupled to create the new damage indicator. Through a series of biaxial experiments on cruciform specimens composed of an aluminum alloy, the applicability of the suggested model is evaluated. There were several different loadings set up, including cumulative fatigue with two or three blocks, repeated blocks, and constant amplitude fatigue. The predictions made using the suggested model and our experimental data show strong agreement.

An experimental investigation was conducted by arwa. S., Mahammed,et al ,.2021 [14] The effects of ultrasonic impact treatment (UIP) and shot peening (SP) on constant cumulative fatigue life and fatigue strength of AA7075-T6 were studied. Fatigue experiments were conducted under constant and variable amplitude (R=-1) at ambient temperature to determine the fatigue life of the S-N curve and fatigue strength during treatment of 3.46% and 8.57% at 107 cycles for (UIT) and SP, respectively (SP). After two steps of cumulative fatigue damage testing, it was shown that SP and UIP treated specimens had better fatigue life than the results of unpeeled specimens. For UIT and SP, the fatigue endurance limit was increased by 35% and 54%, respectively. These findings demonstrate a clear correlation between an increase in the mechanical characteristics of the material utilized and an increase in fatigue strength following the application of (UIT) and (SP).

2.Experimental work

2.1 Material selection

Aluminum alloys are frequently utilized in structural applications in the aviation, automotive, and construction industries because of their high specification dependability, exceptional corrosion resistance, and affordability. Aluminum is this piece's primary material. AA7001-T6 has the greatest strength of any working aluminum alloy. [15]. According to Table 1, the chemical analysis of AA7001-T6 was performed by the Iraqi Geological Survey and compared to the industry standard.

Table 1: Chemical composition of 7001-T6 in wt%

Elements wt. %	Zn	Si	Fe	Cu	Mn	Mg	Cr
Standard [15]	6.8-8	0.35	0.4	1.6-2.6	0.2	2.6-3.4	0.18-0.35
Experimental	6.1	0.33	0.4	1.85	0.18	3.1	0.27

2.2 Roughness test

All tensile and fatigue specimens are subjected to a roughness test using a Pocket Surf Mahr device, as illustrated in Figure 1, and the test was completed at the UOT Metal Engineering Department's production facility. For all of the samples utilized in this investigation, the roughness measurements were recorded to be Ra (average roughness) from 0.35 to 1µm for the tensile and fatigue specimens.

Figure 1. Roughness Surface Apparatus Test

2.3 Tensile test

The experimental mechanical parameters were determined through tensile tests using a (WDW-50) tensile test apparatus with a 200KN capacity. Figure 2 shows the shape and dimensions of the tensile specimen. Standard practice (ASTM A370).

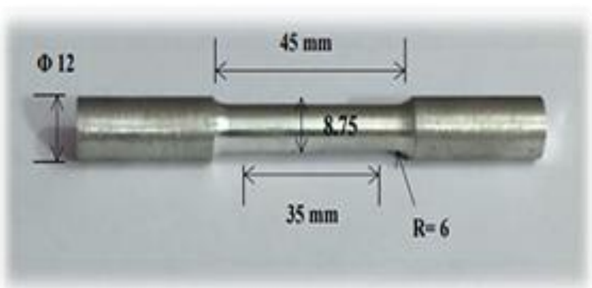

Figure 2. Tensile test specimen according to (ASTM A370), All dimensions in (mm)

The tensile test is carried out using a material tensile test rig to measure the mechanical characteristics of AA7001 at (RT) and 330℃ The tensile test rig is illustrated in Figure 3.

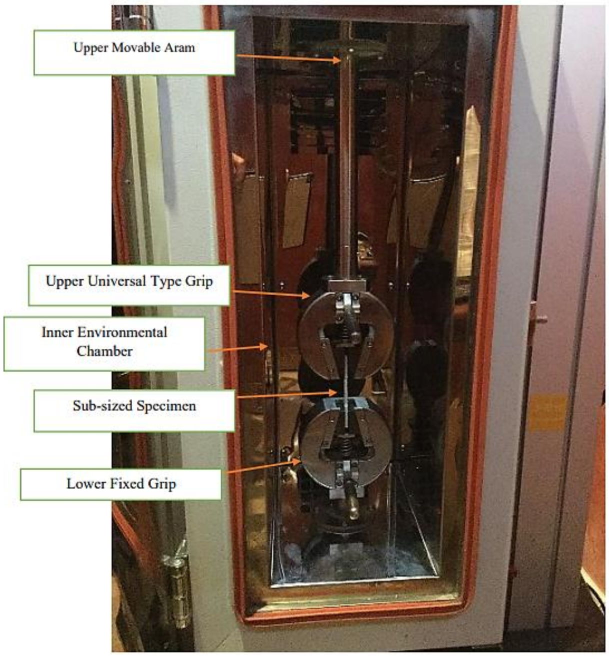

Figure 3. High-temperature tensile test specimen loaded into the grips with proper alignments

2.4 Fatigue test

The sample was produced on a CNC lathe that had been programmed. Fig 4. depicts the fatigue test sample in accordance with the basic parameters for the cylinder fatigue study (DIN 50113).

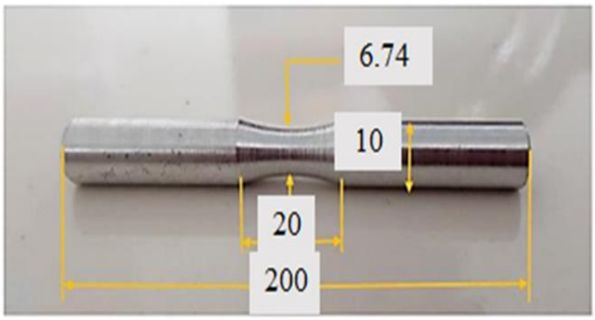

Figure 4. Fatigue test specimen, all dimensions in (mm) according to (DIN 50113) standard specification

as shown in equation (1), the applied bending stress (b) is computed from the applied load (P)

$$\sigma_b\left(\frac{N}{mm^2}(MPa)\right)=\frac{32(N)(125.7)mm}{\pi d^3}, \quad (1)$$

(σ_b) - the stress value measured by (N/mm2)

(P) - the load value (measured by Newton (N) applied to the sample).

The arm of applied force (P) is (125.7) mm.

where (d) - the minimum diameter of the fatigue specimen and equals 6.74 (mm).

Fatigue specimen test A rotating bending fatigue testing rig was used to conduct all fatigue tests with both constant and variable amplitude. A force perpendicular to the specimen's axis and applied from the right side caused a bending moment. The surface is therefore subjected to tensile and compressive forces as the specimen rotates. As shown in Figure 5. depicts the entire system Elevated temperature fatigue test (furnace and digital board).

Figure 5. Furnace and digital board

A fatigue test at high temperatures is necessary for a method for heating the media surrounding the fatigue sample. The electric furnace has the following measurements: (100 * 120 * 140) mm. The furnace is connected to the grips used for the fatigue test along with a digital control circuit board. A steel plate measuring 6 mm thick fills the furnace. To control the temperature, a 2000W electrical heater with a thermocouple type (K) mounting is used within the furnace. The Figure illustrates the entire unit (furnace and digital board).

2.5 Shot peening

Shot tumbleset control panel model STB-OB peening was used in this test as shown in figure (4.11) and carried out at the Institute of Technology—Alzafaranya, Baghdad.

a. General (SP) machine

b. (SP) treatment with samples inside the container rotation

Figure 6. The shot peening device

Table 2: Shot peening process parameters

Peening pressure	12 bar
No. of balls for each operation (run)	50
Speed	40 mm/min
Distance from jet to the specimen (cm)	15
Average ball size	0.6mm
Goverage	100%

3.Results and discussions

3.1 Tensile test results

At different temperatures (RT, 330, and SP+330), the behavior of AA 7001-T6 was investigated utilizing rotating bending loads with a stress ratio of R = -1. symmetric stress amplitudes (R = -1) without adversely influencing the specimen's mechanical behavior: cyclic loading experiments

Table 3: Mechanical properties of AA7001-T6 at various condition [15]

Condition	UTS(MPa)	YS (MPa)	E (GPa)	Ductility
Standard (RT) [17]	676	627	(69-73)	9
Exp (RT)	683	644	71	9
Exp (330℃)	533	500	60	12.7
Exp (SP+330℃)	551	517	62	11.5

Table 4: S-N curve result at foure conditions testing

Condition	Spec. No	Applied Stress (MPa)	Nf cycles	Spec. No	Applied Stress (MPa)	Nf cycles	Spec. No	Applied Stress (MPa)	Nf cycles
Lab-air RT(25℃)	1 2 3	516 (0.75UTS)	18600 22500 24600	4 5 6	447 (0.65UTS)	74800 82800 66000	7 8 9	378.5 (0.55UTS)	190800 225800 244000
(SP+RT)	10 11 12	516 (0.75UTS)	22600 30700 34000	13 14 15	447 (0.65UTS)	102800 110200 98800	16 17 18	378.5 (0.55UTS)	266000 286600 305000
330℃	19 20 21	516 (0.75UTS)	5500 4200 6000	22 23 24	447 (0.65UTS)	21800 19900 24500	25 26 27	378.5 (0.55UTS)	82800 77000 65800
(SP+330℃)	28 29 30	516 (0.75UTS)	6200 7000 5200	31 32 33	447 (0.65UTS)	28200 30000 31600	34 35 36	378.5 (0.55UTS)	106000 94600 88800

Table 5: Fatigue results under variable loading high temperature and (SP)

Condition	Spec. No	Loading Sequences (MPa) Low-High (L-H)	N_f (cycles)	Spec. No	Loading Sequences (MPa) Low-High (H-L)	N_f (cycles)
RT(25℃)	1 2 3	377-502	26800 24600 22800	4 5 6	502-377	16800 13000 22800
330℃	7 8 9	377-502	16600 20500 14800	10 11 12	502-377	10000 11600 13600
(SP+330)℃	13 14 15	377-502	18000 22000 16600	16 17 18	502-377	10800 13600 15000

Table 6: S-N curve equations of AA7001-T6 under three condition of testing [15]

Condition	S-N curve equation	R^2
RT(25℃)	$\sigma_f = 1980\ N_f^{-0.133895}$	0.9939
330℃	$\sigma_f = 1401\ N_f^{-0.1158}$	0.9921
(SP+330℃)	$\sigma_f = 1375\ N_f^{-0.1113}$	0.9832

The S-Ncurve equation were obtained using Basquin power load equation based on resulted listed in table (4)

The S-N curve equations of the condition tests presented in Figure 7 are taken from for the same others, based on Basquin equation

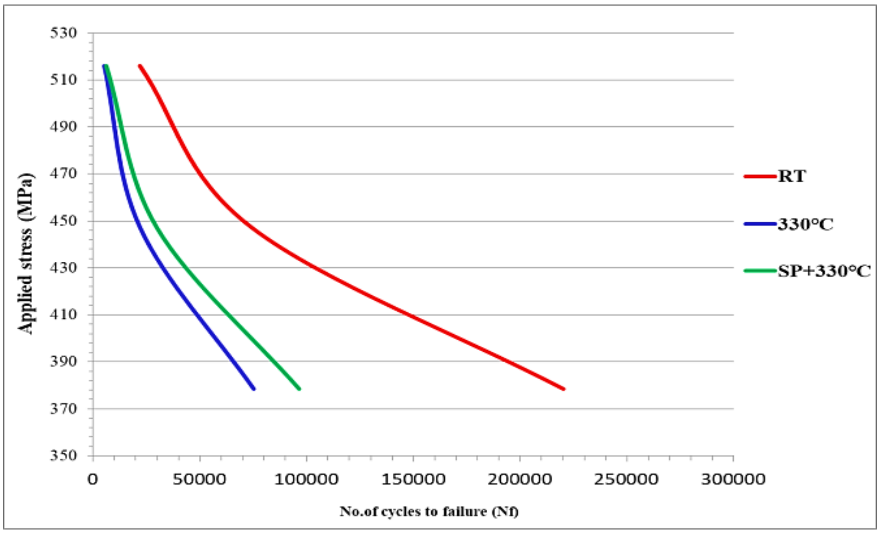

Figure 7. Shows the S-N curves for fatigue

Application of Miner rule to experimental results.

The simplest theory for estimation the fatigue life is to use the Miner method.

$$\sum \frac{ni}{N_{fi}} = 1 \qquad (2)$$

Where n is the number of applied cycles for stress level if n_1 is applied this mean for σ_1, and n_2 for σ_2 and so on. It depends on the number of block stress levels. For the present work, $n_1 = n_2 = 2000$ cycles i.e two blocks program .The fatigue life of AA7001-T6 specimens tested from low to high (L-H) can be expressed as: For fatigue life at (RT).

$$Nf_{Miner} = (n_1+n_2)\,R \qquad (3)$$

Where R is the number of programs till failure as shown in Figure 8

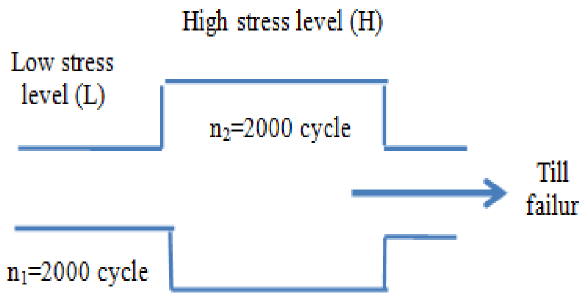

Figure 8: Two block stress level variable loading

R can be obtained from

$$\left[\frac{n_1}{N_{f1}} + \frac{n_2}{N_{f2}}\right] R = 1 \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

according to Miner: N_{f1}, N_{f2} are the number of cycles at failure corresponding to $\sigma_1 = 377$ MPa and $\sigma_2 = 502$ MPa. obtained from the S-N curve equation listed in Table 7.

Table 7: comparison of experimental fatigue life of AA7001-T6 with Miner rule

Condition	Loading Sequence (MPa)	N_f av (cycles)	$N_{f\ Miner}$ (cycles)
RT	377-502 L-H	24733	19747
	502-377 H-L	16433	
330°C	377-502 L-H	17300	14254
	502-377 H-L	11733	
SP+330°C	377-502 L-H	18867	15486
	502-377 H-L	13133	

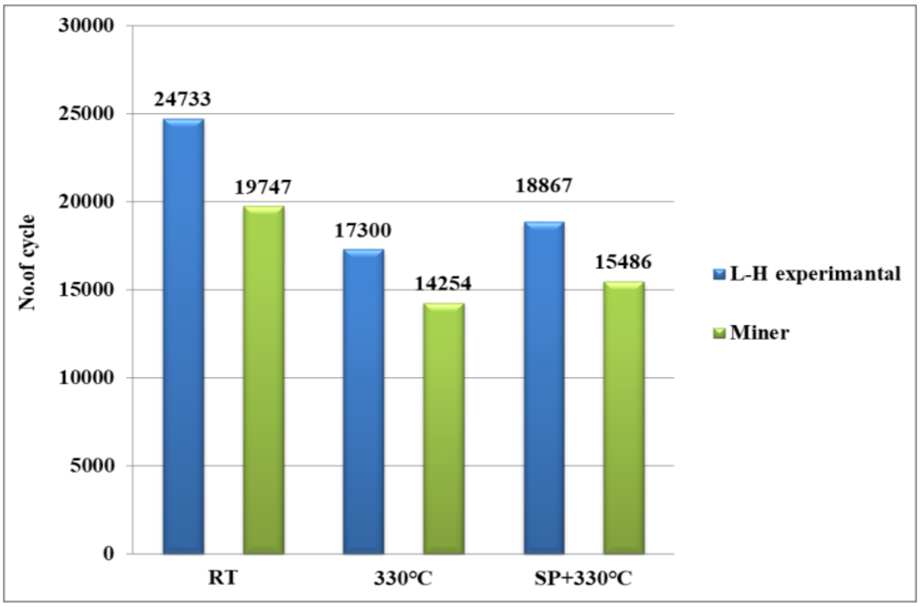

Figure 9. The Low-High cumulative fatigue life prediction for different temperatures

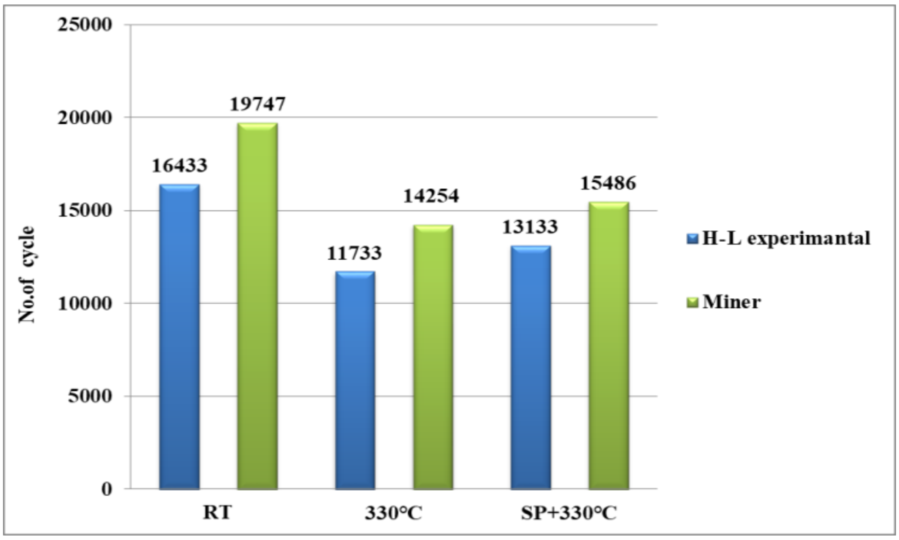

Figure 10. The High-Low cumulative fatigue life prediction for different temperatures

As shown in Table 7, the fatigue life under (L-H) loading is conservation (Nf is less than the experimental) but the fatigue life at (H-L) sequence loading is higher than the experimental (non-conservative). The main reasons may be due to the followings.

1. Miner assumed that the work that can be observed until fatigue has a constant Value.
2. This work observed during n1 and n2 is similar. But practically damage at n1 is not equal to n2 and the damage varies in a non-linear manner while the Miner rule assumed damage varies linearly.
3. Variable loads were tested by a miner on AA2024-T3 sheet material without the influence of the environment (temperature) or surface treatment (SP). utilized two to four distinct blocks. He discovered that the damage total (D) ranged from 0.61 to 1.45, and he chose an average number close to 1.0. [18] Unfortunately, this strategy is unreliable since some specimens can utilize it and others cannot. Additionally, the impact of the surrounding environment and surface treatments is not taken into account by this criterion. The implementation of the Miner rule also disregards the interaction effect of loading sequences. Al-Alkawi et al. [10] tested AA7349 with varying loadings, taking into account the effects of loading sequences and high temperatures.

As shown in Figures 9,10 Miner's rule always gives an unsafe guess (higher), but some samples give less than practical and this indicates that Miner gives an unsafe guess, but for some samples, it gives an honest guess (i.e. less than experimental) and the reason is that the accumulated damage (damage) (1) while The reality of the situation is that the accumulated damage is less than (1) and more than (1) depending on the type of loading and that the process of accumulating damage is a non-linear process, while Miner assumes that it is linear for these and other reasons, such as that Miner does not take into consideration the effect of temperatures and surface hardening processes. These reasons all lead to the failure of this theory.

4. Conclusions

The main conclusions are:

1. At different temperatures (RT, 330℃, and SP+330℃), the behavior of AA 7001-T6 was investigated utilizing rotating bending loads with a stress ratio of R = -1. symmetric stress amplitudes (R = -1) without adversely influencing the specimen's mechanical behavior: cyclic loading experiments.
2. A modification of the AA7001-T6 S-N curve under three testing settings, a comparison of the material's mechanical properties, and a study of its experimental fatigue life in relation to the Miners rule.
3. The Miner rule provided a safety factor for specimens under high-low stress while it predicted some specimen's safety for low-high loading sequences.

The temperature of the turbine reaches 300 ℃ until the requirement is met to replace the aluminum niche factory, as it was found that the specifications were low at this temperature and the temperature of the turbine reached 250℃ to 300℃, Therefore tests were carried out at these temperatures

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