Tikrit Journal of Engineering Sciences (2024); 31(2): 168-174

DOI: http://doi.org/10.25130/tjes.31.2.16

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Fatigue Life Estimation under High Temperature and Variable Loading of AA7001-T6 Using Shot Peening

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Keywords:

AA7001-T6; Mechanical Properties of AA7001-T6; Shot Peening; Cumulative Fatigue Damage.

Highlights:

- *Fatigue life of AA7001-T6 was predicted with shot peening at various temperatures.*
- *Shot peening treatment play a large role in increasing strength and fatigue life.*
- *Fatigue S-N curve was eliminated [reduced by combination fatigue and 330 °C and it improved when using prior shot peening and 330 °C].*

ARTICLE INFO

Article history:

Received	10 Aug.	2023
Received in revised form	20 Oct.	2023
Accepted	10 Nov.	2023
Final Proofreading	27 May.	2024
Available online	28 May.	2024

Citation: Hamzah AK, Abed RM, AL-Mushehdany AM, Alalkawi HJM. **Fatigue Life Estimation under High Temperature and Variable Loading of AA7001-T6 Using Shot Peening**. *Tikrit Journal of Engineering Sciences* 2024; **31**(2): 168-174.

http://doi.org/10.25130/tjes.31.2.16

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Abstract: In this study, the fatigue life of aluminum alloys (7001-T6) was predicted with shot peening at various temperatures. Surface treatment with shot peening steel balls is a mechanism for reducing damage. An experimental investigation was conducted to find the degree of fatigue accumulation for AA7001-T6 under rotational bending loading and stress ratio R = −1. The experiments were conducted at RT (25 ℃), 330 ℃, and SP + 330 ℃ temperatures. A modified damage stress model that considers damage at various load levels was recommended for forecasting the fatigue life under high temperatures. The model and experimental results were compared to determine the most damage (Miner's rule). The experimental results of the fatigue life indicated that the increased testing temperature reduced the fatigue life. However, using shot peening at high temperatures increased the fatigue life by 8% when loading sequence L-H and 10% when loading sequence H-L. The results showed a satisfactory degree of safety for the present model. Nevertheless, Miner's model featured two models: one for low–high loading and high-low loading. The results were proper for prolonging fatigue life.

تقدير عمر الكلال تحت درجات حرارة عالية واحمال متغيرة لسبائك AA7001-T6 بأستخدام قذف كرات معدنية

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٣ قسم تقنيات هندسة الطائرات / كلية بلاد الرافدين / ديالى – العراق.

الخلاصة

في هذه الدراسة تم توقع عمر الكلال لسبائك الألمنيوم (7001-T6) باستخدام طريقة قذف السطح بواسطة كرات حديد الصلب في درجات حرارة مختلفة. يعتبر المعاملة السطحية بقذف السطح بواسطة كرات حديد الصلب آلية لتقليل الضرر. تم إجراء تحقيق تجريبي لتحديد درجة تراكم الإرهاق لـ AA7001-T6 تحت تحميل الانثناء الدوراني ونسبة التوتر .R = -1 تم إجراء التجارب عند درجات حرارة الغرفة (٢٥ درجة مئوية) و٣٣٠ درجة مئوية و SP + 330درجة مئوية. تم التوصية باستخدام نموذج توتر الضرر المعدل الذي يمكن أن يحسب التلف في مستويات الحمولة المختلفة لتوقع عمر الكلال تحت درجات حرارة عالية. تمت مقارنة نتائج النموذج الحالي مع النتائج التجريبية من نموذج التلف التعب المستخدم لتحديد أكثر درجة تلف (قاعدة ماينر). أظهرت النتائج درجة مرضية للنموذج الحالي. ومع ذلك، تميز نموذج ماينر بنموذجين، أحدهما للحمولة المنخفضة إلى العالية والآخر للحمولة العالية إلى المنخفضة. كانت النتائج مناسبة لفترة عمر كلال اطول.

الكلمات الدالة: الخواص الميكانيكية لـ AA7001-T6، الطحن بالطلقات، تلف التوتر التراكمي.

1.INTRODUCTION

Fatigue refers to the deterioration or cracking that may occur in a structure or component after it has been subjected to a dynamic load. Damage is defined as the localized plastic deformation resulting in cracks' development. Fatigue failure accounts for 90% of mechanical failure [1]. This phenomenon occurs when a material is subjected to varying loads. The crack surface lengthens and experiences catastrophic failure when the failure stress is lower than the yield stress [2]. Aluminum is extensively utilized in automobiles, aircraft, and several other applications due to its great strength, low weight, excellent thermal and electrical conductivity, ease of recycling, and other relevant attributes [3]. Fatigue failure is a typical issue with industrial parts. The stress levels at which fatigue does not occur are either lower than the component's ultimate strength or lower than its yield strength [4]. Aluminum alloys that can be heat treated, such as the wrought aluminum alloys in the 7xxx series with maximum strength, are the strongest forging alloys. This type of alloy has a reasonable level of corrosion resistance. Furthermore, the aircraft manufacturing industry uses this alloy for structural components and other highly stressed applications. Several heat-treatment techniques have been recognized to enhance the mechanical characteristics of metals at room temperature [5]. The "Miner's rule" theory, i.e., material damage is directly proportional to the number of cycles at a given stress, is the most fundamentally and widely accepted hypothesis for explaining cumulative fatigue damage. The rule also presupposes that the stress sequence and history are immaterial and do not influence how quickly damage develops at a certain stress level [6]. Although machine and structural components may experience varying levels of reversed stress cycles or randomly fluctuating stress levels, the majority of the data on fatigue failure are acquired from tests with constant amplitude loading. The three main categories of variable amplitude loading are simple V.R. load histories, block load histories, and random service-simulating load histories. Block loadings can be categorized into low–high, high–low, or a combination of these sequences [7]. Most researchers have confirmed that increasing temperature decreases the fatigue life of machine parts exposed to variable loads. Minor's rule neglects the effect of temperature on fatigue life. The present research aims to improve the fatigue life of AA 7001-T6 under high temperatures and variable loads using shot peening. The experimental results showed that using shot peening at high temperatures improved fatigue life under variable loads.

2.LITERATURE REVIEW

Hantoosh [8] conducted an experimental investigation to assess the fatigue accumulation damage performance of aluminum alloy 2024-T4 under rotational bending loads and a stress ratio of R = −1. Room temperature (RT), 25 °C, and 200 °C were employed in the experiments. A modified damage stress model was used to predict the fatigue life under high temperatures and considered four damages at different load levels. The present model outcomes were compared with the experimental findings and estimates obtained with the most popular fatigue damage model (Miner's rule). The comparison showed that the present approach presented satisfactory safety, while Miner's model occasionally provided a safety factor close to unity. Zakaria et al. [9] used the standard S–N curve to forecast an aluminum alloy's S–N curve at high temperatures. According to this study, the temperature sensitivity, c, and the increased temperature test for AA6061 were correlated. This correlation can be utilized to forecast the S–N curve. The AA6061's fatigue life significantly decreased from 75% to 83% when the temperature was increased from 27 °C to 250 °C. Consequently, the S–N curve at high temperatures shifted, demonstrating a shorter fatigue life. The study also found a load sequence effect. The low-to-high sequence loading at RT and higher temperatures produced the longest fatigue life, while CAL demonstrated the shortest fatigue life. However, the load sequence influence was more pronounced at ambient temperatures than at high temperatures. Al-Alkawi et al. [10] examined the behavior of the aluminum alloy AA7349 under cumulative and continuous creep-fatigue interaction with an established electrical system and the creep-fatigue interaction at different temperatures and stress levels. A continuous and variable creep-fatigue test was performed on an hourglass-shaped specimen of aluminum alloy AA7349 under rotational bending loads, stress control, and a stress ratio of one. Miner's rule was used to analyze and compare the results of the creep-fatigue life with the outcomes of the suggested and experimental methods. The study demonstrated that Miner's rule and the recommended model produced results that plausible and closely matched experimental fatigue lifetimes. Ali [11] used the laser shock peening technique with two energies of 250 and 500 mJ. The objective of the study was to determine ways to extend the fatigue life of AA-7075 under constant and varied loads. The results demonstrated that the fatigue life was enhanced to different degrees under various constant stress amplitude loads. The improvements in the life factor of the treated specimens were approximately 1.534 and 1.157 under constant amplitude stress in the range of 0.3–0.8. The experimental results of the cumulative fatigue damage under two-step programs of low–high (156–312 MPa) and high–low (312–156M Pa) stress tests also demonstrated improvements in the life factors of 1.61 and 1.54 compared with those of the untreated specimens. Kadhim and Kamal [12] conducted experimental studies to calculate the lifetime of aluminum alloy thermal fatigue. They studied the fatigue–temperature interactions on aluminum alloy 6063-T6 under different temperatures and a stress ratio of R = −1. A power law relationship was observed between temperature and the number of cycles that would fail and the fatigue strength, both of which decreased with temperature. High temperatures cause interactions between temperature and fatigue service, significantly lowering the number of cyclists. Temperature enhanced the declining life ratio, i.e., Nf evaluated temperature/Nf room temperature. Mahammed et al., [13] examined the effects of shot peening and ultrasonic impact treatment on the fatigue strength and constant cumulative fatigue life of AA7075-T6. The fatigue life of the S–N curve and the fatigue strength during treatment of 3.46% and 8.57% at 107 cycles were determined through fatigue studies under constant and changing amplitude (R = −1) at ambient temperature. The study demonstrated that SP and UIP-treated specimens had better fatigue life than the unpeeled specimens after two stages of cumulative fatigue damage testing. The fatigue endurance limit was increased by 35% and 54% for UIT and SP, respectively. These results demonstrated a direct correlation between an improvement in the material's mechanical properties and an increase in fatigue strength after application.

3.EXPERIMENTAL WORK

Aluminum alloys are often utilized in structural applications in the aviation, automotive, and construction industries due to their high specification dependability, exceptional corrosion resistance, and affordability. The primary material in this work is aluminum, AA7001-T6, which has the greatest strength of any working aluminum alloy [14].

3.1.Tensile Test

The experimental mechanical properties were determined by performing tensile tests at RT and 330 °C with a WDW-50 tensile test apparatus with a 200 KN capacity. Fig. 1 shows the shape and measurements of the tensile specimen. The tensile specimen was selected based on ASTM A370.

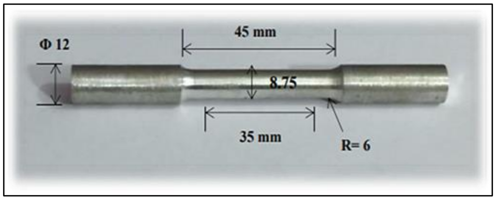

Fig.1 Tensile Test Specimen.

The tensile test is conducted using a material tensile test rig, which measures the mechanical properties of AA7001-T6 at RT and 330 °C. Fig.2 depicts the tensile test apparatus.

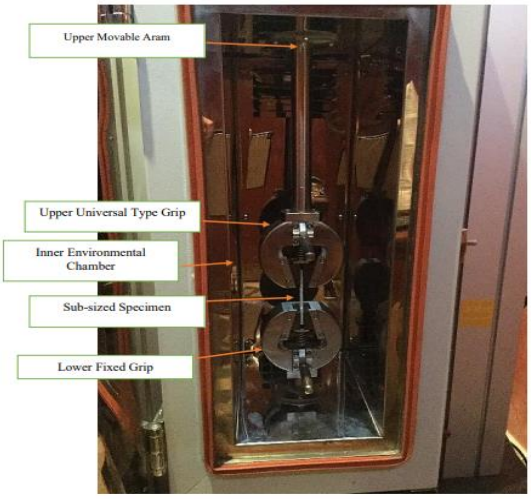

Fig. 2 High-Temperature Tensile Test Specimen Loaded into the Grips with Proper Alignments [15].

3.2.Fatigue Test

The sample was produced on a programmed CNC lathe. Fig. 3 depicts the fatigue test sample following the basic parameters for the cylinder fatigue study (DIN 50113).

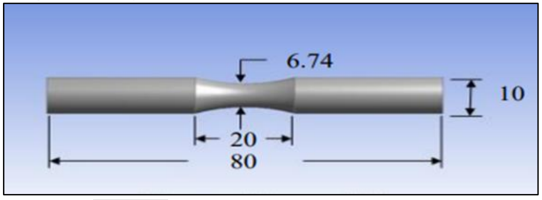

Fig. 3 Fatigue Test Specimen.

The PUNN-type fatigue testing machine, depicted in Fig.4, was used to perform fatigue tests with constant and fluctuating loads through rotating bending. Eq. (1) below is used to calculate the stress (f) at the point of failure [6].

$$\sigma_f(MPa) = \frac{32\times 125.7P(N)}{\pi d^3} \quad (1)$$

Fig. 4 Furnace Connected to the Fatigue Machine with a Digital Thermal Control Board.

3.3.Shot Peening Process

To evaluate the shot peening process, the Shot Tumbleset Control Panel Model (STB-OB) was used as a testing instrument, as shown in Fig. 5. The test specimens were subjected to cast steel balls with an average diameter of 1 mm, propelled at approximately 40 m/s. The nozzle was positioned 10 cm from the specimen's surface, and the balls had a Rockwell hardness of 48-50 HRD. The specimens were dampened with water prior to capturing photographs.

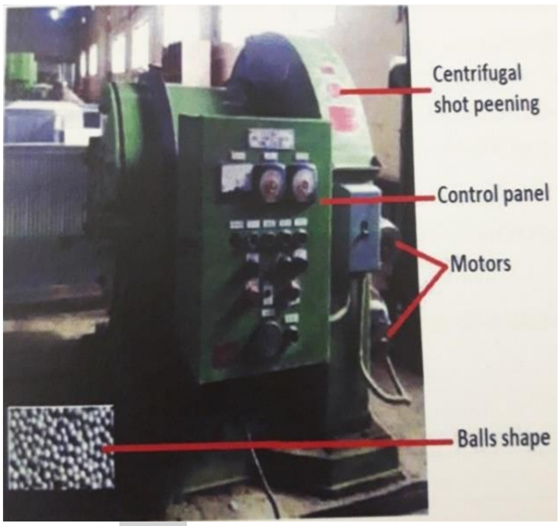

Fig.5 Shot Peening Device.

The primary parameters of the SP device are peening pressure (12 bar), the number of balls for each operation (50 runs), speed (40 m/s), the distance from the jet to the specimen (15 cm), the average ball size (0.6 mm), and coverage (100%).

4.RESULT AND DISCUSSIONS

4.1.Cumulative Fatigue Damage Result

Constant-amplitude fatigue S–N curve is defined as fatigue under cycle loading with constant amplitude and constant mean stress. The amplitude and mean of structures subjected to variable loading (VL) are not constant, and many theories were proposed to describe the fatigue life under VL. The simplest and oldest theory is the Miner's rule. This rule needs to stabilize the S–N curve for the material that estimates the fatigue life. The S–N curve equations of the condition tests presented in Table 1 are drawn from the same sources based on the Basquin equation in Table 2. According to Miner's rule, Nf1 and Nf2 are the numbers of cycles at failure corresponding to 61 = 377 MPa and 62 = 502 MPa obtained from the S–N curve equation listed in Table 3.

Table 1 Fatigue Results under VL High Temperature and SP.

Condition	Spec. no	Loading sequences (MPa) Low–High (L–H)	N_f (cycles)	N_f av (cycle)	Spec. No	Loading sequences (MPa) High–Low (H–L)	N_f (cycles)	N_f av (cycle)
RT (25 °C)	1	377–502	26,800	24,733	4	502–377	16,800	17,533
	2		24,600		5		13,000	
	3		22,800		6		22,800	
330 °C	7	377–502	16,600	17,300	10	502–377	10,000	11,733
	8		20,500		11		11,600	
	9		14,800		12		13,600	
SP + 330 °C	13	377–502	18,000	18,867	16	502–377	10,800	13,133
	14		22,000		17		13,600	
	15		16,600		18		15,000	

Table 2 S–N Curve Equations of AA7001-T6 under Three Testing Conditions.

Condition	S–N curve equation	R^2
RT (25 °C)	$\sigma_f = 1980\, N_f^{-0.148}$	0.9939
330 °C	$\sigma_f = 1401\, N_f^{-0.1158}$	0.9921
SP + 330 °C	$\sigma_f = 1375\, N_f^{-0.1113}$	0.9832

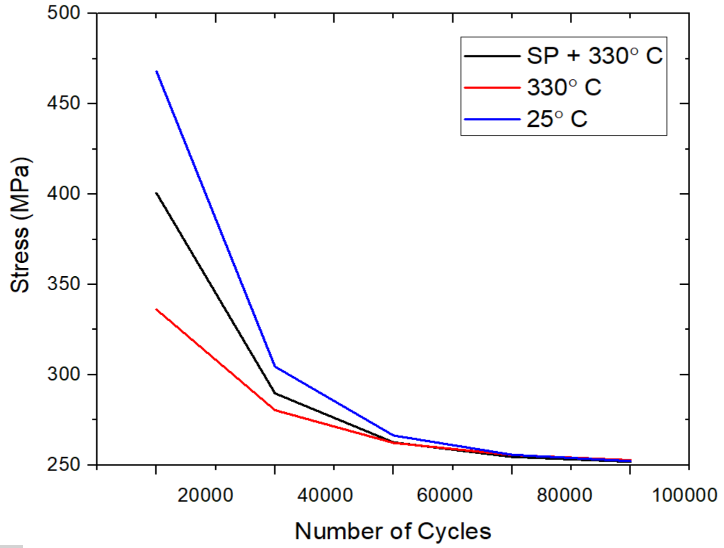

Fig.6 S–N Curve of AA7001 – T6 under Three Testing Temperatures.

Table 3 Comparison of the Experimental Fatigue Life of AA7001-T6, Miner's Rule, and the Proposed Model.

Condition	Loading sequence (MPa)	N_f (av)	N_f Miner (cycles)	N_f model(cycles)
RT	L–H (377–502)	24,733	19,747	19,364
	H–L (502–377)	16,433		17,795
330 °C	L–H (377–502)	17,300	14,254	13,456
	H–L (502–377)	11,733		10,425
SP + 330 °C	L–H (377–502)	18,867	15,486	16,372
	H–L (502–377)	13,133		15,356

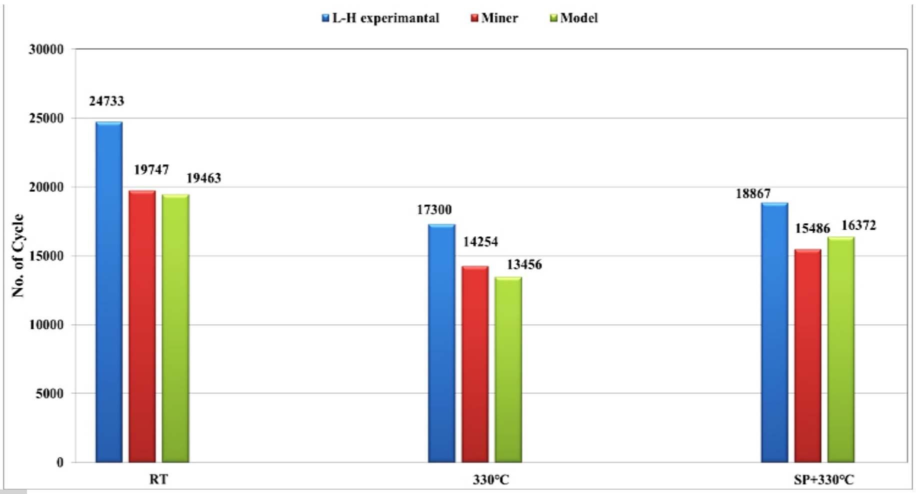

Fig.7 Low–High Cumulative Fatigue Life Prediction for the Different Temperatures.

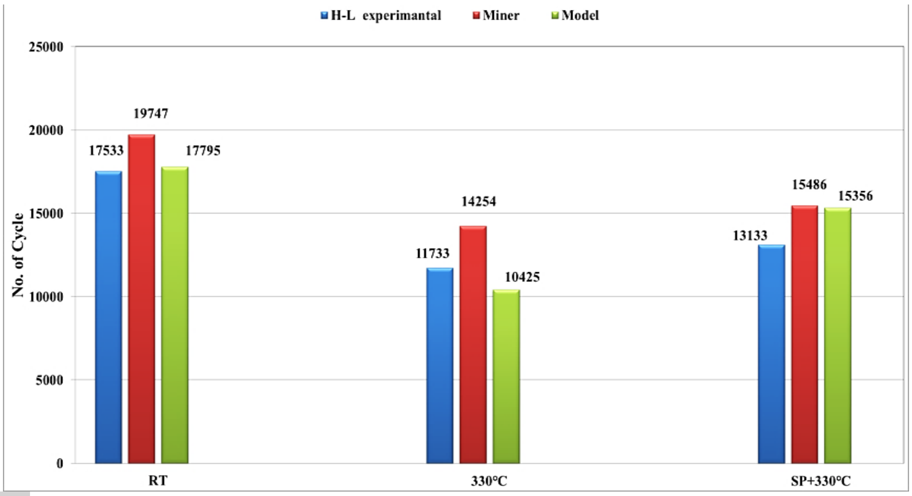

Fig. 8 High–Low Cumulative Fatigue Life Prediction for the Different Temperatures.

5.DISCUSSION

Table 3 illustrates that the fatigue life under L–H loading is conserved, i.e., Nf is less than the experimental value; however, under H–L sequence loading is higher than the experimental one (non-conservative). This result may be due to the reasons reported below. According to Miner's rule, the amount of work can be observed until fatigue stabilizes at a constant value. The work observed during N1 and N2 was comparable. N1 and N2 were the numbers of cycles at failure corresponding to δ1= 377 MPa and δ2= 502 MPa obtained from the S-N curve equation. Nevertheless, damage at n1 unequaled that at n2. Damage nonlinearly varied, while the Miner's rule presupposes that damage linearly varied. The S-N curve equations of AA7001-T6 were used to obtain the fatigue life under variable loading.

The fatigue failure stress was less than the yield stress because the fatigue test was done under high cycle fatigue. The type of failure was mode 1. The values of fatigue lives were reduced as the temperature increased; however, when shot peening was applied at high temperatures, the fatigue lives increased. Using the shot peening at high temperatures increased the fatigue life by 8% with loading sequence L-H and 10% with loading sequence H-L.

Miner's rule was applied to evaluate the variable loads on the AA2024-T3 sheet material without any environmental effect (temperature) and surface treatment (SP). Two to four different blocks were used. It was found that the summation of damage (D) varied from 0.61 to 1.45. The average value was selected close to 1.0. [16]. However, this method is unreliable because it is valid for some specimens but not others. This rule does not consider the environmental effect and surface treatments. The interaction effect of loading sequences was also ignored. Al Alkawi et al. [17] tested AA7349 under variable loading, considering the effect of loading sequences and high temperatures. They proposed two models, one for low–high loading and the other for high–low loading. The results were suitable for fatigue life prediction.

6.CONCLUSIONS

The behavior of AA 7001-T6 was examined under various temperatures and thermal fatigue using rotational bending loads with a stress ratio of R = −1, allowing symmetric strain amplitudes (R = −1) during the cyclic loading studies without negatively affecting the specimen's mechanical behavior. Fatigue S-N curve was eliminated, i.e., reduced by combination fatigue and 330 °C, and it improved using prior shot peening and 330 °C (sp+330 °C). Temperature affected the fatigue strength and life, i.e., increasing temperature reduced life and strength, while shot peening treatment significantly increased strength and fatigue life. This study modified the AA7001-T6 S–N curve under three testing settings, compared the material's mechanical properties, and examined its experimental fatigue life with Miner's rule. Miner's rule provided a safety factor for specimens under high-low stress and predicted some specimens' safety for low-high loading sequences.

ACKNOWLEDGEMENT

The authors acknowledge the Iraqi Ministry of Higher Education and Scientific Research and the University of Technology for their support in performing this work.

NOMENCLATURE

AA	Aluminum Alloy
ASTM	American Society for Testing and Materials
CNC	Computer numerical control
d	Diameter
KN	Kilo Newton
L-H	Low–High
H-L	High–Low
HRD	Rockwell Hardness
mj	Millijoule
Mpa	Megapascal
P	load
R	Stress ratio
RT	Room temperature
S-N	Stress–Number of cycles
SP	Shot peening
T6	Heat treatment process
UIT	Ultrasonic impact treatment
VL	Variable loading
Greek symbols	
σ_f	Stress to fatigue
Subscripts	
f	Fatigue

REFERENCES

[1] Maha NA. **Fatigue Life Prediction of Aluminum Alloy Using Electrical Drop Technique.** Ph.D. Thesis. University of Technology; Baghdad, Iraq: 2016.

[2] Santecchia E, Hamouda AMS, Musharavati F, Zalnezhad E, Cabibbo M, ElMehtedi M, Spigarelli S. **A Review on Fatigue Life Prediction Methods for Metals.** *Advance in Materials Science and Engineering* 2016; **2016**: 9573524 (1-26).

[3] Karakasi Ö, Szusta J. **Monotonic and Low Cycle Fatigue Behavior of 2024-T3 Aluminum Alloy between Room Temperature and 300 °C for Designing VAWT Components**. *Fatigue and Fracture of Engineering Materials and Structures* 2015; **39**(1): 95–109.

[4] Qandil A, Zaid AI. **Effect of Shot Peening and Grain Refinement on the Fatigue Life and Strength of Commercially Pure Al and Two of its Alloys: Al-2024-T3 and Al-7075-T6**. *Materials Science and Engineering* 2016; **146**(1): 012028, (1-8).

[5] Alhamdany AA, Khenyab AY, Mohammed QK, Alalkawi HJM. **Development Mechanical and Fatigue Properties**

of AA7001 After Combined SP with Deep Cryogenic Treatment and UIP with Deep Cryogenic Treatment. *Eastern-European Journal of Enterprise Technologies* 2021; **5**(1): 113, (62-69).

[6] Ertas A. **Engineering Mechanics and Design Applications**. 1st ed., Boca Raton: CRC Press; 2012.

[7] Laseure N, Schepens I, Micone N, De Waele W. **Effects of Variable Amplitude Loading on Fatigue Life**. *International Journal of Sustainable Construction and Design* 2015; **6**(3): 1-10.

[8] Hantoosh ZK. **Fatigue Life Prediction at Elevated Temperature under Low–High and High–Low Loading Based on Mechanical Properties Damage Model**. *Engineering and Technology Journal* 2012; **30**(11): 1886-1896.

[9] Zakaria KA, Abdullah S, Ghazali MJ, **Elevated Temperature Fatigue Life Investigation of Aluminium Alloy Based on the Predicted SN Curve**. *Journal Teknologi* 2013; **63**(1): 75-79.

[10] Al-Alkawi HJ, Kareem FA, Ali AAM. **Prediction of FatigueCreep Interaction Life of Aluminum Alloy AA7349 Using Electromechanical Devices**. *Engineering and Technology Journal* 2015; **33**(3): 535-547.

[11] Ali AJH. **Improvement of Fatigue Life of AA 7075 Using Laser Shock Peening (LSP) Surface Treatment Technique**. *Al-Taqani Refereed Scientific Journal* 2016; **29**: 47-57.

[12] Kadhim MJ, Kamal HM. **Cumulative Thermal Fatigue Damage for Aluminum Alloy under Variable Stresses**. *IOP Conference Series: Materials Science and Engineering* 2018; **454**(1): 012145, (1-9).

[13] Mahammed MS, Alalkawi HJ, Faris ST. **Cumulative Fatigue Damage of AA7075-T6 under Shot Peening and Ultrasonic Surface Treatments**. *Diyala Journal of Engineering Sciences* 2021; **14**(1): 1-10.

[14] Mahdi HS, Alalkawi HJ, Faris ST. **Mechanical Properties and Fatigue Life Evaluation under High Temperature and Shot Peening Application Using AA7001**. *International Journal of Nanoelectronics and Materials* 2023; **16**(3): 1-10.

[15] Taif YG. **Design and Modification of a Computerized Tensile Test Machine at High Temperature**. M.Sc. Thesis. University of Technology; Baghdad, Iraq: 2020.

[16] Schijve J. **The Accumulation of Fatigue Damage in Aircraft Materials and Structures**. Advisory Group for Aerospace Research and Development Neuilly-Sur-Seine (FRANCE): 1972.

[17] Al-Alkawi HJ, Kareem FA, Ali AAM. **Prediction of Fatigue Creep Interaction Life of Aluminum Alloy AA7349 Using Electromechanical Devices**. *Engineering and Technology Journal* 2015; **33**(3): 535-547.