doi: 10.18323/2782-4039-2024-4-70-10

Predictive fatigue life modelling for aluminum alloys winder high temperature and shot peening interact

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Received 18.04.2024 *Revised 22.05.2024* *Accepted 11.09.2024*

Abstract: Enhancing the surface quality of shells subjected to high stress is a major task. A variety of procedures are employed for dealing with this issue. Shot peening is particularly common for aluminium alloys made. In fact, the main method for assessing the surface's durability under consideration is fatigue testing using standard specimens over several cycles. This paper investigates the performance of aluminium alloys under high-temperature exposure, examining their behaviour with and without shot peening-induced hardening. In fact, the study focuses on the fatigue behaviour of aluminium alloys 2024-T4 and 2024-T361 at 250 °C. Experiments on standard-sized specimens were conducted at both room temperature and 250 °C to evaluate how temperature affects fatigue life. The findings were consistent with previously published data, providing useful insights into the behaviour of these alloys at extreme temperatures. Additionally, a mathematical model was developed, integrating the Stress – Number of cycles curve, loading sequence, temperature, and surface hardness from shot peening. This model was compared with Miner's rule to assess its predictive accuracy. The results show that the new model provides more accurate predictions of fatigue life than Miner's rule, thereby improving the reliability and safety of components in high-temperature applications. By offering precise fatigue life predictions, this research aids in the design and development of more durable aluminium alloy components, ensuring optimal performance and safety in challenging operating environments.

Keywords: shot peening; predictive fatigue life; aluminium alloys; AA2024-T4; AA2024-T361; high temperature exposure; variable loading.

For citation: Alwin A.H., Ksibi H. Predictive fatigue life modeling for aluminium alloys winder high temperature and shot peening interact. *Frontier Materials & Technologies*, 2024, no. 4, pp. 111–122. DOI: 10.18323/2782-4039-2024-4-70-10.

INTRODUCTION

For highly stressed aluminium alloy components such as plates and hulls, shot peening (SP) becomes an essential procedure to improve their durability [1]. SP is a process that induces compressive residual stresses, and hardens the outer layer of a material by bombarding its surface with high-speed spherical particles. Al-Obaid previously introduced the statistical and dynamical aspects of this process [2]. More recently, Hou et al. characterised the resulting surface features, using optical and scanning electron microscopy [3].

By pre-stressing the material and strengthening it against surface damage, this hardening helps to prevent fatigue fractures from forming and spreading while it is in use. SP, thus, is essential to guaranteeing the dependability and durability of aluminium alloy structures, that are exposed to harsh operating environments, including those found in automotive, aircraft, and marine settings.

The concept of variable fatigue, also known as cumulative damage, originated in 1924 when Palmgren introduced the concept of linearly varying damage [4]. This theory later became known as Miner's rule, commonly known as the Miner–Palmgren rule [5]. The Miner–Palmgren rule has been widely used in fatigue analysis on a variety of materials and remains a fundamental concept in the field.

According to this assumption, fatigue damage accumulates linearly until failure is reached, which occurs when the stress cycle ratio equals unity. In simpler terms, it posits that the fatigue life of a material can be estimated by summing the damage caused by different stress cycles. Each stress cycle leads to a specific amount of damage, and once the cumulative damage attains a value of one, the material is considered to have reached its fatigue limit, with the likelihood of failure becoming significant.

Several cumulative damage theories exist for metallic materials, with Miner's theory being one of the most important [6; 7]. Miner's cumulative damage theory is widely used to assess the fatigue life of materials subjected to cyclic loading. This theory is fundamental in engineering and structural design for ensuring the reliability and safety of components.

$$(D)Damage = \sum \frac{n_i}{N_i} = 100\,\% = 1\,, \qquad (1)$$

where D is defined as fatigue and is equal to 1, when failure is occurred;
n_i is the applied number of cycles;
N_i is the number of cycles to failure as determined from the Stress – Number of Cycles curve (*S–N* curve). The *S–N* curve depicts the relationship between cyclic stress amplitude (*S*), and the number of cycles to failure (*N*) for a given material, and is commonly employed to estimate fatigue life under cyclic loading conditions.

Mahdi et al. examined AA7001-T6 at creep-fatigue interaction test at room temperature, 150, 280 and 330 °C [8]. It was revealed that the mechanical properties reduced by 37.2, 30 and 24 % for ultimate tensile strength (UTS), yield strength (YS), and Young's modulus (E) respectively. The UTS and YS increased by 5.5 and 5.3 %, respectively, while fatigue strength improved by 12.3 % after 10^7 cycles [9]. The endurance fatigue limit was also reduced from 208 to 184 MPa at 330 °C. A significant reduction was observed in mechanical and fatigue properties at high temperature for AA7001-T6. Mazlan et al. observed the same finding during his investigation of AA2024T351 specimens [10].

In previous studies, Alwin et al. tested AA2024-T4 samples to tensile and fatigue stress during a 10-minute SP procedure [9; 11]. They discovered that adding compressive residual stresses considerably increased fatigue strength and longevity.

Al-Rubaie proposed a theoretical model for the fatigue behaviour of 2024-T3 alloy, drawing on earlier work in the field, particularly the Walker equivalent stress model [12]. The application of this solution to the presented model showed successfully, estimation of fatigue variable loading life under room temperature.

Alalkawi et al. tested AA2024, to study the effect of high temperature (200–250 °C) on fatigue behaviour [13]. They concluded that mechanical properties reduced by a factor of 1.6 to 2.4 while fatigue strength reduced by 1.8 reduction factor.

Therefore, Alalkawi et al. explored the impact of hardening treatments on the cumulative fatigue performance of AA2024 through two block loading tests (120–180 MPa) – one involving low-high stress levels and the other high-low stress levels, both conducted at room temperature [13; 14]. The findings indicated a significant enhancement in cumulative fatigue life attributed to the surface hardening achieved through SP.

Mahdi et al. tested AA7001-T6 under fatigue rotating bending with high temperature (330 °C) and SP + high temperature (SP+330 °C) [8]. They used Miner's rule for variable fatigue loading and it was observed that this rule provided conservative for some samples and non-conservative for the others.

The Miner–Palmgren rule has been improved and adjusted to better suit certain materials and loading conditions in fatigue analysis [7–10]. These developments have resulted in a variety of changes and improvements, including their use as an effective mechanical surface treatment, as noted by Maleki et al. [15].

Fatigue models for alloys like AA2024 are essential for predicting fatigue life under a variety of stress circumstances. Hector and De Waele [16], Fatemi and Yang [17], and Li et al. have all developed well-known models in this field [18]. Therefore, Hector and De Waele's approach integrates experimental data and theoretical principles to estimate fatigue life using characteristics including stress amplitude, loading frequency, and material microstructure [16]. Hence, Fatemi and Yang's widely utilised model takes into account the impacts of average stress, and stress amplitude on fatigue life. This model uses experimental data and analytical approaches to estimate fatigue life under various loading circumstances [17]. Finally, Li et al. AA2024 finite element model correctly predicts fatigue life by integrating numerous material parameters, such as residual stress, strengthening, and loading conditions [18].

Other models for calculating a part's lifetime are available in the literature, including those of Marco and Starkey [19], Zhao et al. [20], and Hwang and Han [21], all from the late 20th century. When these models are applied to regularly used materials as AA2024, they encounter uncertainties. Indeed, Marco and Starkey (1954) investigated uniaxial stresses that were assessed and compounded with numerous harmonic components [19]. Recently, Zhao et al. investigated cumulative damage patterns during fatigue in 2022, based on load interaction and strength degradation [20]. They showed that their suggested cumulative damage model was more consistent with experimental fatigue data, but only at higher cycle loads [21].

Here, we propose to use the grinding spray method in the case of aluminium alloys, especially the alloys of AA2024-T4 and AA2024-T361. This research intends to improve aircraft safety, by creating exact predictive fatigue life models for aluminium alloys, namely AA2024, under high-temperature and SP circumstances. The effectiveness of AA2024-T4 and AA2024-T361 is assessed by comparing them to previously reported data. Analysing various fatigue prediction approaches against experimental data yields, useful insights, refines models, and improves aircraft structural safety.

The study aims to understand the performance of the aluminium alloys AA2024-T4 and AA2024-T361 at high, with and without shot peening-induced hardening. It seeks to understand whether elevated temperatures and shot peening impact the mechanical characteristics and fatigue life of these alloys, offering insights for improving their durability and reliability in high-temperature applications.

METHODS

The experimental phase began with selecting specimens and analysing their chemical composition, which is crucial for ensuring accurate and reliable subsequent testing and analysis.

In fact, we have chosen to focus on two specific aluminium alloys: AA2024-T4 and AA2024-T361. These alloys share the same base composition but undergo different tempering treatments, resulting in distinct mechanical properties. Examining both variants allows for a more comprehensive understanding of the influence of tempering on material behaviour.

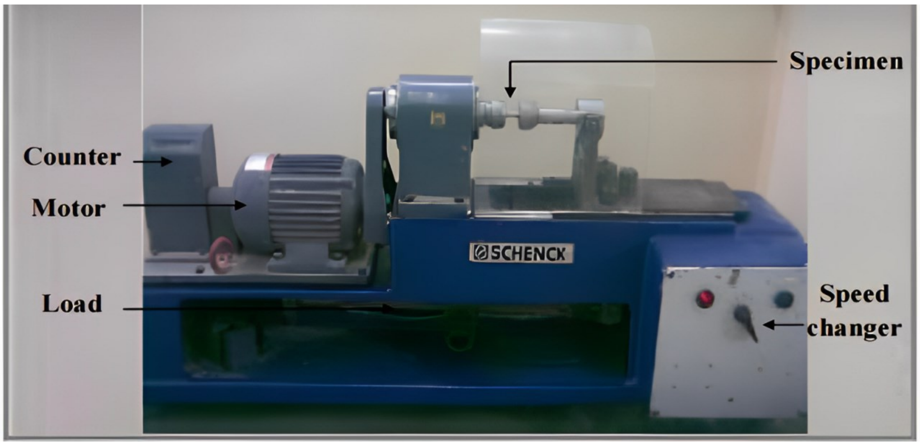
The current model primarily utilises the *S–N* curve and related assumptions, emphasising both the slope (α) and the fatigue endurance limit. It also incorporates the effects of sequential loading at two distinct stress levels: low (σ_L) and high (σ_H).

Furthermore, in this experimental study, we used a SCHENCK PUNU apparatus (SCHENCK USA CORP.), which can perform SP at both room and high temperature (Fig. 1 a). For high-temperature SP, we also utilised a furnace insulated with ka-wool (Fig. 1 b).

The COSQC-Baghdad laboratory carefully examined the alloys through chemical analysis to make sure they satisfied the strict Iraqi Specification Quality (ISQ) 1473/1989 requirements using the state-of-the-art spectrometer ARC-MET 8000 (Verichek Technical Services, USA) for this analytical procedure. Table 1 contains the measured chemical composition, as well as the data of the relevant standards. Mechanical properties of the AA2024-T4 and AA2024-T361 alloys are given in Table 2.

The current study is focused on investigating fatigue behaviour under variable loading conditions. Therefore, we examine four distinct cases under the test conditions outlined in Table 3. We mention that R^2 assess the goodness of fit of a statistical model, particularly in linear regression analysis. In this context, we denote variable D_v as the damage due to variable amplitude fatigue, and n_i is the applied cycles under i^{th} constant-amplitude loading level.

Fatigue analysis is based on experimental data collected during continuous fatigue testing. 18 fatigue samples (Fig. 2) were studied at three stress levels – 323 MPa (0.7 UTS), 277 MPa (0.6 UTS), and 231 MPa (0.5 UTS), with three specimens tested per stress level. The average results were collected immediately from the fatigue test rig. It is therefore necessary to plot the *S–N* curves, and obtain the equations of the *S–N* curve for the above cases. The details of *S–N* curve or Basquin equations are listed in Table 4.



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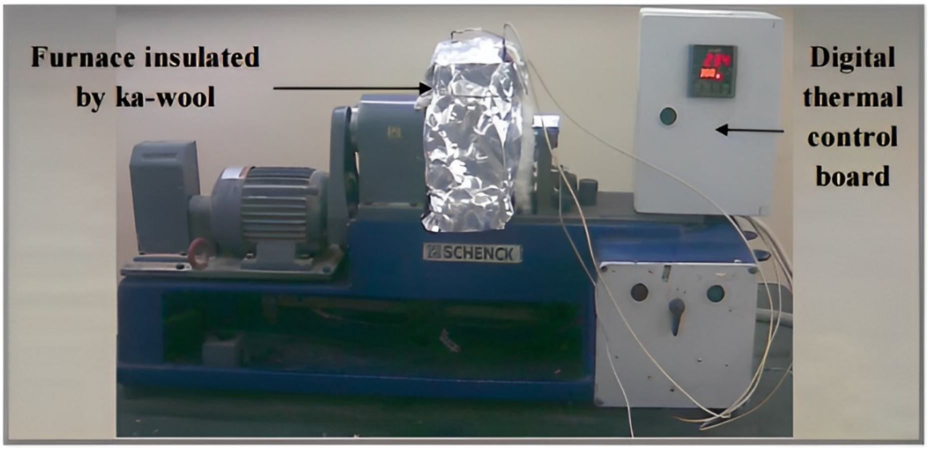

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Fig. 1. *Fatigue testing (SCHENCK PUNU):*
a *– at room temperature;* ***b*** *– at high temperature using a furnace*
Рис. 1. *Машина для усталостных испытаний (SCHENCK PUNU):*
a *– при комнатной температуре;* ***b*** *– при высокой температуре с использованием печи*

***Table 1.** Chemical analysis of AA2024-T4 and AA2024-T361 measured, wt. %*
***Таблица 1.** Результаты химического анализа сплавов AA2024-T4 и AA2024-T361, мас. %*

Element	AA204-T4 experimental measurements	AA204-T361 experimental measurements	Nominal chemical composition AA2024-T4 [24]	Nominal chemical composition AA2024-T361 [24]
Cu	4.10	4.6	3.8 to 4.9	3.8 to 4.9
Fe	0.38	0.5	0.5	0 to 0.5
Si	0.25	0.5	0.5	0 to 0.5
Mn	0.48	0.7	0.3 to 0.9	0.3 to 0.9
Mg	0.42	1.7	1.2 to 1.8	1.2 to 1.8
Zn	0.12	0.25	0.25	0 to 0.25
Cr	0.05	0.045	0.15	0 to 0.1
Al	Balance	Balance	90.9 to 93.0	90.7 to 94.7

***Table 2.** Mechanical properties of aluminum alloys AA2024-T4 and AA2024-T361*
***Таблица 2.** Механические свойства алюминиевых сплавов AA2024-T4 и AA2024-T361*

Mechanical properties	AA2024-T4	AA2024-T361
Ultimate tensile strength, MPa	470	487
Tensile yield strength	325	345
Elongation at break, %	12	11
Modulus of elasticity, MPa	720	710
Hardness, Rockwell B	72	71
Poisson's Ratio	0.33	0.32

***Table 3.** Selection of test conditions [10]*
***Таблица 3.** Условия испытаний [10]*

Setups	Empirical model
Case (1), 250 °C, AA2024-T4	σ_f=2719 $N_f^{-0.2053}$, R^2=0.969
Case (2), SP+250 °C, AA2024-T4	σ_f=2243 $N_f^{-0.1896}$, R^2=0.970
Case (3), 250 °C, AA2024-T361	σ_f=2665 $N_f^{-0.2005}$, R^2=0.996
Case (4), SP+250 °C, AA2024-T361	σ_f=2709 $N_f^{-0.1972}$, R^2=0.924

Note. SP is shot peening.
Примечание. SP – дробеструйное упрочнение.

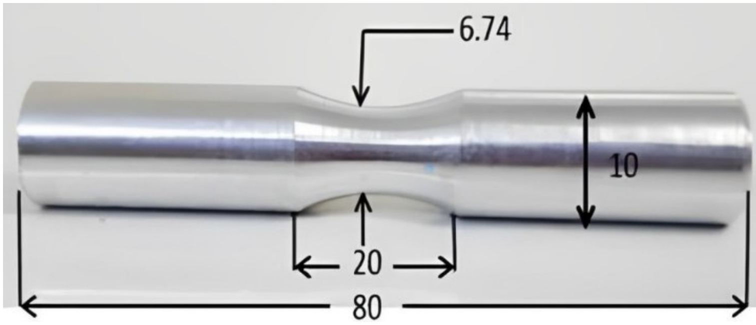


__Fig. 2.__ Fatigue sample dimensions in mm as per DIN 50113 standard specifications
__Рис. 2.__ Размеры образца в мм в соответствии с DIN 50113

The Miner's rule stipulates that failure happens when the cumulative fatigue damage reaches its limit. For the two blocks in question, this implies that failure occurs precisely at the point when:

$$\left[\frac{n_1}{N_{f1}}+\frac{n_2}{N_{f2}}\right]=100\,\%=1\,. \tag{2}$$

If more than two blocks are applied, this equation is generalised to write:

$$\sum\frac{n_i}{N_F}=1\,. \tag{3}$$

It should be mentioned that the experiments with variable loading on flat samples of an AA2024-T3 sheet showed that the damage $\sum\frac{n}{N_F}$ values varying from 0.61 to 1.45, but on the average close to 1.0 as mentioned by Mahdi et al. [8]. In high-temperature environments, the limitations of this rule should be carefully considered to provide a more accurate assessment of fatigue life under variable loading conditions. Elevated temperatures can significantly affect material properties, leading to changes in the behaviour of materials under cyclic loading.

In this study, we conducted tests on 24 round-shaped specimens stress ratio of R=−1. For each case, 6 samples were tested: three for low-high two-block loading and three for high-low two-block loading with variable loading conditions. The study focused on determining the average fatigue life for these specimens.

The safe proposed model (SPM): any fatigue damage D_v under variable loading requires a definition. It appears that the D_v concept should include the sequence effect, mechanical properties and the tested *S–N* curve for the given case.

RESULTS

The reliable fatigue model for shot-peened aluminium alloys, as developed by Alwin et al. [10], utilises Miner's rule, assuming that the *S–N* curve accounts for 100 % of the fatigue damage. However, this assumption is somewhat unrealistic because the *S–N* curve does not

Table 4. *S–N curve equations with correlation factor (R^2) for the four cases*
Таблица 4. *Уравнения S–N кривых с коэффициентом корреляции (R^2) для четырех режимов*

Case No	Symbol	Description
1	250 °C	Cumulative fatigue testes at two stress levels, low-high and high-low for aluminum alloy AA2024T4 under 250 °C
2	SP+250 °C	Cumulative fatigue testes at two stress levels, low-high and high-low for the same alloy under SP and high temperature
3	250 °C	Cumulative fatigue testes at two stress levels, low-high and high-low for aluminum alloy AA2024-T361 at 250 °C
4	SP+250 °C	Cumulative fatigue testes at tow stress levels, low-high and high-low for the same alloy under SP and high temperature

Note. SP is shot peening.
Примечание. SP – дробеструйное упрочнение.

represent a constant damage line. This relationship highlights that fatigue damage is complex and cannot be fully captured by a single damage parameter, especially at high temperatures. For the SP process, only normal impingement was considered to allow for a direct comparison with earlier results.

The optimisation procedure by Miao et al. [22] assumes that individual shots act independently, ignoring interactions between them. This simplifies the analysis and focuses on key parameters. However, it may overlook cumulative effects that could impact the SP process's overall outcome.

The material was subjected to SP during 10 min, which is sufficient for significant increase in durability. The increased durability demonstrates SP's significant benefits in improving material fatigue resistance. Stress decreases dramatically as the number of cycles increases; however, the reduction is more noticeable at higher temperatures, as seen in Fig. 3. The number of cycles decreases from around 105,000 to 80,000 as the temperature rises from ambient to 200 °C, with an even higher reduction recorded at 250 °C. The *S*-curve presented, in conjunction with fatigue life formulas and R^2 values in Table 3, provides a better understanding of fatigue resistance. This analysis helps to optimise the performance of the alloys and processes, resulting in a significant extension of their operational lifespan.

The integration of non-linear models, a single damage parameter has failed to produce an improved Miner's rule, that can offer dependable predictions across a wide range of scenarios. Despite attempts to incorporate non-linear damage functions, the inherent limitations of the Miner's rule remain unresolved. This brings us to the critical question of how to precisely define fatigue damage D_v. It represents the cumulative damage that occurs in the considered alloy due to a cyclic loading. The present work presents a new definition of D_v which depends on the following concepts:

– the mechanical properties such as ultimate tensile strength called σ_{UTS} and yield strength σ_y;

– the *S–N* curve, i.e. the slope of the curve α and endurance fatigue limit σ_e, obtained from *S–N* curve equation at 10^7 cycles for the given case;

– sequence loading effect, low stress σ_L and high stress σ_H.

Based on the above concepts D_v can be calculated from the equation:

for low-high loading sequence:

$$D_v = \left[\frac{\sigma_{UTS} - \sigma_L}{\sigma_{UTS} - \sigma_H}\right]^{\left(\frac{\sigma_b}{\sigma_H}\right)\alpha}; \quad (4)$$

for high-low loading sequence:

$$D_v = \left[\frac{\sigma_{UTS} - \sigma_L}{\sigma_{UTS} - \sigma_H}\right]^{\left(\frac{\sigma_н}{\sigma_u}\right)\alpha}. \quad (5)$$

Following the work of Miller et al. [23], the fatigue life under variable loading can be predicated by the formula:

for high-low loading:

$$N_{fv} = \frac{\left[\frac{\sigma_{UTS} - \sigma_L}{\sigma_{UTS} - \sigma_H}\right]^{\left(\frac{\sigma_н}{\sigma_u}\right)\alpha} \left(\sigma_{UTS} - \sigma_L\right)^{1-\frac{1}{\alpha}}}{A^{\frac{1}{\alpha}}\left(\sigma_H^{1-\frac{1}{\alpha}} - \sigma_L^{1-\frac{1}{\alpha}}\right)}; \quad (6)$$

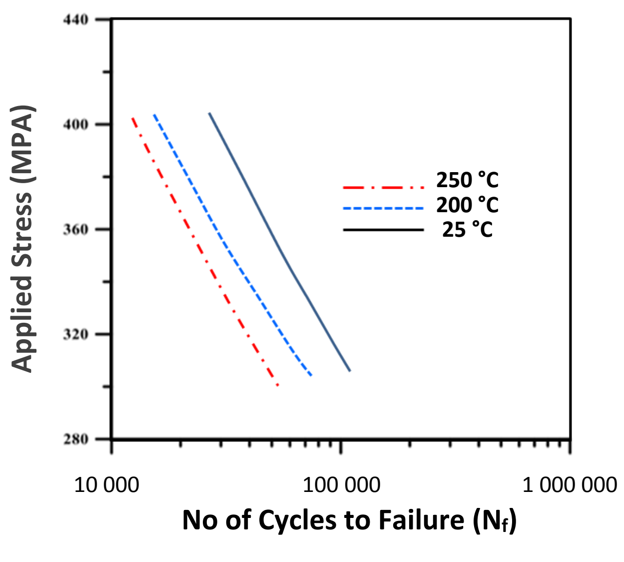


Fig. 3. *Constant S–N curves at three temperatures (room temperature, 200 °C, 250 °C)*
Рис. 3. *Постоянные кривые усталости (S–N кривые)*
при трех температурах (комнатная температура, 200 °C, 250 °C)

for low-high loading:

$$N_{fv} = \frac{\left[\frac{\sigma_{UTS} - \sigma_L}{\sigma_{UTS} - \sigma_H}\right]^{\left(\frac{\sigma_{\text{н}}}{\sigma_{u}}\right)\alpha} \left(\sigma_H - \sigma_L\right)^{1-\frac{1}{\alpha}}}{A^{\frac{1}{\alpha}}\left(\sigma_H^{\,1-\frac{1}{\alpha}} - \sigma_L^{\,1-\frac{1}{\alpha}}\right)}. \qquad (7)$$

Experimental loading tests (high-low) and (low-high) were carried out for both alloys AA2024-T4 and AA2024-T361 at various temperatures, with or without SP, using the previously described apparatus. The observed maximum number of cycles, the mean number of cycles, and the predicted number of cycles based on the SPM are all listed in Table 5.

The analysis, which draws upon the experimental results presented in Table 5 and visualised through corresponding histograms, is illustrated in Fig. 4.

It is evident from the results that the SPM consistently predicts fatigue lives that fall within the safe range, indicating durations shorter than those observed in experimental testing. Indeed, Fig. 5, 6 depict comparisons between these fatigue predictions, providing a clear distinction of how the model's predictions align with or deviate from the experimental data. The given representation offers a valuable insight into the performance and reliability of the SP model in estimating fatigue life for the examined aluminium alloys.

Fig. 5, 6 show a significant difference between the standard Miner's rule technique and the experimental results achieved with identical samples. The Miner's rule consistently yields predictions that exceed the actual fatigue life, primarily because it fails to account for crucial factors such as temperature variations and the impact of SP, which are considered by the safe model.

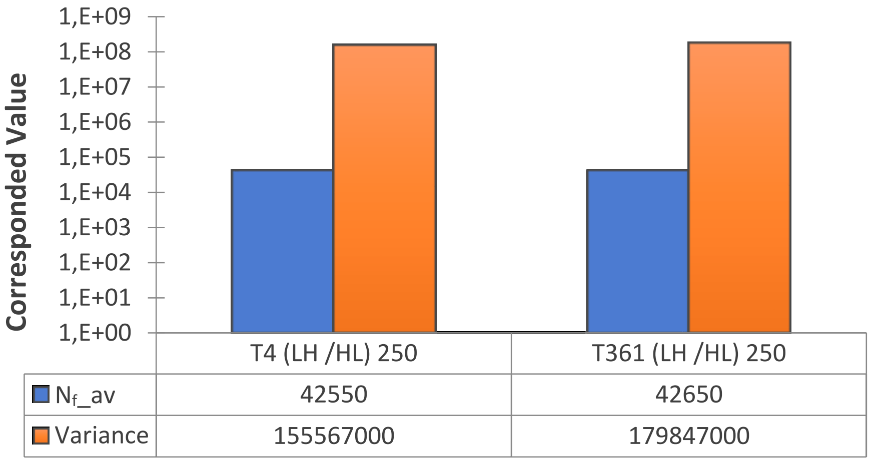
DISCUSSION

Based on data columned in Table 5, a comprehensive fatigue life assessment can be highlighted by comparing the experimentally obtained cumulative fatigue life with the predictions from the SPM. Indeed, the specification of the AA2024 alloy, whether T4 or T361, is a significant factor in fatigue performance. It appears that the SPM model fits better with the AA2024-T361 alloy than

Table 5. *Cumulative fatigue life: experimental results and safe model prediction*
Таблица 5. *Совокупная усталостная долговечность: экспериментальные результаты и модельное прогнозирование*

Loading sequence	Alloy	Specimen number	Experimental number of cycles N_{f_exp}	Mean number of cycles N_{f_av} [10]	Number of cycles modelling N_{f_model}
Low-high 250 °C	AA2024-T4	1 2 3	38,800 51,000 62,600	50,800	40,712
High-low 250 °C		4 5 6	41,800 29,600 31,500	34,300	28,151
Low-high SP+250 °C	AA2024-T4	7 8 9	48,200 71,600 88,000	69,267	35,352
High-low SP+250 °C		10 11 12	60,500 49,600 50,000	53,367	25,765
Low-high 250 °C	AA2024-T361	13 14 15	42,800 66,000 37,800	48,867	47,636
High-low 250 °C		16 17 18	48,200 32,400 28,700	36,433	34,360
Low-high SP+250 °C	AA2024-T361	19 20 21	53,000 84,500 68,800	68,767	61,885
High-low SP+250 °C		22 23 24	62,600 56,800 48,000	55,800	46,143

Note. SP is shot peening.
Примечание. SP – дробеструйное упрочнение.



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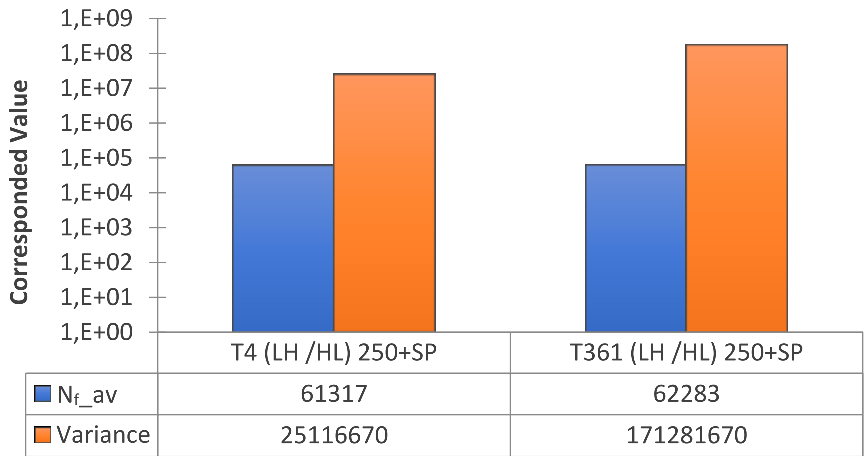

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Fig. 4. *Cumulative fatigue life: a comparative study of AA2024-T4 and AA2024-T361 alloys (average N_{f_av} and variance analysis)*

Рис. 4. *Совокупная усталостная долговечность: сравнительный анализ сплавов AA2024-T4 и AA2024-T361 (усредненный анализ N_{f_av} и вариационный анализ)*

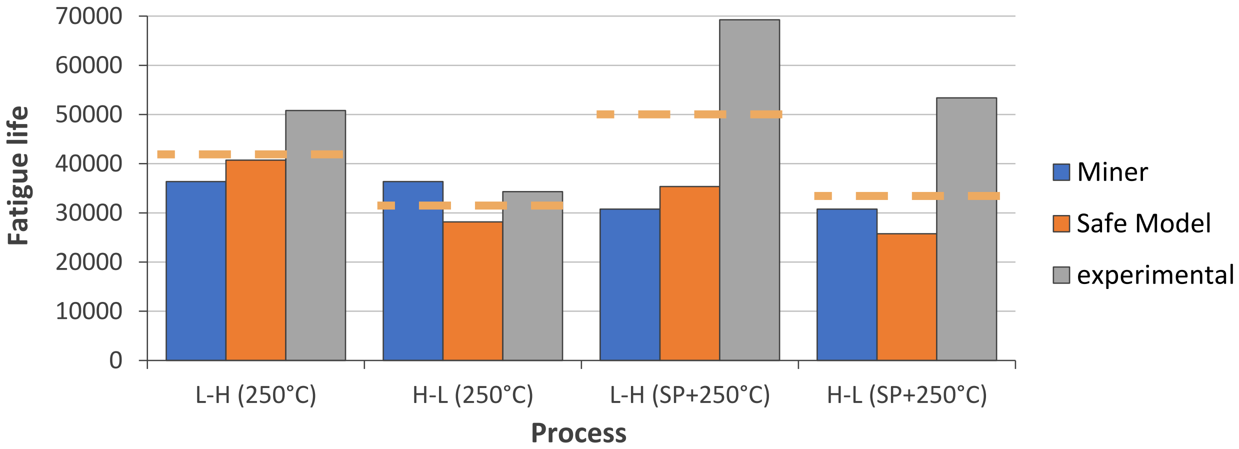

Fig. 5. *Comparison between experimental and model prediction AA2024-T4. The orange dashed line consistently matches both the safe model predictions and the experimental fatigue life values in every shot peening case (shot peening scenario)*

Рис. 5. *Сравнение экспериментальных результатов и результатов моделирования для сплава AA2024-T4. Оранжевая пунктирная линия соответствует модели безопасного прогнозирования и значениям экспериментальной усталостной долговечности для каждого режима дробеструйного упрочнения*

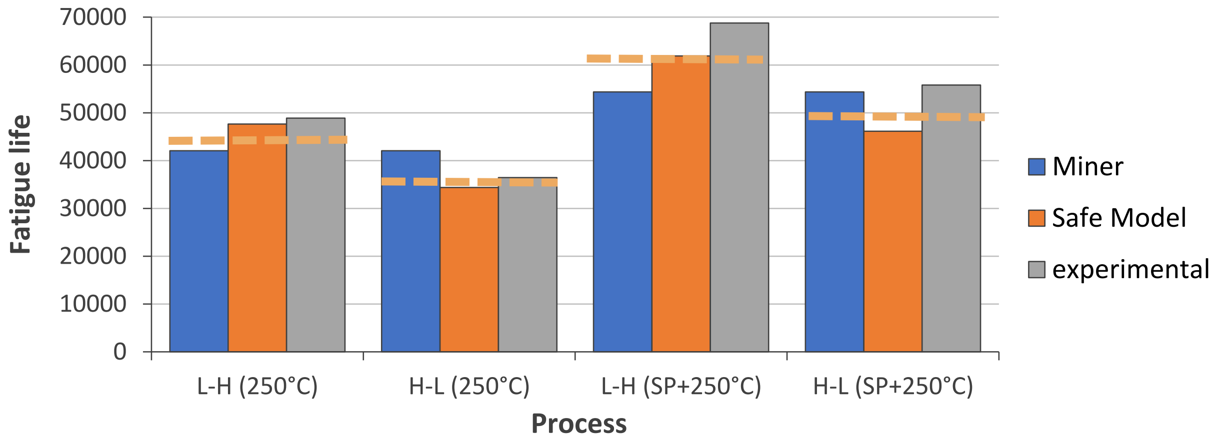

Fig. 6. *Comparison of three methods for fatigue prediction for AA2024-T361.*
The orange dashed line consistently matches both the safe model predictions
and the experimental fatigue life values in every shot peening case (shot peening scenario)
Рис. 6. *Сравнение трех методов усталостного прогнозирования для сплава AA2024-T361.*
Оранжевая пунктирная линия соответствует модели безопасного прогнозирования
и значениям экспериментальной усталостной долговечности для каждого режима дробеструйного упрочнения

with AA2024-T4. Furthermore, it proves to be effective in a SP scenario at high temperatures (250 °C).

Furthermore, the Miner's rule provides only an approximate estimate of fatigue life, with significant errors due to different limitations, as indicated by the histograms in Fig. 5 and 6 for alloys AA2024-T4 and AA2024-T361. First, the rule assumes that stress cycles below the fatigue limit are insignificant. Second, it fails to account for the effects of treatments such as SP and environmental factors such as temperature. Finally, the rule undervalues the significance of loading sequences that alternate between low and high stress levels. In contrast to Miner's rule, we've included the average value, shown by the orange dashed line, to show how close it is to the safe model, see Fig. 5, 6. The histogram illustrates the maximum number of cycles for the low-high and high-low scenarios at 250 °C, both with and without SP. In every SP case, the orange dashed line consistently aligns with the safe model predictions and the experimental fatigue life values. In fact, this observation is particularly evident for the AA2024-T361 alloy compared to the AA2024-T4 alloy.

Indeed, a complex interaction of important variables is the cause of the Miner theory's inaccuracies in fatigue life prediction. First off, a major flaw in the hypothesis is its disregard for fracture initiation, particularly in the early stages of the brief fatigue crack phase. Understanding the initiation dynamics requires an understanding of this phase, which spans approximately 80 % of the fatigue life as the applied stress approaches the fatigue limit. The absence of this important detail leads to a significant underestimate of the total cumulative harm [22], suggesting a key weakness in the theory's prediction power.

The fatigue performance of the two suggested aluminium alloys, AA2024-T4 and AA2024-T361, was assessed by comparing their service life (measured in terms of cycles). The analysis focused on two key metrics: the mean number of cycles to failure (N_{f_av}) and the variance in fatigue life for each procedure. In fact, results indicated that AA2024-T361 demonstrated a significantly longer fatigue life than AA2024-T4, as depicted in Fig. 4. This superior performance of AA2024-T361 can be attributed to its specific damage processes, which may include enhanced resistance to crack initiation and propagation due to its microstructural characteristics or alloying elements [3; 18]. Additionally, the SP treatment, known for inducing compressive residual stresses, may have further improved the fatigue resistance of AA2024-T361 by delaying the onset of fatigue cracks. These findings suggest that AA2024-T361 is better suited for applications where extended fatigue life under high-temperature conditions is critical, offering valuable insights for selecting materials in engineering designs that require durability and reliability.

CONCLUSIONS

The study investigated at the cumulative fatigue behaviour of AA2024-T4 and AA2024-T361 alloys at 250 °C, evaluating both isolated scenarios at temperature T=250 °C, and a combined shot peening (SP) treatment at the same temperature (SP+250 °C), all at a stress ratio R=−1. The results revealed that applying cumulative varied loads resulted in a significant decrease in fatigue life, particularly at high temperatures; however, SP demonstrated a significant improvement in fatigue resistance. Furthermore, classic approaches for estimating fatigue life, such as the linear damage rule or Miner's theory, or models derived from them, have shown limitations in terms of providing unreliable and inaccurate predictions.

As a result, a novel fatigue life prediction model has been developed that incorporates loading sequence data obtained from the S–N curve, as well as pertinent mechanical parameters. This model provides a conservative but robust way to estimating fatigue life under various stress situations, whether encountered at increased temperatures or in combination with SP treatment at elevated temperatures. A comparison of the mean number of possible cycles and variance for the various experimental settings, stated previously, demonstrates the accuracy of the provided model, although at elevated temperatures with SP for AA2024-T361 against AA2024-T4.

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Прогнозное моделирование усталостной долговечности алюминиевых сплавов при повышенных температурах после воздействия дробеструйного упрочнения

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Поступила в редакцию 18.04.2024 *Пересмотрена 22.05.2024* *Принята к публикации 11.09.2024*

Аннотация: Повышение качества поверхности оболочек из алюминиевых сплавов, подвергающихся высоким нагрузкам, остается актуальной задачей, для решения которой используются различные методы. Для алюминиевых сплавов наибольшее распространение получило дробеструйное упрочнение. В статье исследуются усталостные характеристики алюминиевых сплавов 2024-T4 и 2024-T361 после дробеструйного упрочнения и без него при комнатной и повышенной температуре (250 °C). Полученные результаты хорошо согласуются с ранее опубликованными данными, предоставляя полезную информацию о поведении этих сплавов при повышенных температурах. Была разработана математическая модель, объединяющая кривую усталости «напряжение – количество циклов до разрушения», амплитуду нагрузки, температуру и твердость поверхности, подвергнутой дробеструйному упрочнению. Полученные с использованием этой модели результаты были сравнены с гипотезой Майнера для оценки усталостной долговечности. Было установлено, что новая модель обеспечивает более точные прогнозы усталостной долговечности, чем гипотеза Майнера, тем самым повышая надежность и безопасность разработанных на ее основе компонентов при высокотемпературных условиях эксплуатации.

Ключевые слова: дробеструйное упрочнение; прогнозная усталостная долговечность; алюминиевые сплавы; AA2024-T4; AA2024-T361; высокотемпературное воздействие; переменное нагружение.

Для цитирования: Элвин А.Х., Ксиби Х. Прогнозное моделирование усталостной долговечности алюминиевых сплавов при повышенных температурах после воздействия дробеструйного упрочнения // Frontier Materials & Technologies. 2024. № 4. С. 111–122. DOI: 10.18323/2782-4039-2024-4-70-10.