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Fatigue life prediction under different laser coatings for cumulative bending based on a new non-linear model

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ABSTRACT

A non-linear cumulative fatigue model was developed for estimating the fatigue life of high strength aluminum alloy 7049 in high cycle fatigue (HCF) and low cycle fatigue (LCF) regimes with different laser surface coatings. These coatings are water laser peening and the black paint laser peening (bPLP). The results of the application the new non-liner model to the experimental data that the proposed model is quite applicable for interaction cumulative fatigue with laser coating. The paper also indicated that the fatigue limit increased by 2.59 due to bpLp while it reduced by 2.3 due to WLP.The new non linear model showed satisfactory prediction for bpLp cumulative fatigue loading.

Introduction

Surface enhancement technologies, which are mainly made by modifying the surface integrity of parts, are widely employed to improve the properties of components including fatigue, stress corrosion cracking, wear, and fretting. Among these surface enhancement technologies, shot peening is a conventional and widely applied process to increase fatigue performance of parts, which has been applied for many years in aircraft components. Laser peening is a recently developed process and is being widely investigated. Due to its accurate positioning and precise operation, laser peening can be applied to many aircraft components such as blades and gears with good repeatability and reliability. Laser peening induces compressive residual stress in the surface layer by pulse laser impact energy and plastic deformation occurs in the surface layer [1].

More recently, surface treatment technologies have become more and more important in industry to cut costs and avoid the need for expensive materials. Demonstrated approximately 30 years ago, laser shock processing (LSP) is now emerging as a viable surface treatment technique. The compressive residual stresses in the metal material treated by LSP can extend deeper below the surface than those from shot peening. LSP is well suited for precisely controlled treatment of localized fatigue critical areas, such as holes, notches, fillets and welds. It has been proposed as a competitive alternative technology to classical treatments for improving fatigue, corrosion and wear resistance of metals [2].

Laser surface treatments which affect fatigue life rely on (i) generation of compressive residual stresses by phase transformation or by shock peening and (ii) tensile stresses from non-elastic thermal deformation [3].

Finite element models, using the eigenstrain approach, are described that predict the residual stress fields associated with laser shock peening (LSP) applied to aerospace grade aluminum alloys. The model was used to explain the results of laboratory fatigue experiments, containing different LSP patch geometries, supplementary stress raising features and different specimen thickness. It is shown that interactions between the LSP process and geometric features are the key to understanding the subsequent fatigue strength [4]. A healing method for fatigue damage was studied by laser shock peening (LSP) with excimer laser for polycrystalline copper film. It is found that the reduction of plastic strain range due to laser shock peening could be responsible in the improvement of residual fatigue lives for the damaged specimens by LSP, and the degree of reduction in plastic strain range for the damaged specimens by LSP is more evident when the stress range is larger. According to the variation of the fatigue ductility of the specimen before and after LSP, a unified damage-healing model is proposed during the damage-healing process for copper specimens. The predicted lives by the proposed method agree well with the experimental results [5]. A hybrid explicit finite element (FE)/eigenstrain model for predicting the residual stress generated by arrays of adjacent/overlapping laser shock peening (LSP) shots where the use of a completely explicit FE analysis may be impractical. It shows that for a given material, the underlying eigenstrain distribution (in contrast to the resulting stress field) representing a laser shock peen is primarily dependent on the parameters of the laser pulse and the number of overlays rather than the precise component geometry [6]. Crack initiation often occurs along the curved regions or fillets of structural components" because of the presence of high stress concentrations. These critical regions are modeled as a curved geometry to capture the curvature effects using simulation models. Concave and convex simulation models are created and compared with flat geometry to investigate the effects of curvature in a laser peening problem. A mechanism of residual stress generation in curved models is used to explain the residual stress result obtained from finite element models. The results predict that increasing the radius of curvature in a concave model decreases the compressive residual stress generated in the component while increasing the radius of curvature of a convex model increases the compressive residual stress induced in the material when compared [7]. Effects of

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laser energy on fatigue crack growth (FCG) properties of 6061-T6 aluminum alloy subjected to multiple laser peening (LP) were investigated. LP experiments and typical FCG experiments were performed on the compact tension (CT) samples. In order to reveal the enhancement mechanism of laser energy on FCG properties through residual stress (RS), a numerical model of effective stress intensity factor (SIF) was established. The results showed that compressive RS induced by LP can effectively decrease FCG rate and increase FCG lives of CT samples. The experimental results and numerical analysis correlated with each other [8].

Experimental Work

Material Selection

Aluminum alloy of type 7049 class is used in the current work. It is primarily used in applications for many general engineering and aircraft structural purposes in the extruded bars and section sheets, plates, tubes and rivets. This alloy possesses considerably high strength with good fracture toughness. Chemical analysis of the metal used was carried out at state (company for Inspection and Engineering Rehabilitation in Iraq). The results, which are compared to the American Standard ASTM are summarized in table (1), While the tensile test specimen prepared according to the ASTM, have been installed in tensile test machine and test has been done at room temperature (RT). The test results are given in table (2).

Rotating bending fatigue specimen

The material 7049 Al-alloy was received from aircraft repairing factory in the form of rolled rods of 12mm in diameter. Rotating bending fatigue specimen having an hour-glass profile with large curvature was adopted in this study. Shape and dimensions of fatigue specimen are detailed in fig. (1). The specimens were then numbered and polished. First, with grade 400,600,800,100,1200 emery paper and then with diamond pastes of 3 and 1μm respectively.

Measurement of surface roughness for selected specimens was obtained by means of a Perthometer M3A instrument. The output reading were, Ra, (the center line average) and Rt (the maximum surface roughness).The roughness measurements for selected specimens are given in table (3).

All fatigue specimens were tested under constant and variable loading using the fatigue test machine of type PUNN rotary as shown in fig (2).

Fig 1. Dimension of fatigue test specimen according to DIN 50113.(All dimension in mm)

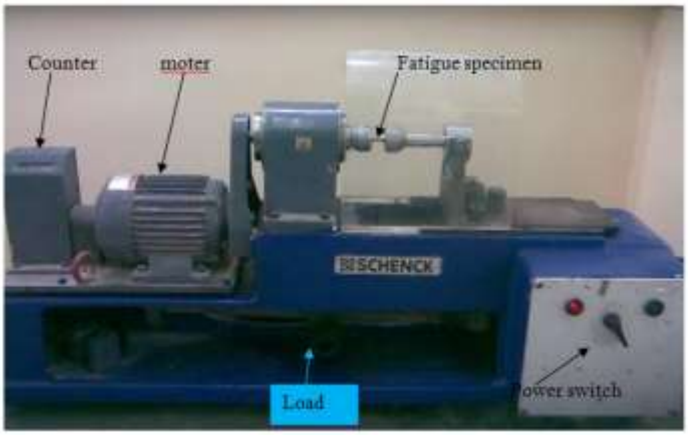


Fig 2. The fatigue testing machine

The Proposed Model

The simple method for describing the relationship between stress (σ) and number of cycles to failure (N) can be expressed in power law regression as [9];

$$\sigma = aN^{b} \qquad (1)$$

Where

σ is the applied stress, and a, b are fitting parameters.

The coefficient (a) related to static fatigue strength, while (b) is the fatigue sensitivity. For the present work, fatigue damage (D) may be defined as based on the workers [10][11] :

$$D = \frac{a(-b)}{\sigma_L} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

For low to high loading sequences.

$$D = \frac{a(-b)}{\sigma_H} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

For high to low loading sequences.

Flowing the work of Zengah et al [12], Alalkawi et al [13], and Zhang et al [14]. Damage can be expressed by a non-liner formula as :

$$D = \left[\left[\frac{n}{N_f}\right]_L + \left[\frac{n}{N_f}\right]_H \right]^{\frac{\sigma L}{\sigma H}} R \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where (n) is the applied stress cycles, N_f is the number of cycles at failure at low or high stress load. N_f can be obtained from equation (1), the S-N curve equation. R is the number of programs of the test shown in figure (3).

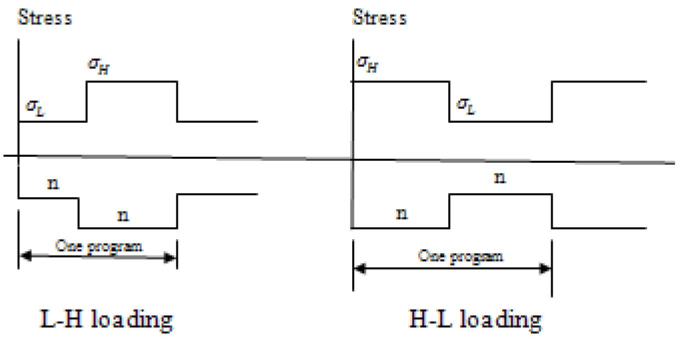


Fig 3. programs of the cumulative fatigue, the applied stress cycle(n) was taken as 5000 cycles

From equations (4),(3) and(2) the proposed cumulative fatigue damage model can be taken the form.

$$D = \left[\left[\frac{n}{Nf}\right]_L + \left[\frac{n}{Nf}\right]_H \right]^{\frac{\sigma L}{\sigma H}} R = \frac{-ab}{\sigma_L} \quad \ldots\ldots\ldots(5)$$

For high-low loadings

$$D = \left[\left[\frac{n}{Nf}\right]_L + \left[\frac{n}{Nf}\right]_H \right]^{\frac{\sigma L}{\sigma H}} R = \frac{-ab}{\sigma_H} \quad \ldots\ldots\ldots(6)$$

Table 1. Experimental and standard chemical composition of 7094 Al-alloy, wt%

Material	Zn	Ti	Si	Cu	Fe	Cr	Mg	Mn	Al
Standard	0.25 max.	0.2 max.	0.8 max.	3.5-4.5	0.7 max.	0.1 max.	0.4-1	0.4- 0.8	Balance
experimental	0.22	0.08	0.15	3.8	0.25	0.06	0.72	0.57	Balance

Table 2. Mechanical properties of 7049 AL-alloy

Property	σ_u MPa	σ_y	E (GPa)	μ	EI%	Fatigue strength (MPa)	Shear modulus (GPa)	Shear strength (MPa)	(HB)
Standard	520	317	74	0.32	20	290	27	280	132
experimental	515	312	73	0.32	19	287	27	277	131

Table 3. Illustrates the roughness values with the min. diameter for selected specimes

Spec. No.	Min. diam. (mm)	Ra µm	Rt µm
1	6.39	0.25	0.75
2	6.41	0.35	0.82
3	6.382	0.19	0.65
4	6.401	0.125	0.45
5	6.375	0.28	0.85
6	6.381	0.37	0.62
7	6.407	0.4	0.85
8	6.402	0.44	0.9
9	6.338	0.29	0.77
10	6.408	0.38	0.89

Table 4. S-N curves results at different laser coatings water laser peening (wLP)

Spec. No.	σ_f (MPa)	N_f cycles	N_f (av.)
1,2,3,4,5,	400	1000,1400,2000 1800,2050	1650
6,7,8,9,10	300	20000,18000,15500 16200,14400	16820
11,12,13,14,15	200	175000,144000, 201000,162000, 152000	166800
16,17,18,19,20	150	1462000,1325000, 1625000,1225000 1385000	1404400

Black paint laser peening (bplp)

Spec. No.	F (MPa)σ	Nf cycles	Nf av.
21,22,23,24,25	400	1850,2900,3200 3600,2450	2800
26,27,28,29,30	300	21500,18700, 20500,17800, 18000	19300
31,32,33,34,35	200	310000,322600, 260000, 288000 273400	290800
36,37,38,39,40	150	2015000,1800000 1776000,2110000 2199000	1980000

Unpeened

Spec. No.	F (MPa)σ	Nf cycles	Nf av.
41,42,43,44,45	400	2000,1600,1800 2080,1900	1876
46,47,48,49,50	300	22500,16800,19600 20200,16900	19200
51,52,53,54,55	200	188000,192000, 205000,194500, 210600	198020
56,57,58,59,60	150	1500000,1668000 1458000,1728000 1821000	1635000

Table 5. S-N curves equations at different laser coatings

condition	R^2	S-N curve equation
WLP	0.97	$\sigma_f = 1216\ N_f^{-0.148}$
unpeened	0.966	$\sigma_f = 1237\ N_f^{-0.176}$
bpLP	0.959	$\sigma_f = 1318\ N_f^{-0.15}$

Table 6. Endurance limit data

condition	Endurance fatigue limit (MPa)	Increase percentage
Unpeened	114.59	-------
WLP	111.92	-2.3
bPLP	117.46	2.5

Table 7. Variable amplitude (VA) fatigue test results of bpLp specimens

Loading sequences (MPa)	N_f	Nf_{av}
L-H 200-300	22000,22500,28000 30000,29000	26300
L-H 150-250	67000,62000,70000 60000,68000	65400
H-L 300-200	21000,18000,22000 17500,23500	20400
H-L 250-150	37000,31000,40000 34000,41500	36700

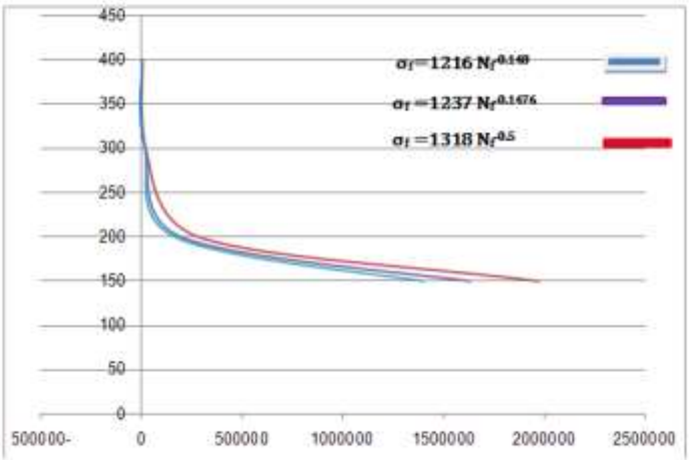
Table 8. Application of the proposed model to VAresults

Specimens No.	Loading sequences MPa	Proposed Model N_f (cycles)	Miner rule N_f (cycles)	N_f experimental
61,62,63	200-300	23285	27694	26300
64,65,66	300-200	15523	27694	20400
67,68,69	150-250	60246	98268	65400
70,71,72	250-150	36147	98268	36700

Experimental results and discussion

The S-N curves experimental results which were done at stress ratio R= -1 and room temperature (RT) are given in table (4).Fig. (4) Shows typical S-N curves of fatigue life. These curves show how fatigue behavior of 7049 AL-alloy change with laser coating. The empirical power law S-N equations with their constants and correlation coefficient (R^2) can be presented in table (5).

Stress



$N_{f\ cycles}$

Fig 4. S-N curves behavior at different laser coatin

Endurance fatigue limit

The endurance fatigue limit at 10^7 cycles can be tabulated in table (6).The experimental results show that laser peening with black paint coating (bpLp) has an important effectiveness to increase endurance fatigue limit.

In case of bpLp only 2.5% of endurance fatigue was increased compared to unpeened condition while reduction in the endurance fatigue limit by 2.3% due to water laser peening (WLP).

The simplest and most cost-effective method is to coat the specimen surface by black paint. The black paint works to increase the plasma generated when the laser beam interacts with the specimen surface. The laser shock waves travel into the material and creating residual compresses stresses. These compressive stresses work to rise the mechanical properties i-e yield and tensile stresses. In general, the deeper compressive stresses produced by laser shock peening, the more substantial property benefits [15].

Generally laser peening (LP) has improved the tensile and fatigue properties of aluminum alloys. This improvement is coming from compressive stress generated at the surface of metal. The compressive stresses are coming from plasma which introduces stress waves or shock waves. Noor [16] gave the reason of reducing the mechanical and fatigue properties using water laser peening (WLP) to that stress waves generated through water and this reason may be the cause for reducing the fatigue property of 7049 aluminum alloy under WLP.

Variable amplitude results

Two type of variable loading tests were carried out at stress ratio R= -1 using the bpLp specimens. Low- high tests (L-H) and high-low tests (H-L) i-e, two black loading tests were conducted for constant applied stress cycles (n) for each stress level.

The results of the above tests are given in table (7). Application of the proposed model to VA results:

Most material exhibits complex behaviors than what Miner rule [17] estimated. Miner theory or LDR (liner damage rule) is still used in design in spite of its major short comings. Most materials have shown than they exhibit highly nonlinear fatigue damage evolution with load dependency [18]

For two block loading test, Miner rule can be written in the form:

$$\left(\frac{n}{N_f}\right)_1 + \left(\frac{n}{N_f}\right)_2 \quad R = 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The prediction of bpLp specimen's lives using the proposed model and Miner rule can be illustrated in table (8). It is observed that the Miners rule or linear damage rule (LDR) overestimates the fatigue lives see table (8) while the proposed model presents lower deviation and the predicted results are more representative than those using LDR. Fig.(5) shows that the proposed model prediction correctly follows the experimental results done on bpLp specimens. The proposed model -nonlinear model takes into account the loading history and the surface coating while Miner rule neglects these effects. The concept of miner rule is that damage happen in a linear manner while the present model exhibits the damage as a non-liner concept.

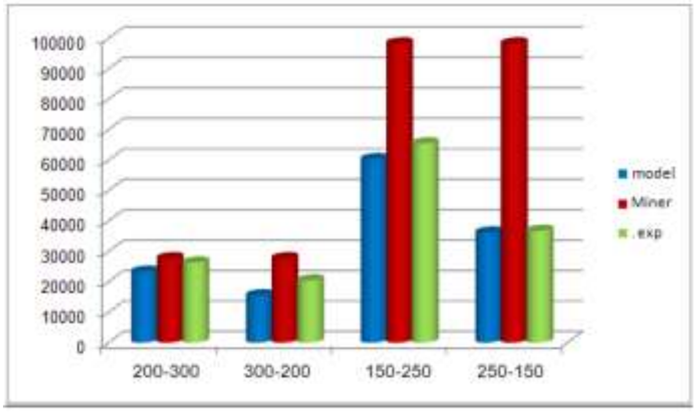


Fig 5. The proposed model, Miner rule and experimental results done on bpLp specimens

Conclusions

1. Black paint laser peening (bpLp) improved the endurance fatigue limit of 7049 AL-alloy by 2.5% while water laser peening reduced the endurance limit by 2.3%.
2. Black paint laser peening significantly increased the fatigue life of 7049 AL- alloy.
3. A new non- linear damage model based on S-N curve and taking into account the influence of load history was introduced. The predicted model results are in good correlation with the experimental results. The present model correctly assess the fatigue life under different loading and surface treatments.
4. It has been verified that materials behave in non-linear manner with load dependency.
5. Miner rule failed to estimate the black paint laser peening tested under variable loading i-e overestimated the fatigue lives.

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