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Experimental Study of the Effect of Shot Peening on Elevated Temperature Fatigue Behavior of 7075-T651 Al. alloy

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ABSTRACT

There is a general interest in increasing the fatigue life of materials. Shot peening is the process commonly used in order to increase the fatigue strength and life of 7075-T651. The effect of a combination of processes, fatigue-creep interaction and shot peening has not been thoroughly investigated so far. The aim of the present investigation was whether further improvements can be achieved by a comb/*ination of the two treatments. Two level experiments (cumulative fatigue damage programe) were used in order to determine the optimal set of process. It was found that the combination of shot peening and fatigue-creep interaction could be applied successfully in order to increase fatigue life for some specimens. Results of variable loading test clearly indicate that Miner rule does not give accurate and reliable predictions on fatigue lives.

Keywords: Stress controlled fatigue creep interaction, shot peening, surface roughness, aluminum alloy.

دراسة تجريبية لبيان تأثير القذف بالكريات على تصرف الكلال في درجات الحرارة العالية لسبيكة الالمنيوم 7075-T651

الخلاصة

بشكل عام هناك إهتمام في زيادة عمر الكلال للمواد ، وإن إحدى الاجراءات الشائعة لزيادة عمر الكلال للسبيكة 7075-T651 هي إستخدام القذف بالكرات الفولاذية. لحد الآن لم تتم الدراسة بشكل كامل لتأثير إرتباط عملية تداخل الكلال مع الزحف مع عملية القذف بالكرات الفولاذية.الهدف من البحث هو لبيان إمكانية تحقيق التحسينات بواسطة جمع العمليتين. تم إستخدام مستويين من التجارب (برنامج ضرر الكلال التراكمي) من أجل حساب أفضل مجموعة للإجراء. وجد بأنه لبعض العينات من الممكن الجمع بنجاح بين عملية القذف بالكرات الفولاذية مع عملية تداخل الكلال مع الزحف وذلك لغرض زيادة عمر

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الكلال. إن نتائج إختبارات التحميل المتغير بينت بوضوح بان قانون ماينر لا يعطي تخمينات دقيقة أو موثوقة لعمر الكلال.

List of Symbols And Abbreviations.	
Symbol	**Title**
D_{exp}	Experimental Damage
D_{miner}	Miner Prediction Damage
D_p	Peak to Peak Distance
K_t	Stress Contraction Factor
N_f	Cycles to failure
$N_{f\ exp.}$	Experimental no. of cycles to failure
N_{fi}	Cycles to failure at stress level i
$N_{f\ Miner}$	No. of Cycles at Failure at Miner Damage Prediction
R_a	Average Roughness
R_t	Peak Roughness
$\sigma_{E.L}$	Endurance Limit Stress
σ_f	Stress failure
LIF	Life Improvement Factor
SPT	Shot Peening Time
VL	Variable Loading

INTRODUCTION AND LECTURE REVIEW

Shot peening is cold working process in which the surface of a part is bombarded with small spherical media called shots. Every shot striking the material acts a tiny peening hammer, importing to the surface a small indentation or dimple. Shot peening has develop an even layer of metal that is in a state of residual compressive stress.

Shot peening increases the fatigue strength of a material, decreases the tension in the surface, gets rid of deformations (or aiming at the creation of deformations) and decreases the susceptibility of stainless steel and aluminum alloys to electrochemical corrosion [1]. Shot peening decreases tensile stresses in the surface and compensation for deformations without thermal treatment. Finally, shot peening is widely applicable and easy to control. The most important application of shot peening is prevention of fatigue. Well known application are peening of crankshaft, gears, turbine blade and fans. Shot peening is especially effective in decreasing residual stresses as a result of mechanical treatment and preventing concentrations of tensile stress in notches, sharp angles, forging pits and other surface defects. Finally, peening can be used in the prevention of stress cracking corrosion in aluminum and magnesium alloys, brass and stainless steel. [2]

Fuchs [3] has reported that the values of the compressive stresses are at least as high as 50% of the ultimate strength of the material. The fatigue limits of specimens containing an artificial small hole were increased by shot peening and stress shot peening (SSP) was more effective in improving fatigue limit. The fatigue limit of spring steel specimens containing a surface defeat increased 22% - 51% for shot peened and 72%- 100% increased for stress shot peened(as shown in Figure (1)). [4]

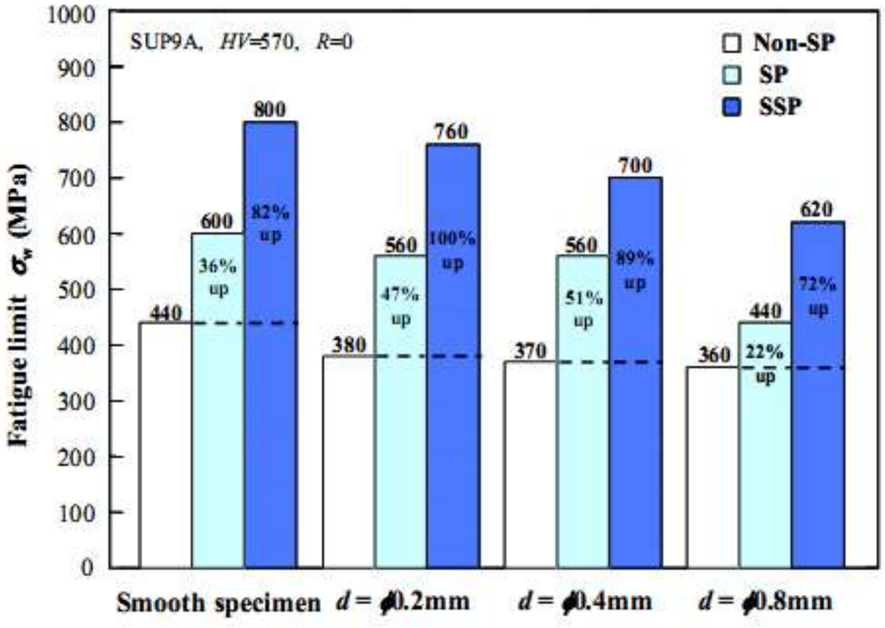


Figure (1); Improvement ratio of fatigue limit for Spring steel specimens. [4]

The aircraft had to fly at twice the speed of sound which implies that aerodynamic heating of the aircraft skin occurs up to a temperature of slightly above 100 °C (212° F). The design team expected that aluminum alloys could still be used, but it was recognized that the age-hardened condition of these alloys could be affected by overaging at the elevated temperature. The Al-alloy selected for using in Rolls Royce alloy used for compressor blades subjected to a moderately elevated temperature, which was artificially aged at 190 °C (374 ° F). Because the aging temperature is significantly above the maximum in-flight temperature, it might be expected that a stable material structure is maintained in service [5].

Mohammed Faycal [6] studied the fatigue properties of different aluminum alloys, namely 1100, 2024, and 5052. He found that the fatigue life of 1100 and 5052 Aluminum alloys was reduced because shot peening causes high surface roughness consequently high local stresses. While the life of 2024 was increased by shot peening of about 50 % as a result of creation of compressive residual stresses. Al-alkawi et. al. [7] investigated the fatigue-creep interaction performance of 5086 and 6061-T651 aluminum alloys under control stress rotating bending at a stress ratio R=-1 and 250°C temperature. The fatigue endurance limit for both alloys reduced at 250°C and the cumulative fatigue-creep interaction damage was found to around 0.5 i.e $D_f + D_c = 0.5$

Sabour [8] proposed a mathematical model to predict the operating life of aircraft components, specifically gas turbine blades subjected to creep–fatigue at high temperatures. Tae [9] presented a creep–fatigue interaction lifetime prediction methodology based on continuum damage mechanics for the Ni-based superalloy under cycling loading at high temperature. Gou [10] proposed a time-dependent fatigue damage model without hold-time based on the linear damage rule and fatigue tests at elevated temperature.

MATERIAL AND EXPERIMENTAL PROCEDURE

The material used in the current experimental investigation is 7075-T651 Aluminum alloy. This alloy is widely used in aircraft structural parts and other highly stressed structural applications where very high strength and good resistance to corrosion are required.

Chemical Compositions And Mechanical Properties

Chemical analysis of the above alloy was conducted at the Specialized Institute using X-rays method. The results, with the standards, are illustrated in Table (1).

Three monotonic tests are carried out for 7075-T651. The results of testing are the average of three readings. For tensile test, the specimens of 7075-T651 aluminum alloy are manufactured according to (ASTM A370), as shown in Figure (2) and tested at the university of Technology to draw stress- strain curve for 7075-T651 as shown in Figure (3). The results are given in table (2).

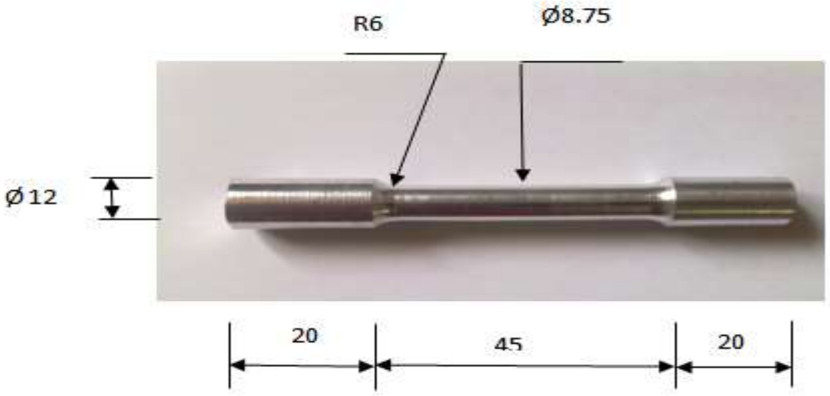


Figure (2); Geometry of tensile test specimen; all dimensions in millimeter according to (ASTM A370) standard specification.

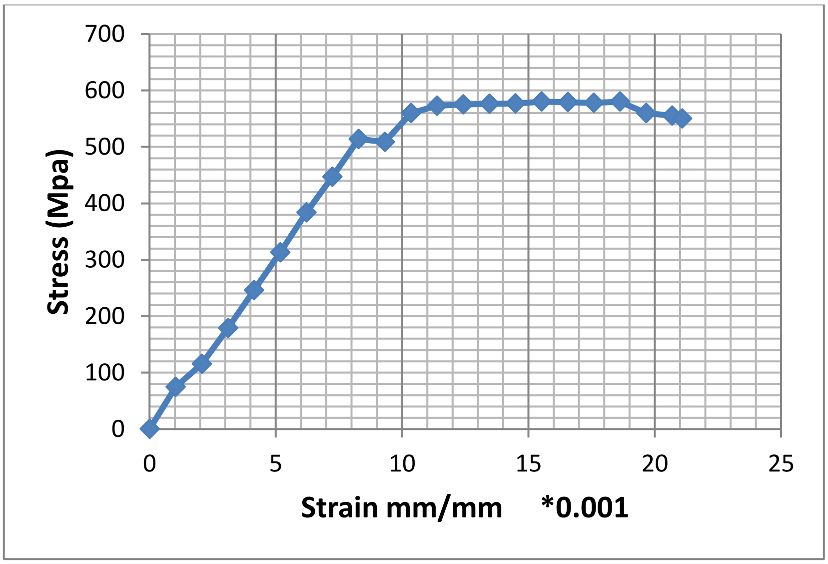


Figure (3); Stress-strain curve for 7075-T651 Al. alloy.

Table (1); Chemical compositions for 7075-T651 Aluminum alloy, wt %.

Al. alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
7075-T651 Standard	0.4	0.5	1.2-2	0.3	2.1-2.9	0.18-0.28	5.1-6.1	Rem
7075-T651 experimental	0.41	0.46	1.6	0.29	2.3	0.22	5.8	Rem

Table (2); Standard and experimental mechanical properties.

Al. alloy	Ultimate strength (MPa)	Yield strength (MPa)	Elongation %	Modulus of Elasticity (GPa)
7075-T651 standard	572	503	11	71
7075-T651 Experimental	580	510	12	74

Fatigue Specimen Preparation

All fatigue specimens are manufactured using programmable CNC lathing machine. Then all the specimens machined, according to the profile of the copy machining. The test specimen is shown in Figure (4).

Fatigue Testing Machine

A fatigue testing machine of type PUNN rotating bending is used to test all fatigue specimens, with constant and variable loading, as shown in Figure (5).

The rotary bending stress (σ_b) was calculated according to the following equation [11]:-

$$\sigma_b = \frac{32*125.7P}{\pi*d^3} \quad \ldots (1)$$

Where the force arm is equal to 125.7 mm, d is the minimum diameter of the specimen 6.67 mm, P is the load applied in Newton and σ_b in Mpa.

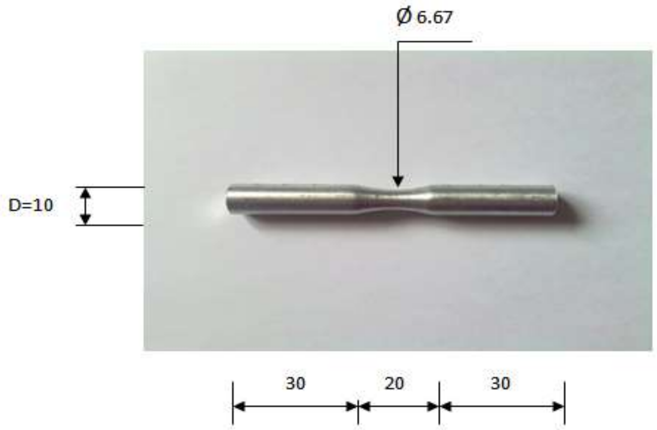


Figure (4); geometry of fatigue and fatigue-creep interaction Specimens; all dimensionsin millimeter according to (DIN 50113) standard specification.

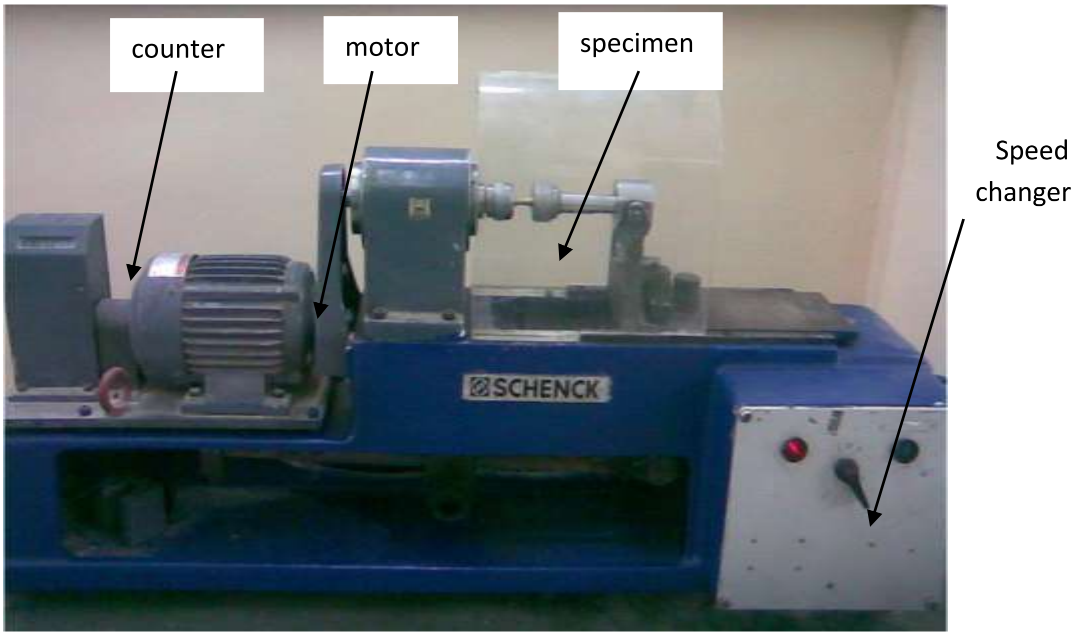
FATIGUE-CREEP TESTING MACHINE

A small furnace is required to heat the specimen to a known elevated temperature. Thus, an elevated furnace is designed and made with suitable dimensions of (10×12×140 mm^3). The furnace can be attached to the fatigue testing machine. A digital thermal control unit board was designed and manufactured for this purpose. More details of this machine can be seen in Mohammed [12].

Shot Peening Test

The peening operation was performed at room temperature in a special test device (shot tumblast control panel model STB-0B). This apparatus enables a defined shot peening treatment on round and flat specimens.

The ball material was cast steel with an average ball size of diameter 1 mm and a Rockwell hardness of 48-50 HRD. The number of balls at the whole operation time was kept constant for a wide range at peening pressure around 12 bars resulting in ball velocity of nearly 40 m/s. More details about this device can be seen in Mohammed [6]. Figure (6) shows the shot peening device.



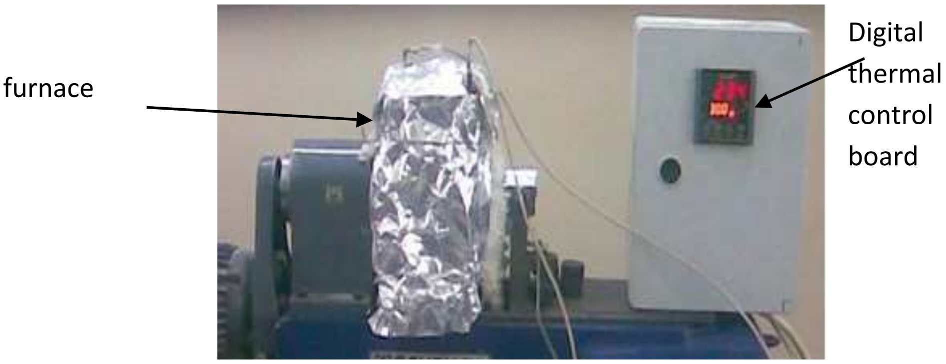


Figure (5); PUNN Rotary fatigue bending machine.

EXPERIMENTAL RESULTS AND DISCUSSION

Failure was defined as the point of instability, i.e. at the instant when the load bearing capacity of a structure or specimen begins to decay rapidly and the test stopped.

The behavior of 7075-T651 Al. alloy at constant applied stresses and room temperature can be seen in table (3) and Figure (7). This figure shows an endurance fatigue limit of 141 MPa at 10^7 cycles and the fatigue behavior of the above alloy can be described by the equation, (based on the Basquin principles).

$$\sigma_f \;= 796\, N_f{}^{-0.1074} \qquad \dots (2)$$

Table (3); S-N curve data at room temperature.

Stress (Mpa)	N_f (cycles)
300	9000,13000,14000
275	15000,17000,21000
250	31000,35000,37000
225	111000,120000,129000
200	495000,539000,556000
180	774000,862000,921000

Figure (6); Shot peening device.

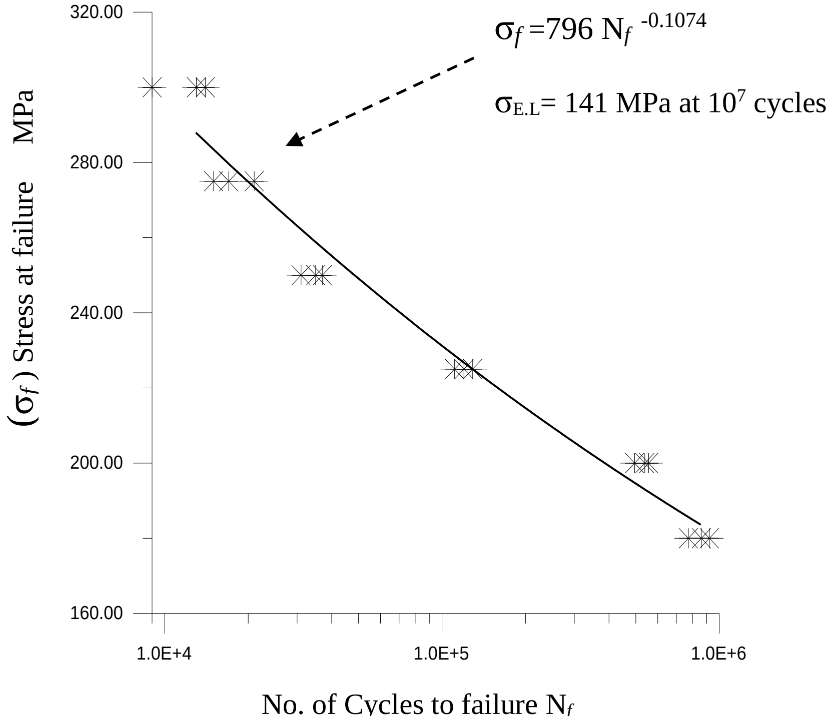


Figure (7); S-N curve behavior for 7075-T651 Al. Alloy at room temp.

The S-N curve data of the above alloy at the same stresses but at 250 C° condition is given in table (4).

The fatigue behavior at elevated temperature in comparison with room temperature is shown in Figure (8).

Table (4); basic S-N curve data for 7075-T651 Al. alloy at 250 C°.

Stress (Mpa)	N_f (cycles)
300	8000,10000,11000
275	13000,15000,18000
250	27000,32000,33000
225	42000,46000,50000
200	61000,63000,66000
180	75000,78000,80000

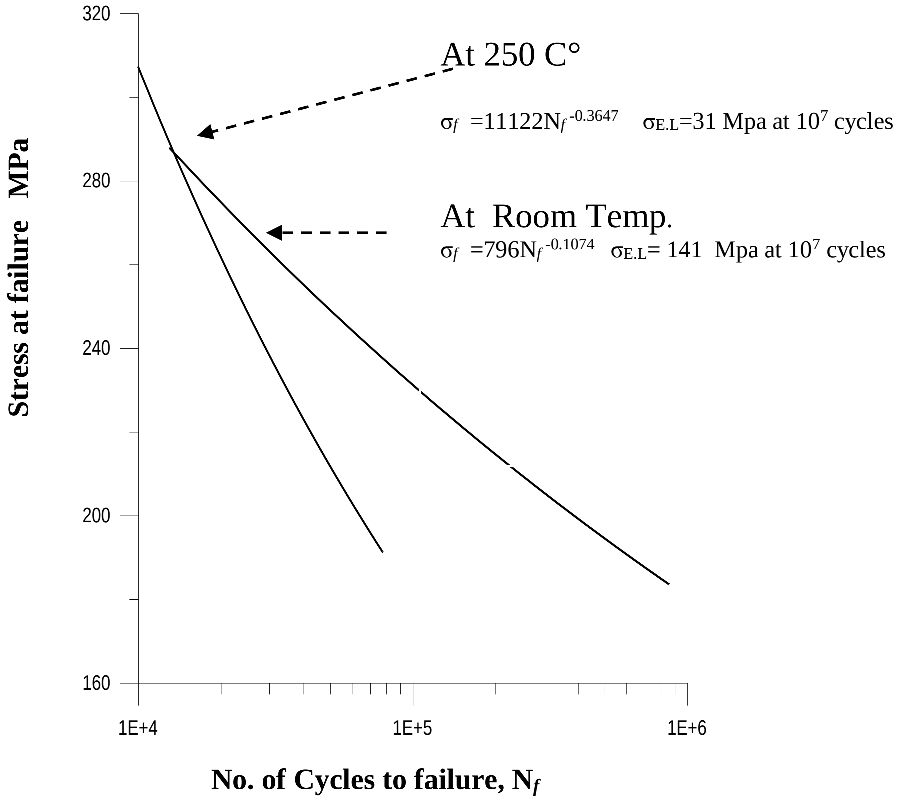


Figure (8); S-N curves at room temperature and 250 C°.

The fatigue behavior of the present alloy at 250 C° can be described by the equation:-

$$\sigma_f = 11122\,N_f^{\,-0.3647} \qquad \dots(3)$$

The above equation gives an endurance fatigue limit $\sigma_{E.L}$ = 31 MPa.

Figure (8) shows detrimental effect due to heating environment (250 C°) on the fatigue lifetimes and thus led to stronger lifetime reduction factors compared to room temperature fatigue tests. The fatigue strength at 10^7 cycles reduced by 78 % at 250 C° in comparison with the fatigue at room temperature.

The reduction of fatigue endurance limit of the present aluminum alloy at elevated temperature is a result of overaging of the precipitation hardened material structure. [7]

The effect on the surface roughness exerted by the shot peening treatments is quantified in table (5), where the results of profilometer measurements are summarized. Accordingly, the estimated peak to peak distance D_p, R_t is the maximum peak to valley height and the mean spacing of adjacent local peaks (D_p) were used to estimate the notch effect exerted by the surface dimples according to the following proposed by Li. Jk et.al [١3].

$$K_t = 1 + 4\left(\frac{R_t}{D_p}\right)^{1.3} \qquad \dots (4)$$

The value of the estimated stress concentration factor (K_t) for the conditions considered are listed in table (5). It can be noted that increasing the shot peening time (SPT) introduce increasing in (R_t), (D_p) and (K_t).

Table (5); roughness properties.

SPT (min.)	Ra(μm)	Rt (μm)	D_p (μm)	K_t
As-received	0.82	1.2	100	1.013
5	2.23	3.7	110	1.048
8	2.165	3.8	160	1.031
12	2.37	4.4	200	1.028
15	3.391	6.2	310	1.025

The average Vickers hardness measured on the surface of unpeened 7075-T651 was about 280 HV. The magnitude of hardness was increased by increasing SPT. The results are given in table (6).

Table (6); SPT against HV hardness for 7075-T651.

SPT (min.)	HV
As received	280
5	305
8	336
12	368
15	387

The surface hardness of samples increased by 38 % of the based hardness HV_{base}. The microhardness of different aluminum alloys increased in the range of 20-40 %, 10-25 % and 10-30 % of the base hardness HV_{base} during shot peening [١4], laser shock peening [15], water jet peening [16] respectively.

The hardness (HV) against (SPT) can be illustrated in Figure (9).

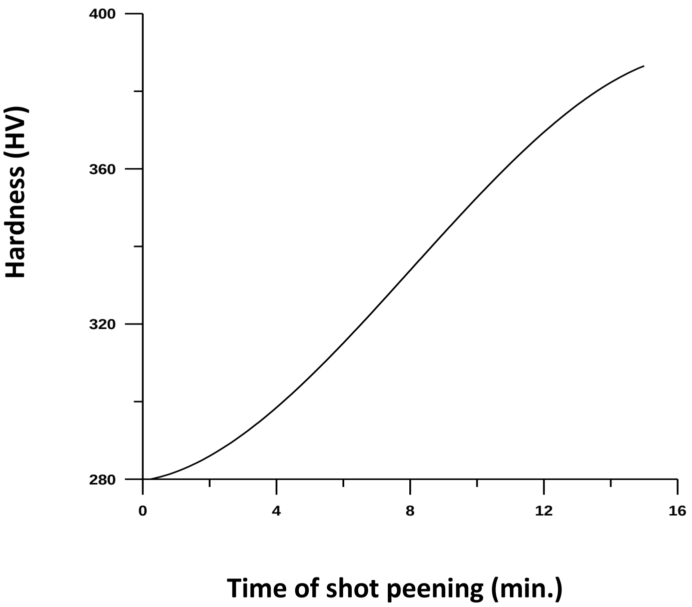


Figure (9); Hardness (HV) against shot peening time (SPT).

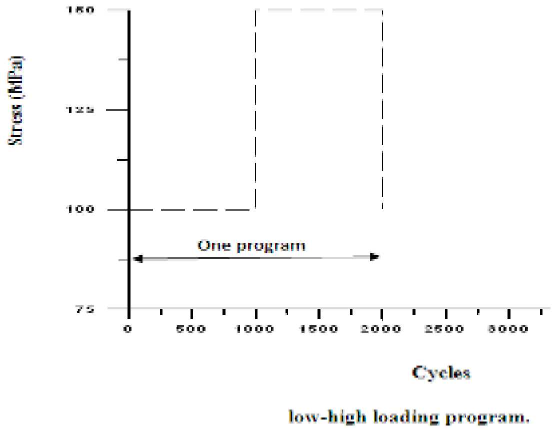
The hardness (HV) of 7075-T651 may obeys the relation:-

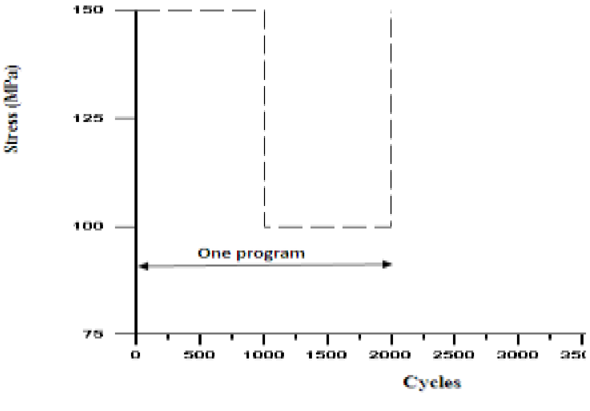
$$\mathrm{HV} = 279.65 + 1.285(\mathrm{SPT}) + 1.0247(\mathrm{SPT})^2 - 0.0423(\mathrm{SPT})^3 \ldots (5)$$

RESULTS OF FATIGUE TESTS UNDER VARIABLE LOADING

Results of round specimens under elevated temperature and load sequence are given in Table (7).

Table (7); Cumulative Fatigue Test Results at 250 °C.

Loading program MPa	Fatigue life cycles	Loading sequence diagram
100-150	41000	
100-150	103000	
100-150	283000	

150-100	77000	 I igh-low loading progr
150-100	177000	
150-100	304000	

While the test results of the same loading sequence and elevated temperature but the specimens before testing were treated by shot peening at different time are shown in Table (8).

Table (8); Test results under variable loading, elevated temperature and shot peening.

SPT (min.)	Load Sequence MPa	Fatigue life Cycles
5	100-150	80000
8	100-150	205000
12	100-150	300000
15	100-150	189000
5	150-100	167000
8	150-100	255000
12	150-100	141000
15	150-100	200000

FATIGUE LIFE PREDICTIONS FOR VARIABLE LOADING (VL):

Results of VL fatigue tests clearly indicate that the Miner rule does not give accurate and reliable predictions on fatigue lives [7]. The shortcomings can be understood. For the present study, three major objections are:-

1- The loading sequence effect is not accounted for the Miner rule.

2- Temperature and shot peening treatments do not contribute to fatigue damage and
3- Notch (roughness average due to shot peening process, Rt) leads to interaction effects between cycles of different magnitude which are not accounted for in the Miner rule.

The Miner rule

$$\sum_{1}^{N} \frac{n_i}{\mathrm{N_{fi}}} = 1 \qquad \dots (6)$$

Where n is the applied cycles, 10^3 cycle in the selected program here, and N_f is the number of cycles at failure obtained from the S-N curve. Experimental Fatigue damage is calculated when the right-hand side of equation (6) is not unity (as suggested in many researches like Sabour[8] and Tae[9]), hence equation (6) will be :

$$\sum_{1}^{N} \frac{n_i}{\mathrm{N_{fi}}} = \mathrm{D_{exp}} \qquad \dots (7)$$

The fatigue damage and life estimation experimentally and due to Miner rule is given in table (7) for variable loading (VL).

Table (9a); fatigue damage and life at 250 °C without shot peening.

Specimen No.	Load sequence MPa	D_{exp}	D_{miner}	$N_{f\ exp.}$	$N_{f\ Miner}$
49	100-150	0.203	1	41000	201960
31	100-150	0.510	1	103000	201960
29	100-150	1.401	1	283000	201960
8	150-100	0.381	1	77000	201960
33	150-100	0.876	1	177000	201960
5	150-100	1.505	1	304000	201960

Table (9b); fatigue damage and life at 250 °C and shot peening treatment.

Specimen No.	Load sequence MPa	SPT(min)	D_{exp}	D_{Miner}	$N_{f\ exp.}$	$N_{f\ Miner}$
28	100-150	5	0.8269	1	80000	201960
15	100-150	8	1.26	1	205000	201960
14	100-150	12	0.797	1	300000	201960
41	100-150	15	0.990	1	189000	201960
6	150-100	5	0.396	1	167000	201960
16	150-100	8	1.015	1	255000	201960
18	150-100	12	1.485	1	141000	201960
24	150-100	15	0.936	1	200000	201960

After shot peening the fatigue-creep life under VL was increased clearly for some specimens and the life improvement factor (LIF) can be seen in table (10).

Table (10); Fatigue-Creep life under SPT and (LIF).

Sequence loading	Average fatigue life at 250 C° (cycles)	SPT (min.)	N_f under VL at 250 C° and SPT (cycles)	LIF
Low-high	142333	5	8000	0.562
		8	205000	1.44
		10	300000	2.107
		12	189000	1.327
High-low	186000	5	167000	0.897
		8	255000	1.3709
		10	141000	0.758
		12	200000	1.075

The effect of the different shot peening treatments on the VL fatigue-creep interaction life is illustrated in table (10). The LIF is less than unity and this produce (LRF) life reduction factor for some specimens. The reason for this may be attributed to the effect of the surface roughness exerted by the shot peening treatments [17] and the notch effect exerted by the surface dimples according to equation (4) [١3]

The combined effect of shot peening and fatigue-creep interaction on fatigue lives cause an improvement of fatigue lives due to the formation of a hard layer on which exist compressive residual stresses. It is clear that the shot peening of 12 min. showed a significant improvement in cumulative fatigue lives while at 15 min. of shot peening the material becomes brittle. As a result, it can be said that the shot peening has a threshold value beyond which an inverse effect will appear. [6] [14]

CONCLUSIONS

In this study, the effect of shot peening on fatigue-creep performance was studied on Al. 7075-T651 and the following results were obtained.

- The combination of fatigue-creep interaction and shot peening can be applied successfully in order to increase the fatigue life for some specimens subjected to cumulative fatigue damage.
- Miner rule predictions was overestimated the life of fatigue-creep interaction with shot peening.
- When SPT increased, the surface roughness increased, and the relation which described SPT against average roughness (Ra) may written as:

$$Ra = 0.822 + 0.6(SPT) - 0.083(SPT)^2 + 0.0036(SPT)^3 \qquad \dots(8)$$

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