Al-Khwarizmi Engineering Journal,Vol. 13, No. 4, P.P. 1- 11 (2017)

Al-Khwarizmi Engineering Journal

Effect of optimal shot peening time on fatigue life for aluminum alloy 6061-T651

Ahmed N. Al-Khazraji

Department of Mechanical Engineering/ University of Technology

Email: dr_ahmed53@yahoo.com

(Received 2 January 2016; accepted 10 May 2017)

https://doi.org/10.22153/kej.2017.05.001

Abstract

The compressive residual stresses generated by shot peening, is increased in a direct proportional way with shot peening time (SPT). For each metal, there is an optimum shot peening time (O.S.T) which gives the optimum fatigue life. This paper experimentally studied to optimize shot peening time of aluminium alloy 6061-T651 as well as using of and analysis of variance (ANOVA).

Two types of fatigue test specimens' configuration were used, one without notch (smooth) and the other with a notch radius (1,25mm), each type was shot peened at different time. The (O.S.T) was experimentally estimated to be 8 minutes reaching the surface stresses at maximum peak of -184.94 MPa.

A response surface methodology (RSM) is presented to optimize the surface properties of fatigue life due to effect of two parameters (shot peening time and fatigue stresses). A statistical software was used to perform analysis of variance (ANOVA) to predict the optimum shot peening time. The results were 8.007 minutes without notch and 7.53 minutes with notch. Two 2nd degree polynomials were obtained for the two studied cases with confidence level of 95%. Experimentally26.67% enhancement in fatigue life was obtained, but after using (RSM), the results gave 61% improvement, compared with ref. [2].

***Keywords**: Shot peening, fatigue life, RSM & ANOVA.*

1. Introduction

Shot peening one of the most way to improve the mechanical properties of machine and structural parts. Shot peening is a surface treatment process aimed to increasing material's fatigue strength by strain hardening an inducing favorable compressive residual stresses [1,2]. G. A. Butz and J.O. Lyst 1961[3], studied improvement in fatigue resistance of aluminum alloy 2014-T6 by shot peened and found the fatigue strength improvement is percentage by which stress for shot peened exceeds the residual stress all results improvement between (18-29%). J.E. Locke et.al. 2005 [4], investigate of the fatigue crack growth of short crack embedded in the layer of residual stress that induced by shot peened for 7050-T7451 and 7075-T7351 aluminum alloys, the depth of the compressive residual stresses is less than 0.254mm and the depth of initial cracks smaller than 0.0254mm will be tested to determine the crack growth rates of the peened material. K.Ch. Seong et. al. 2005 [5], experimental results shows that (S.P) has superior effectiveness to increase the corrosion fatigue life of submerged in 3.5% NaCl for different time of AA7075-T6. H.J. Alalkawi et.al. 2010 [6], studied the effect of shot peening on the cumulated fatigue damage for 2024 aluminum alloy for round test specimen , the optimal time of shot peened found 10 minute to give the maximum compressive residual stresses. M. Bendetti et. al. 2010 [7], investigate the effect of different shot peening treatments on the fatigue life for 7075-T651 aluminum alloy, using rectangular cross section fatigue test specimens with two types of notches , filler radius 0.2 and 2 mm on each side of specimen. The fatigue improvement is more pronounced with increasing stress concentration. Shot peening reduce the fatigue notch sensitivity factor about 20%. The maximum fatigue strength gain 79% for combined shot peening at notch radius 0.5 mm. M.Wollmann et.al. 2011 [8], studied and comparing the notch sensitivity factor of various alloys before and after shot peening, one of this alloy is 2024 aluminum alloy. The higher work hardening capability or normalized high cycle fatigue strength, the lower notch sensitivity. The notch sensitivity were q=0.8 and 0.79 for 2024-T4and 2024-T6 aluminum alloys respectively. T.A. Al-taie 2014 [2], investigate the effect of induced compressive residual stresses by (S.P.) at different time for AA6061-T651 and AA7075-T6, experimentally predicted the (O.P.T.) which was (10minute.) from insufficient different (S.P.Ts) with 44.4% gain enhancement. N.A. Hammied and Saad A.H.2014 [9], used different (S.P.Ts), were (5, 10, 15, 20 and 30min.) and its effect on mechanical properties of AA2024-T4, the results showed an increase in yield and tensile strength values up to (15 minute.) (S.P.T).

The aim of this paper is to determine experimentally the optimum shot peening time of AA6061-T651 from sufficient different (S.P.Ts), and then using RMS to optimize by (ANOVA) software to accurate the time.

2. Experimental Details

2.1. Material and Experimental Procedures

The Al, Mg, Si aluminum alloy 6061-T651 is apperceptions hardening; it has good mechanical proportions and used in general purpose applications in civilian and military industries. A chemical analysis of this alloy is tested by spectra device, it summarized in Table (1).

Table 1,
Chemical composition of 6061-T651 aluminum alloy.

	Cu	Mg	Mn	Zn	Si	Fe	Cr	Ti	AL
Standard ASM [10]	0.15-0.4	0.8-1.2	0.15 Max.	0.25 Max.	0.4-0.8	0.7 Max.	0.04-0.35	0.15 Max.	Bal.
Received	0.31	1.2	0.012	0.056	0.727	0.104	0.123	0.029	Bal.

According to ASTM-E8 [11], tensile test was down. The specimen geometry and dimensions shown in figure (1).

High-cycle fatigue tests by used cantilever fatigue testing machine type GUNT-WP140 as shown in figure (2). The fatigue conditions are pure reversed bending stress with zero mean stress.

The geometry of the fatigue specimen [12] and his a circumferential notch radius 1.25mm made by using CNC machine to give perfect dimensions for all specimens.

The specimens were classified into two groups, the first one without notch (smooth) and the second with notch radius 1.25mm as shown in figure (3). All groups are shot peened at the obtained optimal time 8min to induced the maximum surface compressive residual stresses by mechanical treatment.

The degree of concentration is a factor in the fatigue strength of notched parts. The elastic stress concentration factor, K_t as a ratio of the maximum stress σ_{max}, at the notch to the nominal stress σ_{nom}. The stress concentration factors for a homogenous isotropic material depend only on the geometry and mode of loading, figure (4), [13].

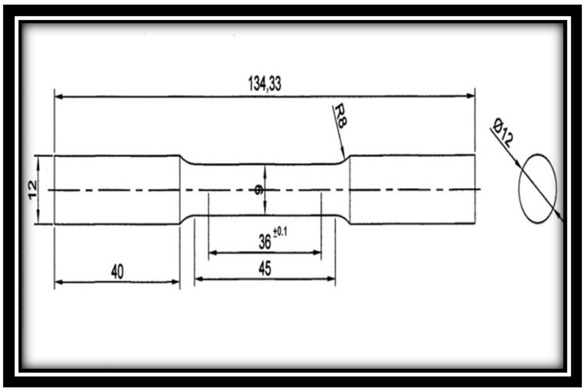


Fig. 1. Tensile test specimen (ASTM –E8) (all dimensions in mm).

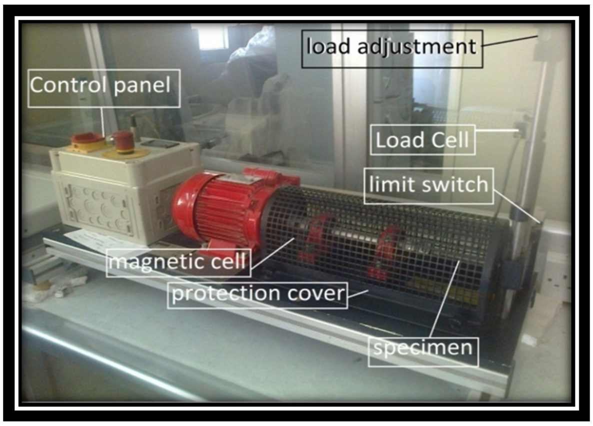
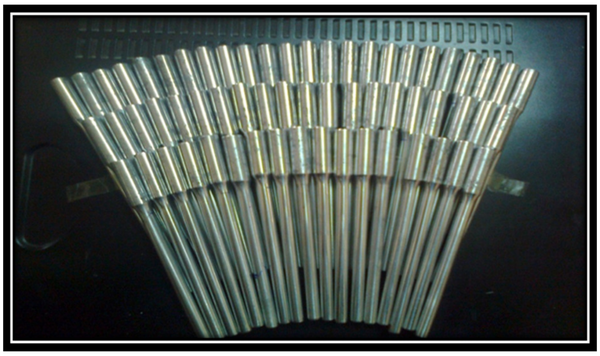
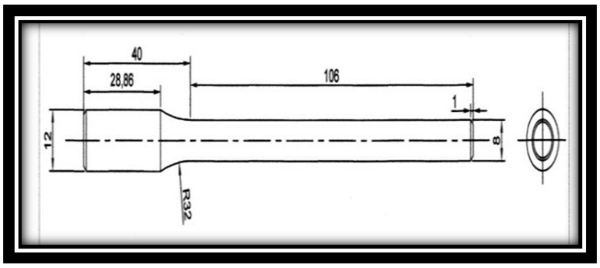
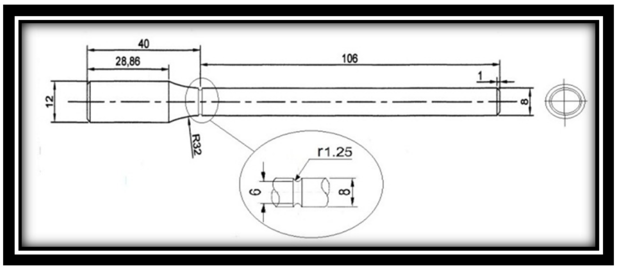


Fig. 2. Fatigue testing machine type Gunt-Hamburg WP140.





(a)



(b)

Fig. 3. The dimensions of fatigue test specimens (all dimensions in mm), (a) schematically smooth specimen. (b) Schematically notch specimen.

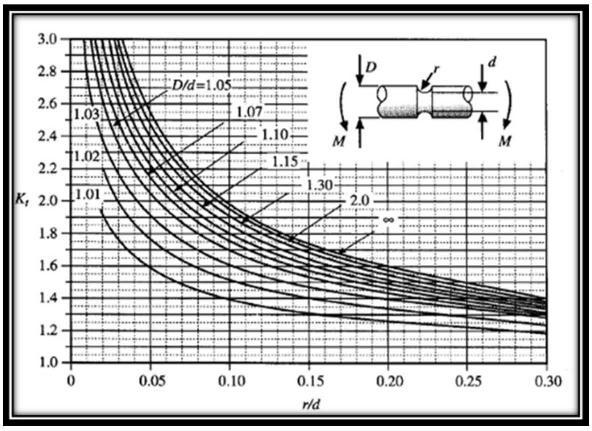


Fig. 4. Theoretical stress concentration factor K_t for a round bar with a U notch subjected to bending [14].

The shot peening was accomplished by sintokagio centerfugal machine model STB-OB and by using the portable electrical additional device to ensure shot the specimens identical as shown in figure(5). In this machine, the motor rotates an impeller which bombards the shots towards the specimens at 1435 r.p.m motor rotational speed with one jet of shots at an average speed of 40 m/s. The material of the shooting balls is a low carbon steel with average diameter of 1.2 mm.

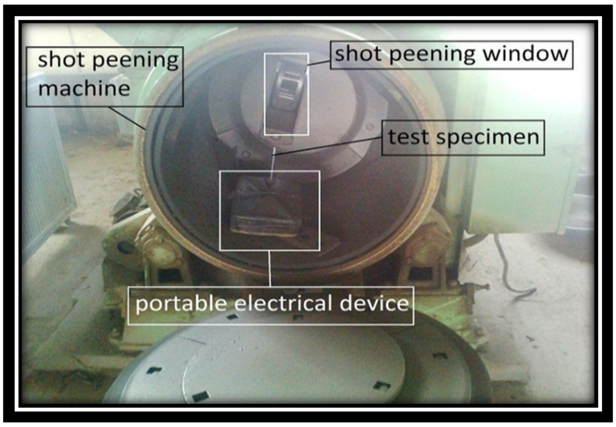


Fig. 5.The additional device put and fixed inside the rotary cylinder of the shot peening machine.

The round shaft with shoulder fillet in bending, is extracted from applying the relation below [15].

$$\sigma = \frac{M.C}{I} \quad \ldots(1)$$

Where:

$M = P * a$

$C = d/2$

$I = \pi d^4/64$

3. Result and Discussion

The tensile tests of the alloy are performed to obtain the value of the ultimate, yield tensile stresses before and after the shot peening. The results as shown in the table (2).

There are a little increasing in the yield and ultimate tensile strength occurred due to shot peening effect ,which was (3.3%) and (2.5%) respectively.

The x-ray diffraction (XRD) technique used to measurements the residual stresses on the surface of specimens after shot peened at optimal SPT-8 minute to give the maximum residual stress is (-184.94MPa) with a (919%) enhancement compared with the metal as received (best shot penning) show the results of residual stresses at different S.P.T .

It was observed from table (3) the optimum shot peening time was (8 minutes.).

The surface roughness (R_a) was measured for three random selection specimens before and after shot peening and taken the average value micron) by using portable surface roughness device type pocket surf as shown in table (4).

The S-N results that obtained from the fatigue tests for smooth (un-notch) specimens and notch at radius 1.25mm with depth 1mm specimens, after shot peened at optimal time 8 min. All tests were carried out at constant stress amplitude leading. The mean results of three specimens of each point of fatigue tests are in table (5), and plotted in the S-N curves as shown in figure (6).

Table 2,
Tensile tests results before and after optimum SPT

Condition	**σ_u(MPa)**	**σ_y(MPa)**
Standard	310	276
Received	320	300
Optimum shot peened 8 min	328	310

Table 3,
Experimental residual stresses at different (S.P.T.)

S.P.T min.	**0**	**4**	**6**	**8**	**10**	**20**
Residual stress [MPa]	-18.14	-119	-155	-184.94	-154.19	-138.7

Table 4,
Average surface roughness.

Shot peening time	**Surface roughness$R_a(\mu m)$**	**Variation %**	**Ref.**
As received	0.43	-	-
8 min.	4.5	904	Present work
10 min.	5.1	1144	[2]

Table 5,
Final Average S-N Data for AA6061-T651

Un-notch peened 8 min		**Notch 1.25mm peened 8 min**	
σ_l MPa	Nf cycle	σ_l MPa	Nf cycle
230	26023	205	28200
200	85481	190	40513
190	132175	175	73567
180	201893	160	106293
170	317642	145	221782
160	521007	130	506193
150	798601	115	1017230
140	1556580	100	2394647
120	4462196		

It is clear from table (4) that the roughness in present work was less than in ref [2], because the optimum shot peening (O.S.T) less than at ref [2].

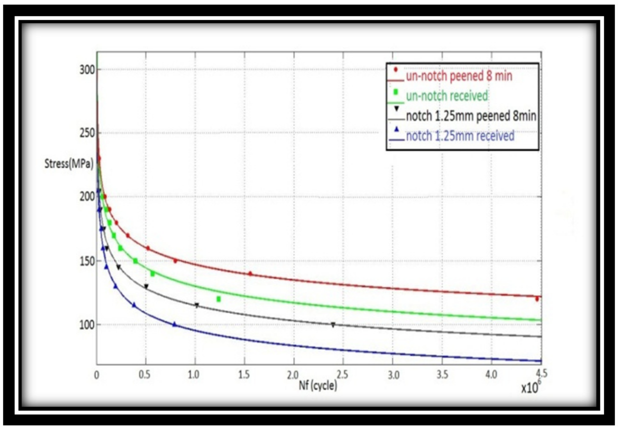


Fig. 6. Smooth and notch radius 1.25 mm for 6061-T651 aluminum alloy at different SPTs

To comparing fatigue results with the other as in ref. [2] and plotted the results as shown in figure (7).

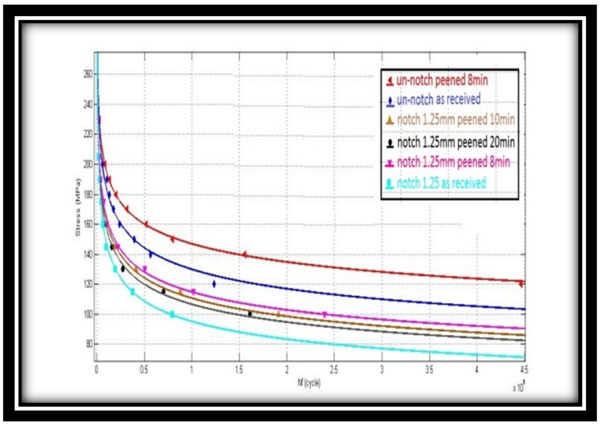


Fig. 7. Smooth and notch radius 1.25 mm for 6061-T651 aluminum alloy at different SPTs

These curves give an indication about the variations in fatigue life. The fatigue life estimation equations were obtained. The consideration of endurance limit at $N_f = 10^6$ cycles, fitting curve with an accuracy 95%. The stress concentration factor (K_f), notch sensitivity factor (q) and the gain in endurance limit put it in table (6).

$\sigma_l = 821.3 * N^{-0.1246} = 146.859$ MPa For (SPT 8 min. un-notch).

$\sigma_l = 1035 * N^{-0.1592} = 114.747$ MPa For (SPT 8 min. notch).

$$K_f = \frac{Smooth\ fatigue\ strength}{Notched\ fatigue\ strength} = \frac{146.859}{114.747} = 1.28$$

$K_t = 1.62$ From figure (4)

$$q = \frac{K_f - 1}{K_t - 1} = \frac{1.28 - 1}{1.62 - 1} = 0.451$$

$$gain = \frac{\sigma_l(notch\ and\ peened) - \sigma_l(notch\ and\ received)}{\sigma_l(smoth\ and\ received) - \sigma_l(notch\ and\ received)} * 100\%$$

$$gain = \frac{114.747 - 95.222}{129.94 - 95.222} * 100\% = 56.24\%$$

$$gain = \frac{56.24 - 44.4}{44.4} * 100\% = 26.67\%$$

From the results of the fatigue tests, it can be observed that the value of the endurance limit at $N_f = 10^6$ cycles, given the highest value of compressive residual stress given at optimal time of shot peening (8 minutes for this alloy), the enhancement of the endurance limit gain is (56.24%) and the total enhancement percentage gain compering with ref. [2] is (26.67%), the comparison with others put it in table (7).

Table 6,
Values (K_f, K_t, q) for specimens with 1 mm notch radius (6061-T651)

Shot peening time(min)	Smooth strength σ (MPa)	Notch strength σ (MPa)	K_f	K_t	q	Variation % q
As received	129.940	95.222	1.36	1.62	0.58	received
8	146.858	114.747	1.28	1.62	0.451	-22.24

Table 7,
Comparing gain results with references.

Alloy type	SPT min	Type of beads	Gain %	Ref. No.
7075-T651	6	Ceramic	79	[7]
6061-T651	8	Steel	56.24	Present work
6061-T651	10	Steel	44.4	[2]

4. Modeling of Fatigue Life

According to the experimental results of residual stresses induced for (un-notched& notched) specimens due to different (S.P.Ts) and using Response Surface Methodology(RSM) it has been selected the levels of input factors which shown in table (8).

Table (9) show the design matrix which was constructed to predict the optimum polynomials of fatigue life for the two cases (un-notched& notched) depending on two parameters (shot peening time& fatigue stress). It is clear from table.(9) a (13) tests were carried out according to (RSM) for each studied case(un notched & notched),and also observed for each S.P.T. the fatigue life obtained and level of fatigue stress.

Using Analysis Of Variance (ANOVA) a statistical program for the given data in design matrix, it was obtained the details of a significant parameters and values of the two obtained optimum polynomials which give the optimization of fatigue life (N_f) for the two studied cases:

Table 8,
Used levels of input factors

Specimens type	Input Factor	Levels - 1	+ 1
Un-notch	Stress (MPa)	140	200
	Time (min)	6	10
Notch	Stress (MPa)	120	160
(1.25mm)	Time (min)	6	10

Table 9,
Design matrix for input factors and response (No. of cycle to failure)

Std. No.	Run No.	Stress (MPa)	Time (min)	No. of cycle to failure
		Un-notch		
1	8	140	6	1.6E+006
2	9	200	6	50000
3	2	140	10	1.6E+006
4	13	200	10	70000
5	4	110	8	4E+006
6	6	230	8	900000
7	10	170	4	140000
8	11	170	12	150000
9	7	170	8	360000
10	5	170	8	370000
11	1	170	8	400000
12	3	170	8	390000
13	12	170	8	350000
		notch		
1	2	120	6	1.01723E+006
2	13	180	6	73567
3	6	120	10	1.01723E+006
4	9	180	10	50000
5	3	90	8	2.5E+006
6	12	210	8	600000
7	4	150	4	180000
8	1	150	12	100000
9	7	150	8	250000
10	11	150	8	235000
11	10	150	8	210000
12	5	150	8	245000
13	8	150	8	200000

For Notch Specimen

$$No.of\ cycle\ to\ failure = 1.05822E+007 - 1.26048E+005 * stress + 80144.01293 * time + 367.27982 * stress^2 - 5487.03987 * time^2 \quad \ldots(3)$$

For Un-Notched Specimens

$$No.of\ cycle\ to\ failure = 2.04862E+007 - 2.21807E+005 * stress + 2.31063E+005 * time - 576.5565 * stress^2 - 14337.28448 * time^2 \quad \ldots(4)$$

The predicted optimum shot peening times (O.S.T) according to (RSM)&(ANOVA) are listed in Table (10).

Table (8) show the results of significant values for the two cases according to ANOVA software used.

Table 10,
The optimum shot peening times for un-notched&notched specimens.

Stress(Mpa)	O.S.T(min.)	N_f(cycles)	case
140.00	8.007	1664700	Un-notched
120.00	7.538	1037950	Notched

Table 11,
ANOVA for Response Surface Reduced Quadratic model for (No. of cycle to failure)

Un-notch

Source	Sum of Squares	df	Mean Square	F value	p-value Prob > F
Model	1.439E+013	4	3.598E+012	14429.97	< 0.0001 significant
A-Stress	7.177E+012	1	7.177E+012	28784.71	< 0.0001
B-Time	1.333E+008	1	1.333E+008	0.53	0.4855
A^2	6.170E+012	1	6.170E+012	24746.22	< 0.0001
B^2	7.536E+010	1	7.536E+010	302.27	< 0.0001
Residual	1.995E+009	8	2.493E+008		
Lack of Fit	2.745E+008	4	6.864E+007	0.16	0.94 not significant
Pure Error	1.720E+009	4	4.300E+008		
Cor Total	1.439E+013	12			

Std. Dev.	15789.79	R-Squared	0.9999
Mean	7.985E+005	Adj R-Squared	0.9998
C.V. %	1.98	Pred R-Squared	0.9997
PRESS	3.901E+009	Adeq Precision	402.085

notch

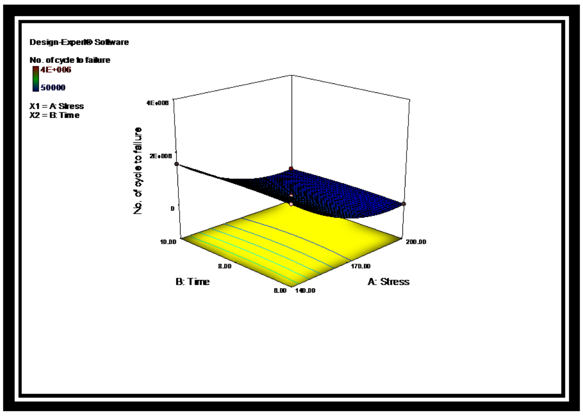
Source	**Sum of Squares**	**df**	**Mean Square**	**F value**	**p-value Prob > F**
Model	5.559E+012	4	1.390E+012	4204.11	< 0.0001 significant
A-Stress	2.718E+012	1	2.718E+012	8222.39	< 0.0001
B-Time	2.808E+009	1	2.808E+009	8.5	0.0194
A^2	2.504E+012	1	2.504E+012	7574.32	< 0.0001
B^2	1.104E+010	1	1.104E+010	33.39	0.0004

Figure (8) is a three dimension surface curves constructed between fatigue lives as a response results depending on two significant parameters due RSM (shot peening time&fatigue stress).

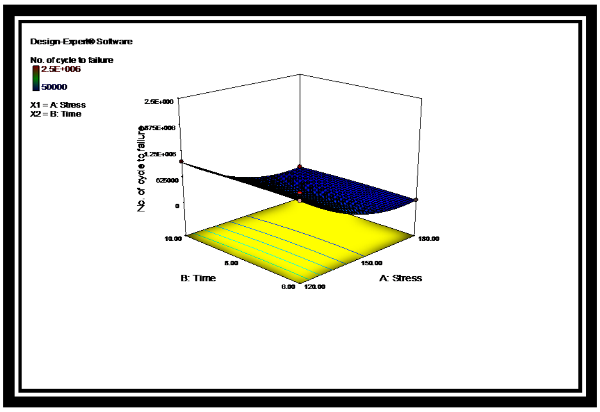
It is observed from table (10) & figure (8) that the optimum fatigue life was (1664700 cycles at predicted O.S.T 8.007min.&140Mpa for un-notched specimens) and (1037950 cycles at predicted O.S.T. 7.538min.&120Mpa fatigue stress) .

The gain obtained of fatigue life due to this method for notched shot peened specimens compared with notched un peened specimens was (71.4%),calculated according to the following equation[2]:

Gain = (σ_{l}(notched&peened)) – σ_{l} (notched &unpeened))/((σ_{l}(smooth as received) –σ_{l}(notched &unpeened)) *100%.



(a) Un-notch specimen



(b)Notch specimen

Fig. 8. 3D surface plot showing the optimum input and output values.

The value of σ_l (notched&unpeened taken 95.222Mpa ref.[2]& smooth as received 129.94Mpa. ,while the experimental gain in this work of fatigue life was (56.24%),that is mean a 27% enhancement in gain more using (RSM) compared with experiment and a 61% more than gain obtained by ref.[2]. Table (12) explain the comparison between RSM results& experimental results of this work and references for shot peened notched specimens of AA6061-T651.

Table 12,

Comparing gain results with references (for peened notched) specimens of AA6061-T651.

Alloy type	**Excremental Or Theoretical**	**SPT min**	**Type of beads**	**Gain %**	**Ref. No.**
6061-T651	Exp.	8	Steel	56.24	Present work
6061-T651	Exp.	10	Steel	44.4	[2]
6061-T651	The.	7.30		71.4	Present work

5. Conclusions

1. The same optimum shot peening time, which was 8min. experimentally obtained for the two cases (un-notched& notched) specimens which gave a 56.24% gain for notched peened.
2. The optimum shot peening time for notched &peened specimens according to (RSM) was 7.538min. This gave a 71.4% gain in fatigue life compared with un-notched as received.
3. A 61% improvement by RSM method in fatigue life compared with ref. [2].
4. A 26.6% improvement using RSM method in fatigue life compared with experimental results for this work
5. Quadratic equations for two cases (notched& un-notched specimens) obtained using RSM &ANOVA softwares to give the optimum fatigue life.

6. References

[1] Uros Zupanc and Janez Grum, "Surface Integrity of Shot Peened Aluminum Alloy 7075-T651", Journal of Mechanical Engineering, Vol. 57, pp.379-384, 2010.

[2] Thamer A. Al-Taie , "Effect of Compressive Residual Stresses on the Notch Sensitivity Factor of Different Aluminum Alloys" Thesis for the Degree of Master of Science, University of Technology, Iraq, 2014.

[3] G. A. Butz and J. O. Lyst,"Improvement in Fatigue Resistance of Aluminum Alloys by Surface Cold Working", Materials Research and Standards, USA, pp.951-956, 1961

[4] J. E. Locke, B. Kumar and L. Salah, "Effect of Shot Peening on The Fatigue Endurance and Fatigue Crack Growth Rate of 7050 & 7075 Aluminum Alloys", International Conference on Fracture, ICF11, Issue 5476, Italy, 2005.

[5] K.Ch. Seong, H.L. Jae "Effects of shot peening on corrosion fatigue life of AA7075-T6"; Nowon-Gu, Seoul Korea 2005

[6] Hussain J. Al-Alkawi, Qusay K. Mohammed and Waleed S. Al-Nuami, "The Effect of Shot Peening and Residual Stresses on Cumulative Fatigue Damage", Engineering and Technology Journal, Vol. 28,Issuo 15, pp.5055-5071, 2010.

[7] M. Benedetti, V. Fontanari, C. Santus and M. Bandini, "Notch Fatigue Behavior of Shot Peened High Strength Aluminum Alloys; Experiments and Predictions Using a Critical Distance Method", International Journal of Fatigue, Vol. 32, pp.1600-1611, 2010.

[8] M. Wollmann, J. Atoura, M. Mhaede, L. Wagner," Comparing Fatigue Notch

Sensitivity of Various Alloys Before and After Mechanical Surface Treating", International Conferences on Shot Peening (ICSP-11), Issue 71, USA, 2011.

[9] Nashwa Abdul Hammied , Saad A.H." Effect of shot peening time on mechanical properties of Aluminum Alloy 2024-T6; Iraqi Journal of mechanical & material engineering , Volume 14; 2014 p(46-54) , Babylon University.

[10] American Society for Metals (ASM), Material Data Sheet for 6061 aluminum alloy, 1990.

[11] American Society for Testing and Materials (ASTM) E8/E8M-09, "Standard Test Methods for Tension Testing of Metallic Materials", Annual Book of ASTM Standards, EDT 2010.

[12] Instruction Manual WP-140 , Fatigue testing apparatus p. 17, Gunt Hamburg , Germany.

[13] R. I. Stephens, A. Fatemi, R. R., Stephens and H. O. Fuchs, “Metal Fatigue in Engineering”, 2nd ed., John Wiley and Sons, Inc, 2001.

[14] R. E. Peterson, “Stress Concentration Factor”, 2nd Edition, John Wiley & Son, 1997.

[15] M. A. Meyers and K. K. Chawla, “Mechanical Behavior of Material”, Prentice-Hall Inc., USA, 1999.

تاثير زمن السفع بالكرات المثالي على عمر الكلال لسبيكة الالمنيوم 6061-T651

احمد نايف ابراهيم
قسم الهندسة الميكانيكية /الجامعة التكنولوجية
البريد الالكتروني: dr_ahmed53@yahoo.com

الخلاصة

الاجهادات المتبقية الضغطية التي تتولد بطريقة السفع بالكرات، تزداد طرديا مع وقت السفع. لكل معدن وقت مثالي للسفع (O.S.T) الذي يعطي افضل عمر كلال في هذا البحث تم تحديد الوقت المثالي للسفع وباستخدام البرنامج الاحصائي لسبيكة الالمنيوم 6061-T651 .
تم تهيأة نوعين من العينات لفحص الكلال, النوع الاول بدون حز , النوع الثاني بحز نصف قطره (1.25mm) وقد تم سفع كل من النوعين باوقات مختلفة للسفع. تم تحديد الوقت الامثل مختبريا حيث كان (8 minutes) الذي اعطى اعلى اجهادات ضغطية متبقية (184.94-).
تم استخدام برنامج (منهجية استجابة السطح RSM وذلك للحصول على امثل الخواص السطحية لعمر الكلال وذلك باختيار معاملين هما (وقت السفع وجهادات الكلال).
وقد تم استخدام البرنامج الاحصائي (تحليل التباين (ANOVA للتنبؤ بالوقت الأمثل للسفع. وكانت النتائج (8.007 minutes) للعينات المحززة و (7.53minutes) للعينات غير المحززة. تم الحصول على نموذجين رياضيين متعددة الحدود من الدرجة الثانية للحالتين التي تم دراستها وبمستوى وثوقية ٩٥%.
عمليا تم الحصول على تحسين في عمر الكلال بنسبة 26.67% مقارنة بالمصدر[2] واكن بعد استخدام برنامج RSM كانت نتيجة التحسن 61% في عمر الكلال مقارنة مع المصدر [2].