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Analysis the Effects of Shot Peening Upon the Mechanical and Fatigue Properties of 2024-T351 Al-Alloy

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ABSTRACT

This paper presents an experimental study on the effect of shot peening on mechanical properties and residual stresses of 2024-T351 Aluminum alloy. Under the effects of shot peening time SPT the results show that the existence of SPT can improve the mechanical properties and fatigue life up to a limit value of SPT. The 15 minutes SPT gave the highest value of (σ_u, σ_y) which is about 6.7 % for (σ_u) and 11.7 % for (σ_y). Empirical equations were proposed to evaluate the SPT with the endurance limit stress and the residual stresses.

$$_{.L} = \mathbf{167.6(SPT)^{0.}}$$

$$_{.S} = \mathbf{10.755(SPT)^{0.}}$$

Keywords: Shot peening; Mechanical properties; Fatigue life; Residual stresses; Aluminum alloy (2024-T351).

تحليل تأثيرات القذف بالكريات المعدنية على الخواص الميكانيكية و الكلالية لسبيكة الالمنيوم (2024-T351)

الخلاصة

البحث الحالي يعرض دراسة عملية لمعرفة تأثير القذف بالكريات المعدنية علـــى المواصـــفات الميكانيكية و الاجهادات المتبقية لسبيكة الالمنيوم ذات الرقم (AA 2024-T351) تحت تأثير زمـــن القذف SPT. اظهرت النتائج ان وجود SPT يؤدي الى تحسين المواصـــفات الميكانيكيـــة وعمـــر الكلال لحد قيمة معينة من SPT. الزمن 15 دقيقة اعطى اعلى قيم للمواصفات الميكانيكيـــة بنســـبة 6.7% لاقصى اجهاد شد و11.7% لاجهاد الخضوع. تم اقتراح معادلة لحساب العلاقة بـــين SPT مع حد الكلال والاجهادات المتبقية.

$$_{.L} = \mathbf{167.6(\mathit{SPT})^{0.}}$$

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INTRODUCTION

Engineering components and structures are regularly subjected to cyclic loading and they are consequently prone to fatigue damage. In most cases, fatigue damage will initiate at the surface due to localized stress concentrations caused by machining marks [1]. Controlling the surface damage (initiation of cracks) is paramount for prolonging the fatigue life of components. Shot peening is extensively used for the above purpose as it produces near surface plastic deformation leading to the development of work-hardening and high magnitude compressive residual stresses [2]. Experimental determination and analysis of 2024-T351 aluminum alloys revealed that at high stress levels, low cycle fatigue, life improvement is due to slow crack growth rates, while in high cycle fatigue the extension of life is attributed to a prolonged period of crack arrest [1].

Curtis et al [3] studied the effect of controlled shot peening (CSP) on fatigue damage of high strength aluminum alloys. They concluded that, in general CSP is expected to increase the fatigue life of high fatigue limit and yield stress materials.

Guagliano, Vergani [4] proposed an approach for prediction fatigue strength of shot peened of alloy steel known as 39NiCrMo3 according to the Italian code. On the basis of the experimental evidence it was considered that the fatigue alleviation due to shot peening is mainly due to the ability of stopping crack propagation. The results enable the prediction of the improvement of fatigue strength due to shot peening.

James et al [5] Presented information regarding the residual stress profiles in aluminum and steel welds, and in shot peened aluminum, obtained via synchrotron and neutron diffraction.

The effect of different shot peening treatments on the reverse bending fatigue behaviour of Al-7075-T651 was investigated. An analytical model was built up for predicting the fatigue resistance taking into account the effect of both residual stresses and surface roughness. The concluded remarks were, controlled shot peening employing ceramic beads determines a remarkable increment of the high-cycle fatigue resistance of high-strength aluminum alloys, ranging between 15% and 50% [6].

Miao et al [7] presented the shot peening results including saturation curve, coverage curve, roughness curve as well as residual stress profiles. Also the relationship between prebending moment and resulting heights in narrow strip and square strips have been presented. Also experimental study of intensity and surface coverage on aluminum 2024 has been performed compressive residual stresses have beneficial effect for the improvement of the fatigue life of the peened component and the surface roughness has detrimental effect on the fatigue life of peened component. The influence of the shot peening velocities and peening time on the residual stress profile as well as their influence on the surface roughness have been experimentally measured and presented.

This study originally intended to attempt to compare the properties of 2024-T351 specimens under different shot peening times. However, certain conclusions can be made in regards to the mechanical properties and fatigue life.

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EXPERIMENTAL
MATERIAL

The material investigated in this paper was 2024-T351 aluminum alloy whose composition is presented in table (1).
Figure (1) shows the microstructure of the material used, which is composed of grains that are highly elongated in the extrusion direction.

TESTING SPECIMENS AND SURFACE PREPARATION

All specimens were prepared according to DIN 50113. The shapes of the specimens are hour-glass type in order to obtain stress concentration in the middle of the specimens (the minimum diameter) figure (2). At all tests, crack initiation and fracture occurred at the midpoint of the specimens.
The tensile properties of unpeened and peened specimens at different shot peening times are given in table (2).
Figure (3) illustrates the behavior of the material used under tensile test with different times of shot peening.

FATIGUE TESTING

Tension-compression axial fatigue tests have been conducted at room temperature in order to explore fatigue lives around 10^5 cycles. Tests were performed with servo-hydraulic testing machine type INSTRON-8874 with maximum capacity 25KN at stress ratio R= -1 and a frequency of 20 Hz (1200 r.p.m.). Figure (4) shows the fatigue test rig used for all the fatigue specimens.

PEENING DEVICE

The peening operation was carried out in a special device in Oriental Heat Treatment Company in Malaysia with the help of University Malaysia Pahang-Mechanical Engineering Faculty. This enables a defined shot peening treatment on round specimens only. The material of the ball was steel with an average ball size of diameter 0.4mm and Rockwell hardness of 50 HRC. The number of balls at the whole operation time was kept constant for a wide range of peening pressure around 20 bars resulting in ball velocities of nearly 50 m/sec. figure (5) Shows the device for shot peening treatment.

RESULTS AND DISCUSSION
ULTIMATE TENSILE STRENGTH (s_U)

The results of the tensile tests are shown in table (2) and figure (3). The shot peening treatment resulting in an increase in the σu (tensile stress) value at 3, 5, 10 and 15 min. respectively while above 25 min. a clear reduction was observed as compared to the unpeended specimens. The 15 minutes shooting time gave the highest value of σ_u which is about 6.7 %. This increase in the σu is due to compressive residual stresses induced at the surface as a result of shot peening [9].

YIELD STRENGTH

Similarly the yield stress was determined for peened specimens as given in table (2) and figure (3) the shouted specimens showed an increase in the yield strength up to 15 min. shooting which was 11.7% after that a reduction was observed as compared to unpeened specimens. This observation is in good agreement with Ref. [10], table (3).

ELONGATION

The present elongation of all specimens tested in tension is shown in table (2). The elongation percentage decreased up to 15 minutes and then increased.

Shot peening is known to improve the mechanical properties of metallic materials. The improvement in the mechanical behaviour is derived from compressive residual stresses that are introduced into the near-surface of the components and which hinder crack initiation and growth [11].

Surface integrity changes induced by shot peening mainly include work hardening due to the increase in the dislocation density, gives the surface layer higher ultimate and yield strength and hardness but lower ductility [12].

The variation in the σu, σy and elongation may be the result of the plastic deformation and strain hardening resulting in higher strength hardness and compressive residual stresses [13].

S-N CURVE

S-N curves of all laboratory specimens are presented in figure (7). The influence of shot peening time on the fatigue life is more important for high cycle fatigue. The experimental constant (A, m) for the S-N curve equations with shot peening time can be shown in table (4).

The relation between SPT and Endurance limit can be described by the formula.

$$\sigma_{E.L} = B(SPT)^{\alpha} \quad \text{....(1)}$$

It is clear that over 10 min. SPT, the endurance limit is slightly improved and over 15 min., reduction in endurance limit will be occurred. This conclusion is agreed well with the finding of Ref. [1] and [14].

RESIDUAL STRESSES

Based on the S-N curve equations for different shot peening time compared with the S-N curve equation of unpeened specimen the residual stresses can be calculated at different life as shown in table (5).

The residual stresses were determined using the $sin^2\varphi$ technique and x-Ray diffraction [15]. The stresses cannot be measured directly by the above technique. Rather, the strain is measured and the stress is calculated.

By plotting the peening time as a function of compressive residual stress up to 15 min. peening time, the following equation can be described the endurance limit and residual stresses as.

$$\sigma_{E.L} = 167.6(SPT)^{0.055}$$

$$\sigma_{R.S} = 10.755(SPT)^{0.512}$$

The negative sign for the residual stress means that the residual stresses were compressive resulting from the peening effect while the positive sine means that the residual stresses were tensile resulting from crack initiation on the surface due to peening effect [15].

CONCLUSIONS

Based on the preliminary data and results, the following remarks may be obtained.

1. It is observed that the σ_u and σ_y increase with the increasing SPT up to a certain point 15 min. SPT and then the static strength decrease when SPT increase. The 15 min. shooting time gave the highest value of (σ_u, σ_y) which is about 6.7 % for (σ_u) and 11.7 % for (σ_y)
2. The optimal SPT decrease the elongation up to 15 min. and then sudden increase will occurred when SPT is increased.
3. The fatigue live improved by shot peening treatment up to a certain point. The 15 min. SPT gave the highest fatigue live which is about 21% comparing with the unpeened specimens.
4. An equation is proposed to decide the optimal compressive residual stresses while may take the form.

$$\sigma_{E.L} = 167.6(SPT)^{0.055}$$

$$\sigma_{R.S} = 10.755(SPT)^{0.512}$$

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List of Symbols

Symbols	**Description**	**Units**
A, n	Constants	
CSP	Controlled shot peening	minute
E	Young's modulus	GPa
El	Elongation	mm
HB	Brinell Hardness	
K	Strength coefficient	MPa
n	Strain hardening exponent	
RA	Reduction in Area	mm^2
SPT	Shot peening time	minute
$\sigma_{E.L}$	Endurance limit stress at 10^7 cycle	MPa
σ_u	Ultimate tensile strength	MPa
σ_y	Tensile yield strength	MPa

Table (1) Chemical composition of 2024-T351 wt% [8].

Materials \ Elements		Si	Fe	Cu	Mn	Mg	Zn	Cr	Al
AA 2024-T351	Nominal composition	0.5 max.	0.5 max.	3.8-4.9	0.3-0.9	1.2-1.8	0.25	0.1	Rem.
	Actual composition	0.041	0.022	4.49	0.716	1.28	0.055	0.028	Rem.

Table (2) Mechanical Properties for 2024-T351

SPT (minute)	Mechanical Properties for AA 2024-T351							
	σ_u (MPa)	σ_y (MPa)	El %	RA %	K (MPa)	n	E (GPa)	HB
0	520	367	17.6	19	1100	0.167	72	124
3	526	370	17.3	16	1160	0.158	72	128
5	532	385	17.2	13	1160	0.158	72	134
10	545	400	16.8	13	1160	0.158	72	140
15	555	410	16.8	10	1200	0.158	72	144
25	508	360	18	25	1160	0.176	72	122

Table (3) Comparing this study with Ref. 10

SPT \ σ_y (MPa)	This study	Ref. 10
5 min.	385	405
15 min.	410	417

Table (4) S-N curve constant with shot peening time For 2024-T351 Al-alloy.

SPT (min.)	A	m	S-N curve equation	$\sigma_{E.L.}$* (MPa)	Increase in $\sigma_{E.L}$%
Zero	1208	-0.1251	$\sigma_f = 1208N_f^{(-0.1251)}$	161	0
3	1172	-0.1165	$\sigma_f = 1172N_f^{(-0.1165)}$	179	11.18
5	1210	-0.1177	$\sigma_f = 1210N_f^{(-0.1177)}$	181.5	12.73
10	1199	-0.114	$\sigma_f = 1199N_f^{(-0.114)}$	191	18.63
15	1232	-0.1145	$\sigma_f = 1232N_f^{(-0.1145)}$	194.6	20.87
25	1204	-0.1264	$\sigma_f = 1204N_f^{(-0.1264)}$	157	-2.48

*** Endurance limit stress at 10^7 cycle [3]**

Table (5) Residual stresses at different fatigue life.

Fatigue life	3 min.	5 min.	10 min.	15 min.	25 min.
10^3	-15.058	-27.585	-36.473	-49.555	+6.222
10^4	-19.149	-27.596	-37.933	-47.501	+5.791
10^5	-20.366	-25.962	-36.583	-43.562	+5.184
10^6	-19.864	-23.485	-33.71	-38.766	+4.517
10^7	-18.407	-20.674	-30.075	-33.756	+3.856
Average	-18.5688	-25.0604	-34.9548	-42.628	+5.114

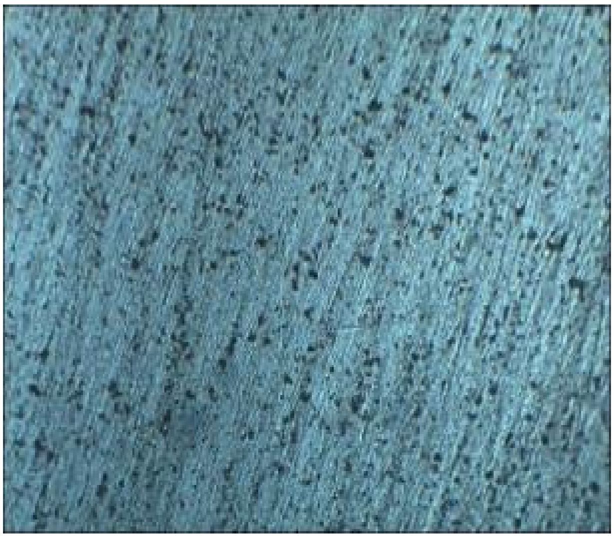

Figure (1) Microstructure of the material (Aluminum alloy2024-T351)

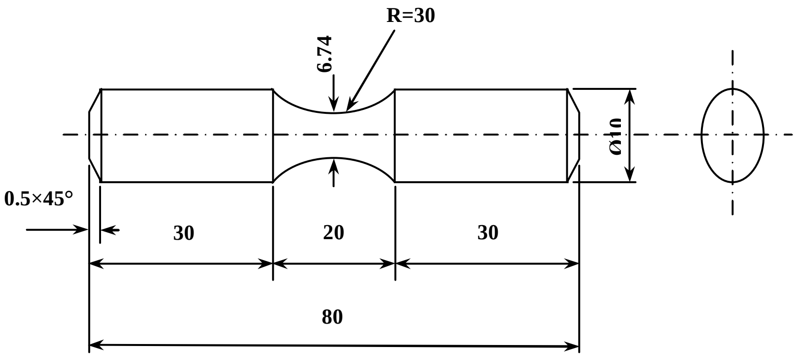

Figure (2) Shape and Dimensions of testing specimen (all dimensions in mm)

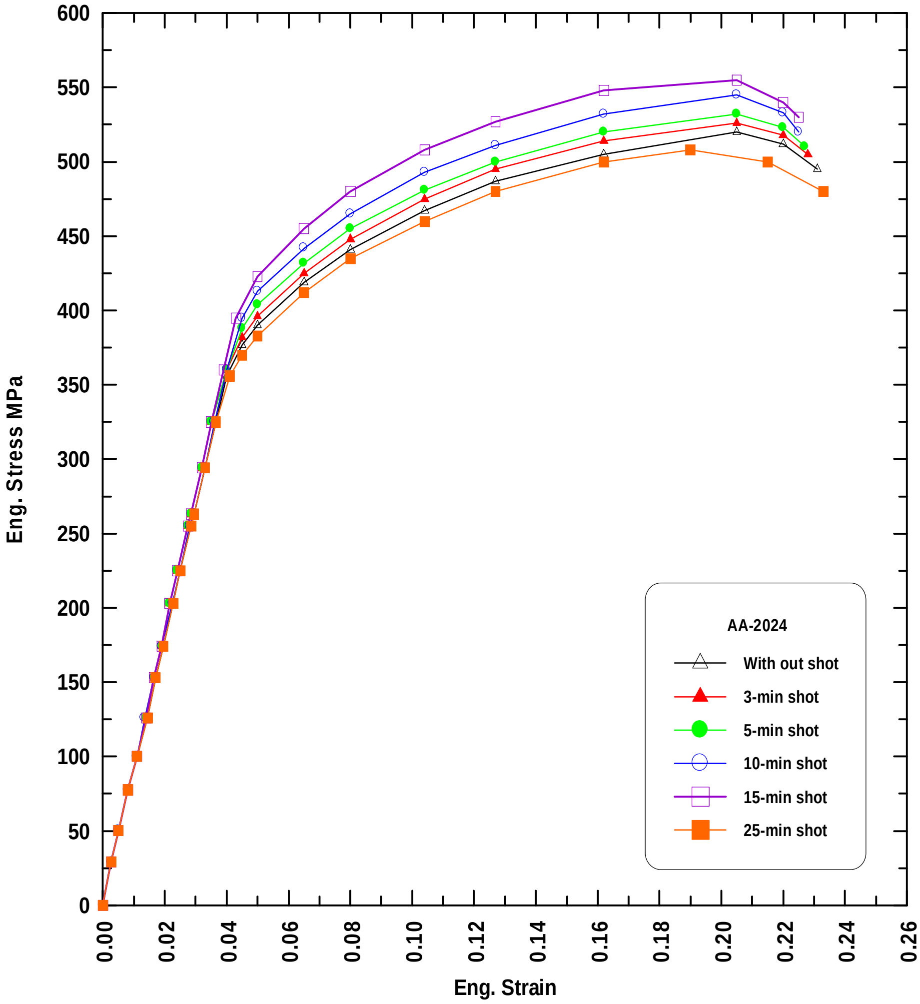

Figure (3) the behavior of 2024-T351 Al-alloy under tension tests and different shot peening time

Figure (4) Push Pull Fatigue test machine type (INSTRON-8874, with Max capacity 25 KN)

Figure (5) shot peening machine type (TOCHU)

(a) (B)

Figure (6) the specimen (a) before shot (b) after shot.

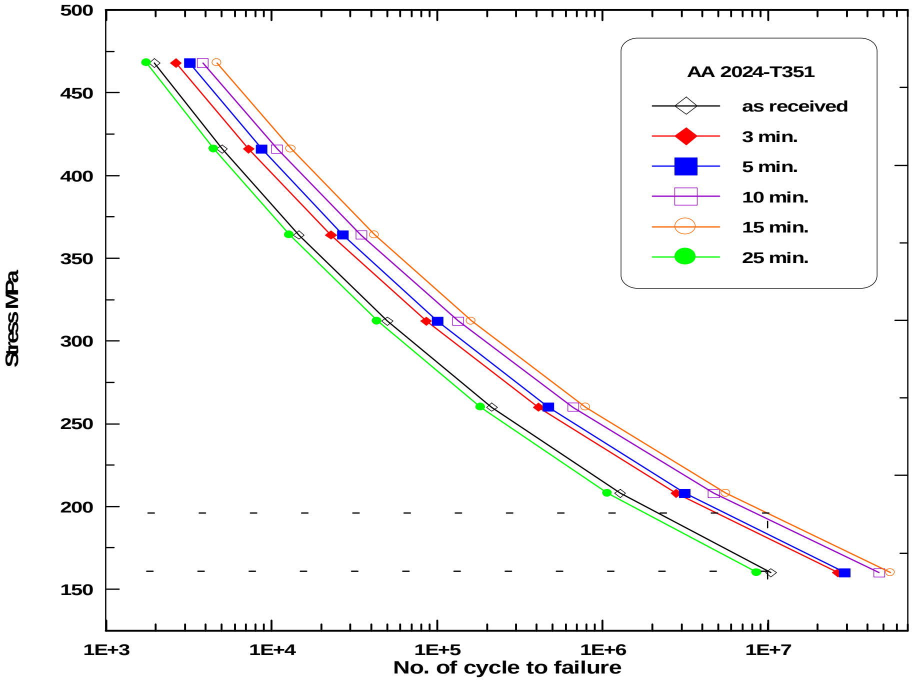

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Figure (7) S-N Curve for2024-T351with different times of shot peening