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The effect of shot peening on the notch sensitivity factor and Neuber characteristic length for 7075-T6 Aluminum alloy

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Abstract:

This paper has been studied the effect of shot peening to improve the mechanical properties, especially the enhancement of fatigue life, also to study the effect of shot peening on notch sensitivity factor (q) for two kinds of notched circular cross-sectional area of (AA7075-T6) with radii of notches (1, 1.25 mm). Due to the dimensions of specimens and notch radius, the stresses concentration factors (K_t) were (1.62, 1.73), respectively. This paper was included the effect of compressive residual stresses on the Neuber characteristic length (ρ).The experiments of shot peening were carried out at two different shot peening times (SPT) (0, 8, 10, 12, 20 min). The tensile test after shot peening was done to know the improvement in mechanical properties, The surface roughness, microhardness, and the compressive residual stresses by X-ray diffraction (XRD) were measured. The results showed the maximum decreasing in notch sensitivity factor (22.35 %) and maximum increasing in Neuber characteristic length which was (270.2%) at the same shot peening time (10 min) and notch radius (1.25 mm).

Key words : Residual stress, Notch sensitivity factor, Neuber characteristic length.

تأثير سفع الكرات على معامل حساسية الحز و الطول الخصائصي لنيبر لسبيكة الالمنيوم (7075-T6)

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الخلاصة

في هذا البحث تم دراسة تأثير السفع بالكرات على تحسين الخواص الميكانيكية و خاصة تحسين حد الكلال و تأثيره على معامل حساسية الحز (q) لعينات من سبيكة الالمنيوم (AA7075-T6) دائرية المقطع ، لحالتين من الحز بأنصاف أقطار (1, 1.25) ملم ، تم تحديد معامل تركيز الاجهاد (K_t)(1.62, 1.73) بالاعتماد على ابعاد العينة والحز وكذلك تأثير حد الكلال على الطول الخصائصي لنيبر (ρ) .

تم اجراء التجارب للسفع لزمنيين مختلفين هما (10, 20) دقيقة . بعد ذلك تم أجراء فحوصات الشد ، الخشونة السطحية، الصلادة الميكروية و الاجهادات المتخلفة الضغطية بطريقة حيود الاشعة السينية (XRD) أظهرت النتائج حدوث اعلى نقصان في معامل حساسية الحز و اعلى زيادة في الطول الخصائصي لنيبر وذلك عند حالة السفع بزمن (10) دقيقة مقارنة بالمعدن قبل عملية السفع . حيث بلغ اعلى نقصان لمعامل حساسية الحز بنسبة (22.35%) واعلى زيادة بالطول الخصائصي لنيبر (270.2%) عند نصف قطر حز (1.25) ملم.

d' : Lattice spacing of crystal planes (A°)
d_n: Lattice spacing of planes normal to the surface (A°)
d_{ψ}: Inter planar spacing of planes at an angle ψ (A°)
E : Modulus of elasticity (GPa)
El : Elongation (%)
HV: Hardness Vickers
K_f : Fatigue strength reduction factor.
K_t : Stress concentration factor.
N_f : Number of cycles to failure (cycle)
q : notch sensitivity factor.
R : Stress ratio.
Ra: Arithmetic mean surface roughness (μm)
r : Radius of notch root (mm).
ρ : Neuber characteristic length (mm).
σ_u: Ultimate tensile stress (MPa)
σ_y: Yield stress (MPa)
σ_{res} : Residual stress (MPa)
ψ : Tilt angle (degree)
θ : Diffraction angle (degree)
λ : Wave length of x-ray radiation (A°)
ν : Poisson's ratio

1. Introduction

Notches cannot be avoided in many structures and machines. To improve the mechanical properties and fatigue life, to avoid tensile stresses on the surface and to create compressive stresses, shot peening is one of the most effective methods which induce residual compressive stresses. **Butz and Lyst** [1], studied the improvement in fatigue resistance of aluminum alloy 2024-T6 by surface cold working (shot-peening and surface rolling). The surface cold working can have a large effect on the fatigue resistance of aluminum alloys. The degree of response varies widely, depending on many factors. In certain situations , the fatigue strength of a specimen may be more than doubled**.** As received or shot peened 7075-

T7351 single edged notch bend (SENB) specimens, 8.1mm thick were fatigued at a constant load and at stress ratio of R=0.1 and 0.8 to predetermined fatigue cycles or to failure. **Honda et. al.** [2]. The crack growth rate was determined by crack profile measurement and fractography at various fatigue cycles. The fatigue crack growth rate near the specimen surface of a SENB specimen was smallest for the as received and increased with increasing shot peening intensity. The calculation and measuring the notch sensitivity factor (q) are associated with presence of non-propagating fatigue cracks the notch root. **Meggiolaro et. al.** [3]**.** As expected, the results depend on the Neuber characteristic length, change in stresses. Moreover, a significant dependency is observed with respect to the aspect ratio . Therefore, the entire notch geometry, not only its radius, is an important factor when evaluating its sensitivity. **M. Benedetti et. al.** [4] **,** investigated the effect of different shot peening treatments on the fatigue behavior of 7075-T651aluminum alloy samples carrying different types of notches. They found a different improvement of the fatigue strength depending on the peening intensity, and a particularly, a different effectiveness of the treatments for different notches geometries. They used flat specimen and notches (0.5, 2) mm, the shot peened treatment employed small ceramic beads leading at 210 sec, whereas the second one has a larger size at 160 sec, the third one combined a double peening. The result showed the notch sensitivity factor decreased with effect of shot peening, and the Neuber characteristic length was found. **Khaled M. Ibrahim et. al.** [5], examined the influence of notch sensitivity of fatigue behavior of austempered ductile iron (ADI). The sample were heat treated at 900°C for one hour and rapidly quenched into two different salt baths at 350°C and 400°C for 1h each . Experimental testing was performed using rotary bending fatigue test and samples with notch (1, 1.5, 2 mm). The results showed that the predicted fatigue strength estimated theoretical is close to experimental one. **M. Benedetti et. al.** [6]**,** used reverse bending S-N curves to determine the notch and un-notch condition and measured the residual stress by XRD after shot peening treatment, were used for predicting by means of finite element modeling respectively the residual stress distributions in the notched sample and the residual stress relaxation in the vicinity of the notch due to application for 7075-T651 aluminum alloy.

This study dealt with the rotating fatigue test with a circumferential notch open mode and showed the effect of compressive residual stress induced by steel beads peening to investigate the effect of notch sensitivity factor at different shot peening times and different notch radii, for aluminum alloy 7075-T6.

2. Notch Sensitivity Factor

When the theory of elasticity was used to compute stress concentration, there was hope that the fatigue strength of a notched component could be predicted as the strength of a smooth component divided by a factor computed from the theory. The facts, however, are different. Notched fatigue strength depends not only on the stress concentration factor, but also on other factors, such as the notch radius, the material strength, and the mean and alternating stress levels. The ratio of smooth to net notched fatigue strengths, based on the ratio of alternating stresses, is called Kf [7].

$$K_f = \frac{Smooth\ fatigue\ \ strength}{Notched\ fatigue\ \ strength} \qquad (1)$$

It is important to know where the most dangerous stress concentrations exit in a part. Charts of stress concentration factors (K_t) are available in the literature. As shown in Figure (1). It is important, however, to remember that the stress concentration factors for a homogenous isotropic material depend only on geometry and mode of loading, and that apply only when the notch is in the linear elastic deformation condition [7].

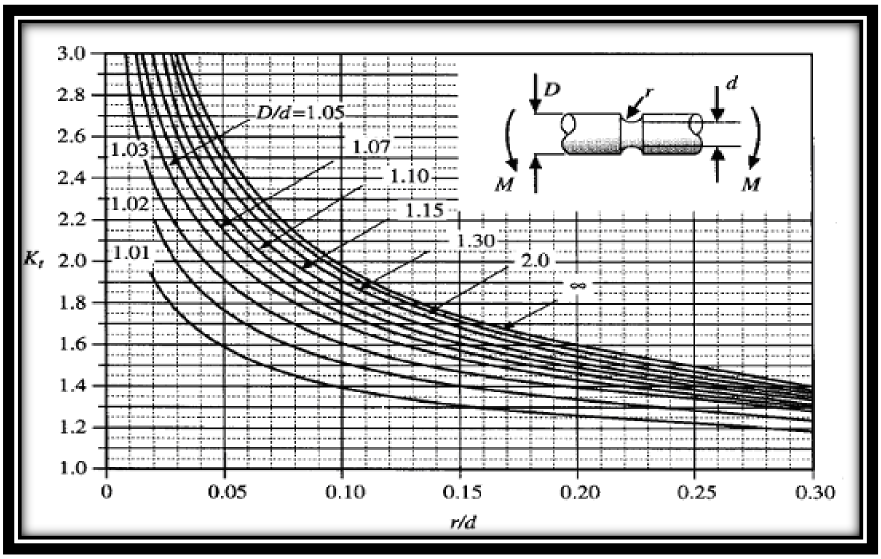


Fig. 1: Theoretical stress concentration factor K_t for a round bar with a U groove subjected to bending [8]

Notch sensitivity factor is a measure of how sensitive a material to notches or geometric discontinuities. A notch sensitivity factor (q) can be defined as a factor which relates the strength reduction factor, K_f, and the stress concentration factor, K_t, such that;

$$q = \frac{K_f - 1}{K_t - 1} \qquad (2)$$

$$K_f = 1 + q(K_t - 1) \qquad (3)$$

Where q=0 for no notch sensitivity, q=1 for full sensitivity.

Neuber developed the following approximate formula for the notch factor for R=-1 , loading:

$$q = \frac{1}{1 + \sqrt{\rho / r}} \quad or \quad K_f = 1 + \frac{K_t - 1}{1 + \sqrt{\rho / r}} \qquad (4)$$

Where the characteristic length, ρ, depends on the material.

Notch sensitivity is a very complex factor depending not only upon the material, but also upon the grain size. A finer grain size results in a higher value of (q) than a coarse grain size. It also increases with the section size and tensile strength; thus under some circumstances, it is possible to decrease the fatigue life by increasing the tensile strength and as has already been mentioned. It depends upon the severity of notch and type of loading [7].

3. X-ray Diffraction (XRD)

The X-ray diffraction (XRD) techniques exploit the fact that when a metal is under (applied or residual), the resulting elastic strains cause the atomic planes in the metallic crystal structure to change their spacing's. X-ray diffraction can directly measure this inter-planar atomic spacing; see Figure (2), from this quantity, the total stress on the metal can then be obtained [9].

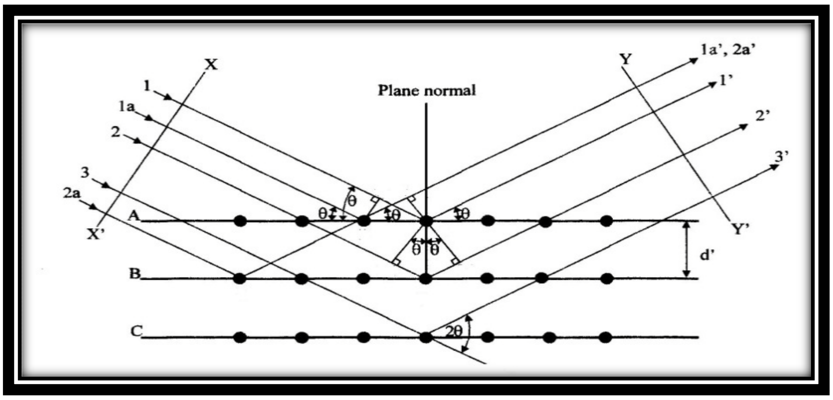


Fig. 2: Diffraction of x-ray by a crystal lattice

The diffraction is governed by the Bragg's equation;

$$n\lambda = 2d' sin\theta \qquad (5)$$

If we consider the strains in terms of inter-planar spacing for elasticity theory, and use the strains to evaluate the stresses, then it can be shown that the final equation [10];

$$\sigma_{res} = \frac{E}{(1+v)\partial sin^{2}\psi}\left(\frac{d_{\psi}-d_{n}}{d_{n}}\right) \qquad (6)$$

4. Experimental Work

The materials used were described and distinguished with the corresponding chemical composition and mechanical properties. The machining of the specimens and equipment used were mentioned. Shot peening processing via additional device was described. The specimens were subjected to fatigue tests. Some specimens were prepared for specific tests (tensile, surface residual stress, surface roughness and micro hardness).

The materials used in this study is 7075-T6 aluminum alloys, the chemical analysis of this alloy is in Table (1).

Table 1:Chemical composition of 7075-T6 aluminum alloy

	Cu	Mg	Mn	Zn	Si	Fe	Ti	Al
Nominal [ASM] [11]	1.2-2	2.1-2.9	0.3 Max.	5.1-6.1	0.4 Max.	0.5 Max.	0.2 Max.	Bal.
Received	1.71	2.18	0.225	5.18	0.064	0.223	0.014	Bal.

Rod tensile specimens were of the geometry and dimensions shown in Figure (3). The result exhibits the main important mechanical properties, including the yield strength, tensile strength, and percentage of elongation. Tensile tests were done before and after shot peening by three specimens of each type for (7075-T6) aluminum alloys.

When dealing with fatigue test specimens preparation, three groups (smooth , notch 1 mm , notch 1.25 mm) of specimens and each group in three types of sub-group according of shot peening time (0, 10, 20) minutes were classified, as showing in the Table 2.

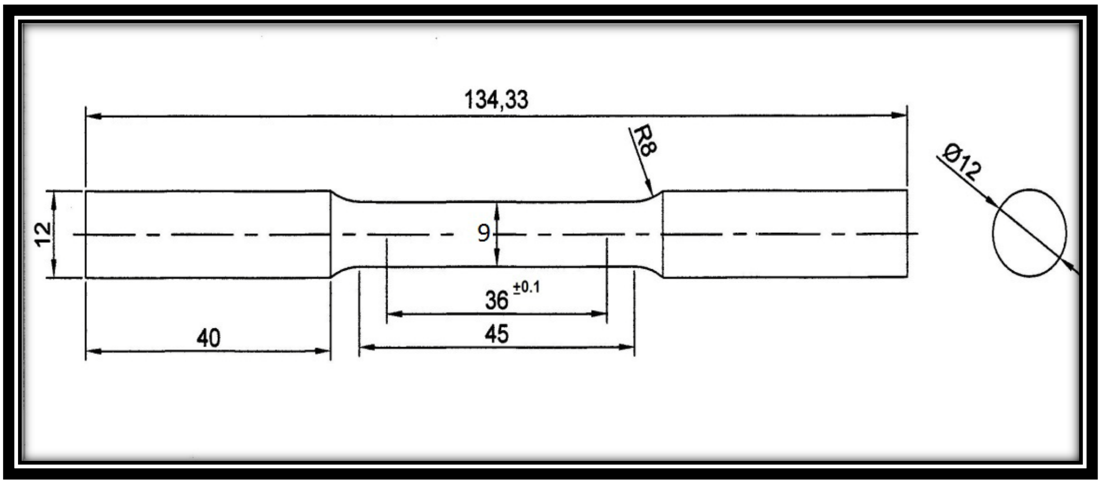


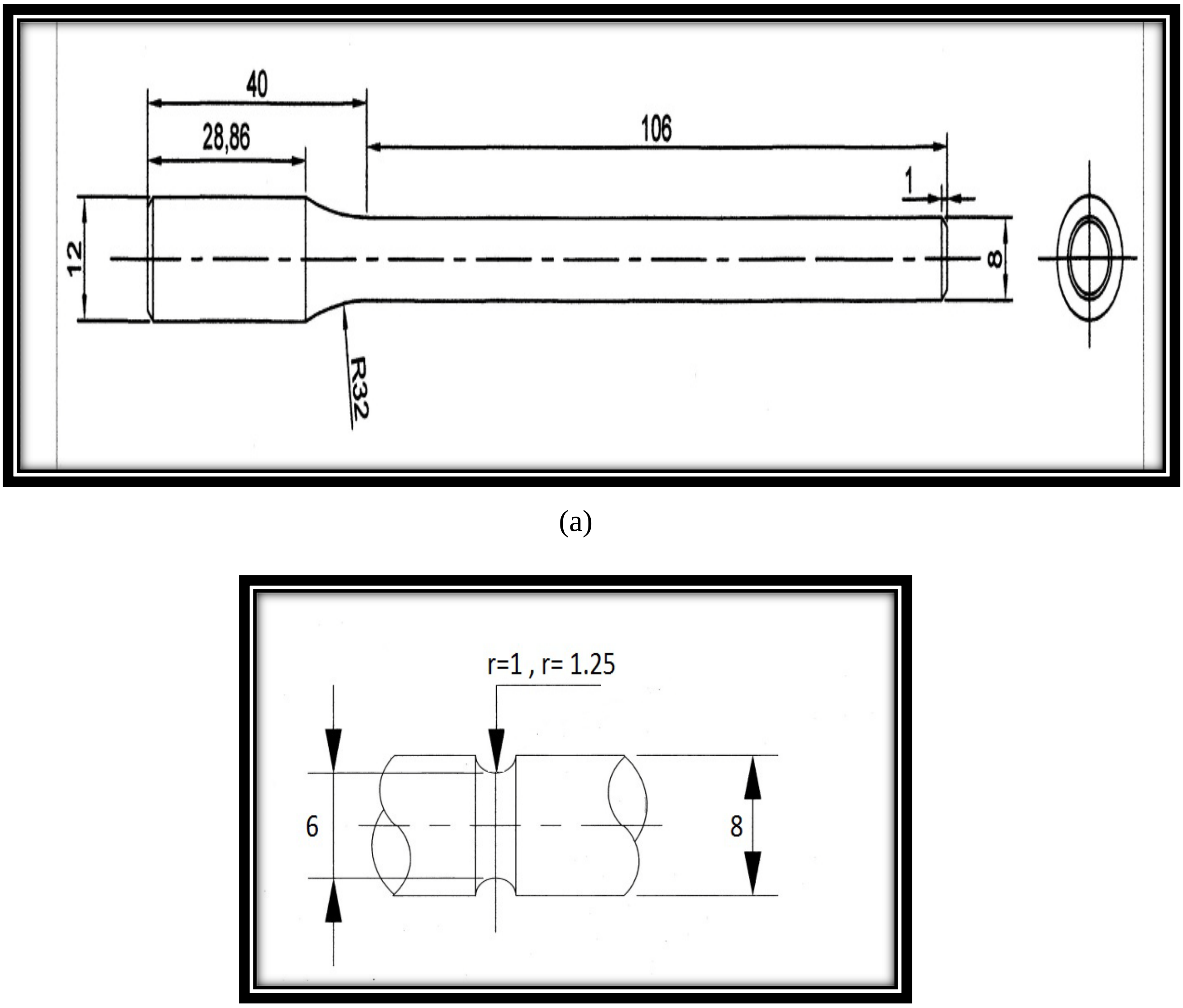
Fig. 3: Tensile test specimen according to (ASTM-E8)
(all dimensions in mm)

Table 2: Classification the groups of 7075-T6 specimens

Group	Shot peen Time (minute)	Radius of notch (mm)
A	0	smooth
B	10	smooth
C	20	smooth
D	0	1
E	10	1
F	20	1
G	0	1.25
H	10	1.25
J	20	1.25

The circumferential notches of two groups were made by using special cutting tools with radius (1, 1.25) mm. The special cutting tools was formed by using wire cutting machine to give perfect dimensions .

The fatigue test specimens are shown schematically in the Figure (4). The finishing operation was carried out by using wet aluminum oxide paper from (1000) to (3000) for finishing with a string cloth soaked in liquid alumina 0,05 μm for polishing.



(a)

(b)

Fig. 4: The dimensions of fatigue test specimens (all dimensions in mm), (a) schematically smooth specimen (b) schematically notched specimen

The shot peening was done in two groups (10 , 20) minute. to induced the residual stresses by mechanical treatment , using rotary type machine (Sintokogio model STB-OB) with centrifuges shot peening of small iron ball size diameter (1.2 mm) with average speed 40 m/s to ensure shooting the notch uniformly, A special rotating machine device was fabricate by researcher to modified the shot peening machine to peened the specimen notch identical as shown in Figure (5) , and fixed inside the rotary dram of shot peening machine at (30 cm) in front of shot peening window shown in ,Figure (6).

Fig. 5: The portable electrical additional device

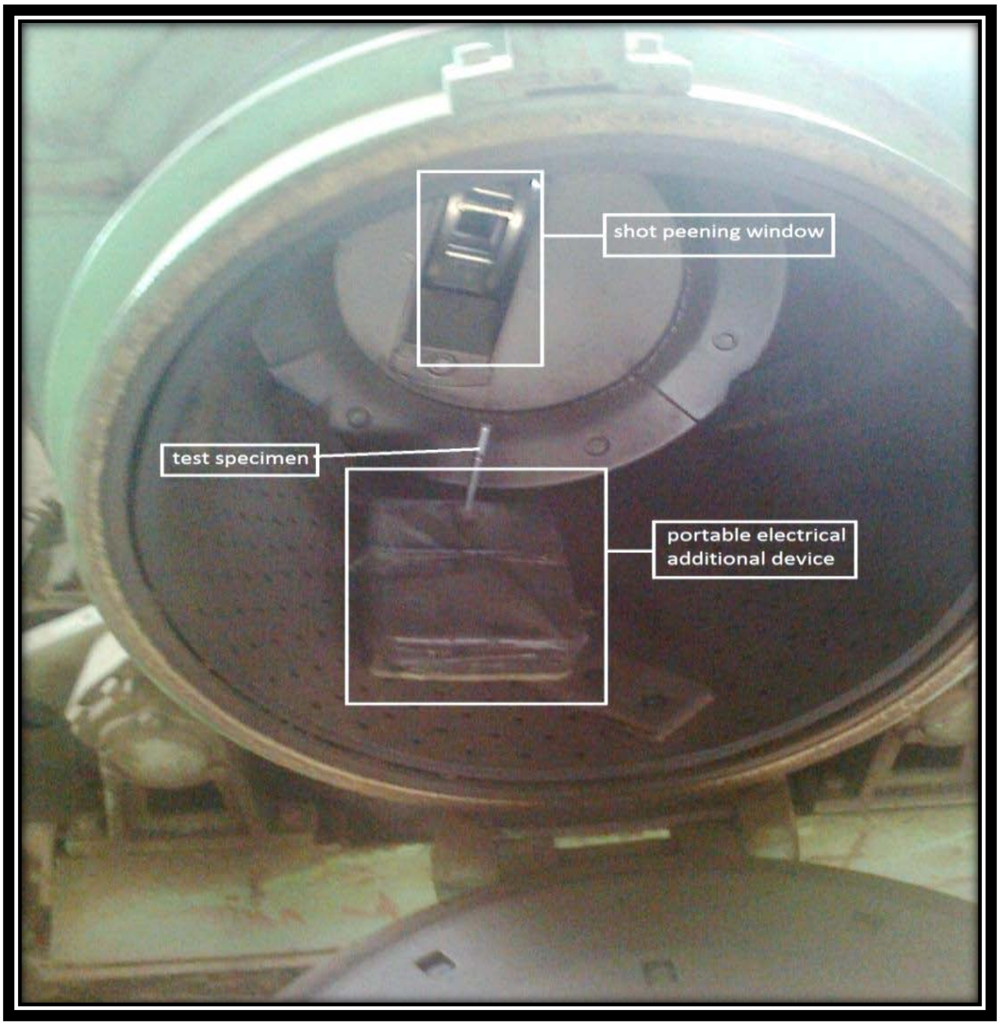


Fig. 6: The additional device put and fixed inside the rotary cylinder of the shot peening machine,

5. Results and Discussion

To obtain the mechanical properties, the tensile tests of the chosen material 7075-T6 aluminum alloys were performed to obtain the values of the ultimate tensile stress σ_u , yield stress σ_y and elongation $El\%$. Table (3), lists the tensile values for the as received and after SPT (10, 20 minute) compared to the ASM data sheet (Standard).

Table 3: Tensile tests results

Alloy type	Condition	σ_u (Mpa)	σ_y (MPa)	$El\%$
7075-T6	Standard	573	504	10
7075-T6	Received	612	549	9
7075-T6	peened 10 min	623	556	9.2
7075-T6	peened 20 min	619	554	9.1

The results of tensile tests showed that the ultimate tensile strength has a small increasing according to shot peening effect, but the amount of increasing depends on the compressive residual stress and variation with it. The maximum percentage changes of ultimate tensile is (1.79%) for aluminum alloy 7075-T6 peened for 10 minutes.

The results of surface roughness tests, **Figure (7)**, showed that the surface roughness increases with shot peening time for the 7075-T6 Aluminum alloy.

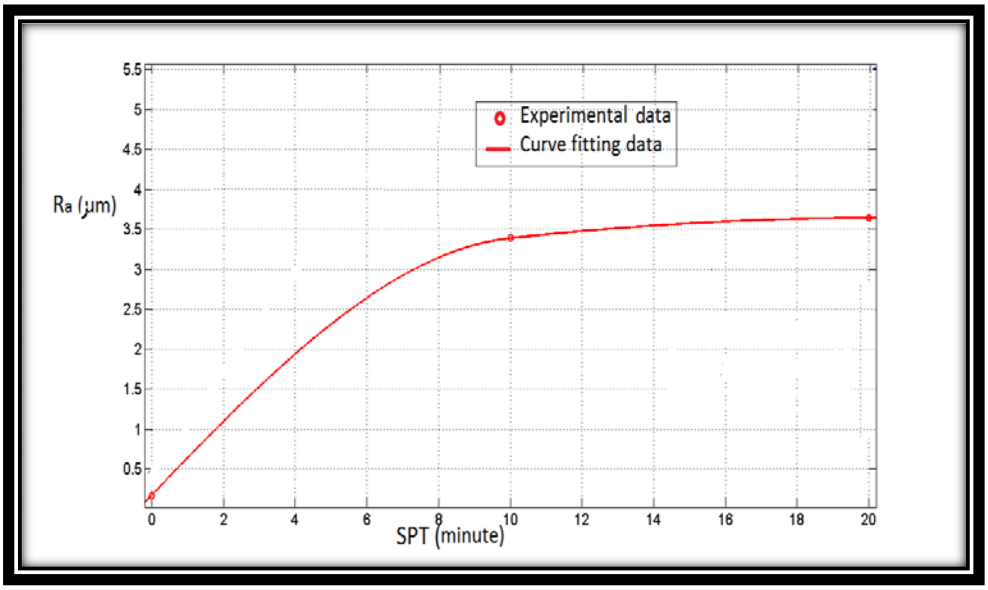


Fig. 7: Surface roughness distribution for 7075-T6 aluminum alloy

On one specimen of all series, Vickers micro-hardness was measured by using a mass equal to 100 gram at 15sec. (ASTM E384) [12]. The effect of shot peening induced the surface compressive residual stress making increasing the surface hardness.

It is possible to observe from Figure (8) that the shot peening influences the values just under the surface and that trend dose not vary significantly. The surfce hardness generally increases with shot peening processes. It can be also seen from Figure (8) that the increasing was a maximum in a surfce hardness at 10 minutes SPT for the material used in this work, while the increasing at 20 minutes SPT was less than at 10 minutes SPT compared with the case of without shot peening. The percentage of the increased surface hardness for 0.1 mm. depth was (17.25%) at 10 minutes SPT.

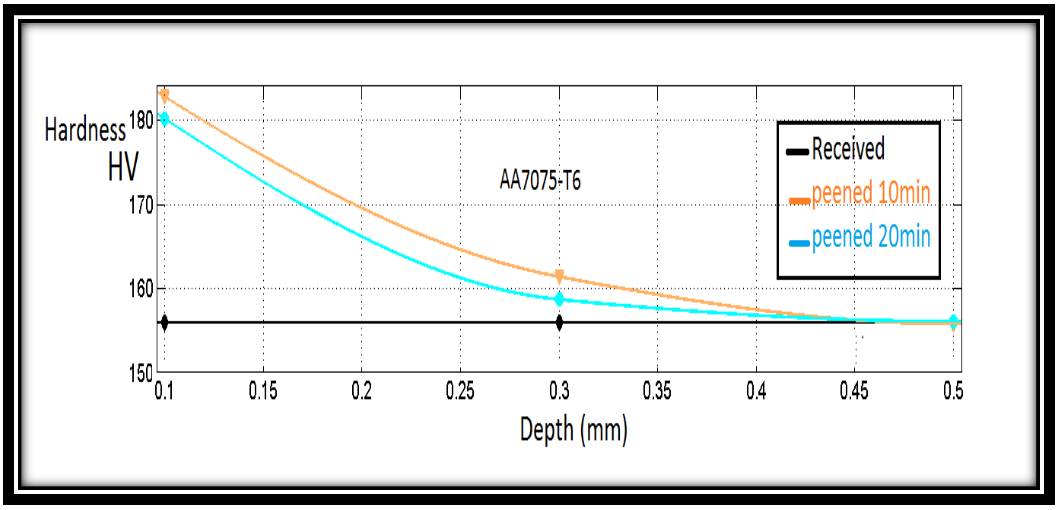


Fig. 8: Hardness profile of the specimens before and after SPT (10, 20 min) for 7075-T6 aluminum alloy

The X-Ray diffraction (XRD) measurements of the residual stress on the surface were taken by using machine type Lab6000 with stress analysis adapter before and after shot peening of specimens, the result are shown in the Table 4.

Table 4: Experimental residual stresses results for 7075-T6 aluminum alloy at different SPTs

SPT(min)	ψ(deg)	2θ(deg)	d'(Å)	σ_{res} (MPa)
0	0	156.116	1.170175444	-59.403
	15	156.521	1.169308693	
	30	156.595	1.169152039	
	45	156.557	1.169232417	
8	0	155.305	1.171959018	-264.86
	15	155.745	1.170981209	
	30	156.533	1.169283253	
	45	156.778	1.168766913	
10	0	155.30	1.171836032	-279.167
	15	156.009	1.170407095	
	30	156.595	1.169152039	
	45	157.007	1.168289531	
12	0	155.151	1.172304952	-297.059
	15	155.661	1.1711682	
	30	156.315	1.169747572	
	45	156.843	1.168636898	
20	0	156.444	1.171648771	-219.861
	15	155.790	1.170884691	
	30	156.401	1.169563851	
	45	156.667	1.169000128	

The relationship shown in Figure (9) represents the distribution of stresses with SPT to 7075-T6 aluminum alloy, by taking the final results for the residual stresses of Table (4) to develop this relationship with SPTs (0, 8, 10, 12, 20 minutes). The optimal value of the alloy surface was obtained at 12 minutes. After that, the opposite effect of the shot peening starts, after the optimal value, the effect of peening beads decreased the residual stress due to initiation microcracking, microtearing the formation of small laps and seams significant (over peened) condition on the surface.

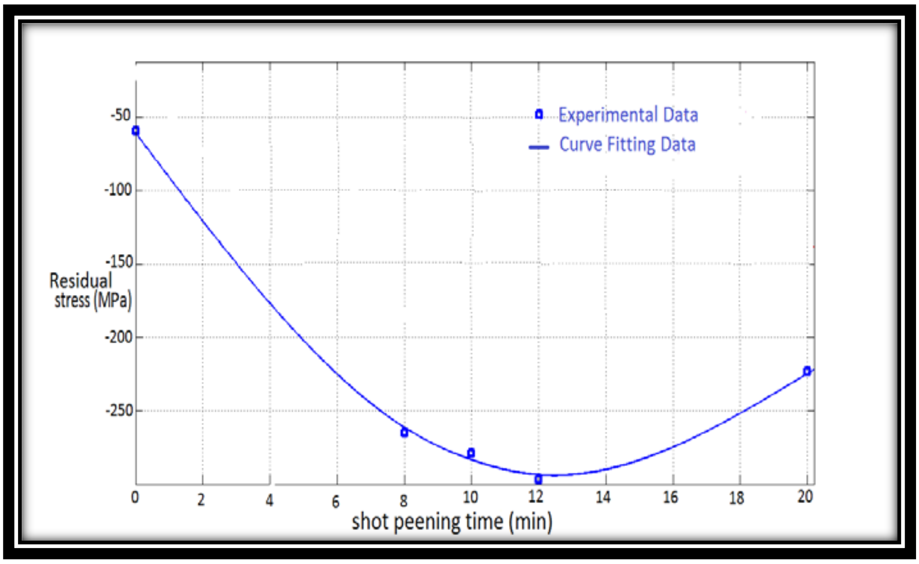


Fig. 9: The optimization of residual stress with peening time for AA7075-T6

The S-N results were obtained from the fatigue tests for all groups as received, and shot peening at two times which are 10 and 20 min. All the tests were carried out at constant stress amplitude loading. The main results of fatigue test are plotted in the S-N curves and endurance limit from Figure (10) to Figure (12). These curves give an indication about the variations in fatigue life. From these data, the fatigue life estimation equations were obtained, the endurance limit at $N_f = (10^6)$ cycles.

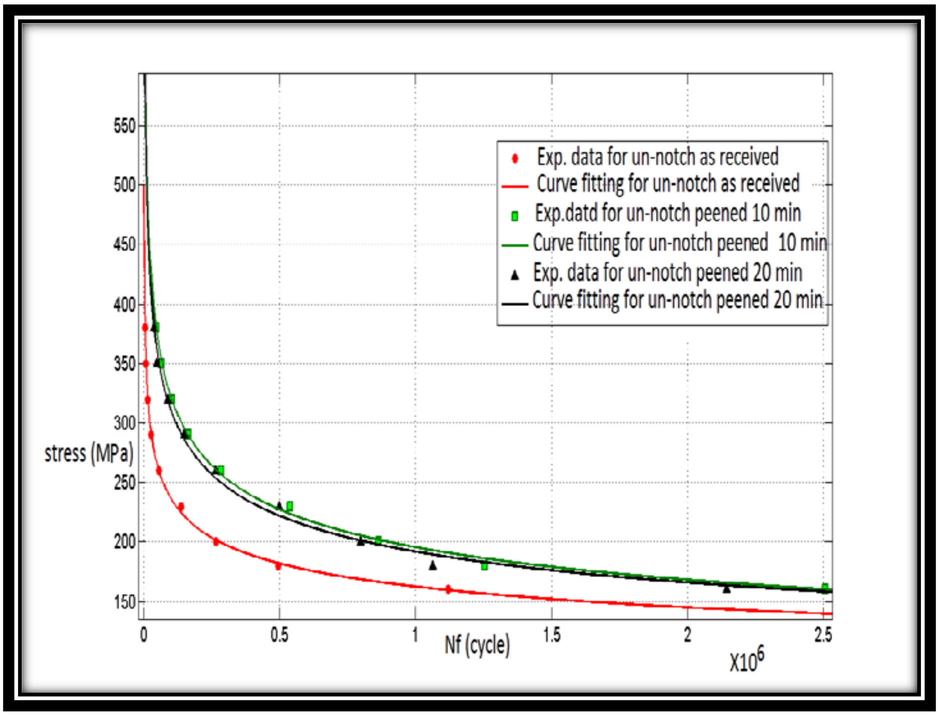


Fig. 10: S-N curves for un-notch specimens at different SPTs for AA7075-T6

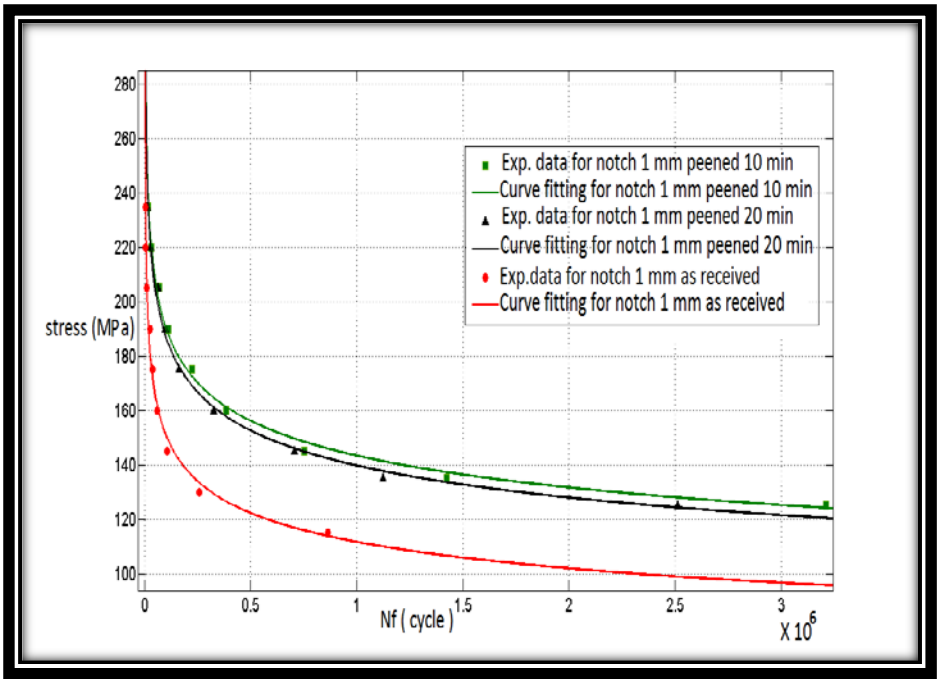


Fig. 11: S-N curves for 1mm notch radius specimens at different SPTs For AA7075-T6

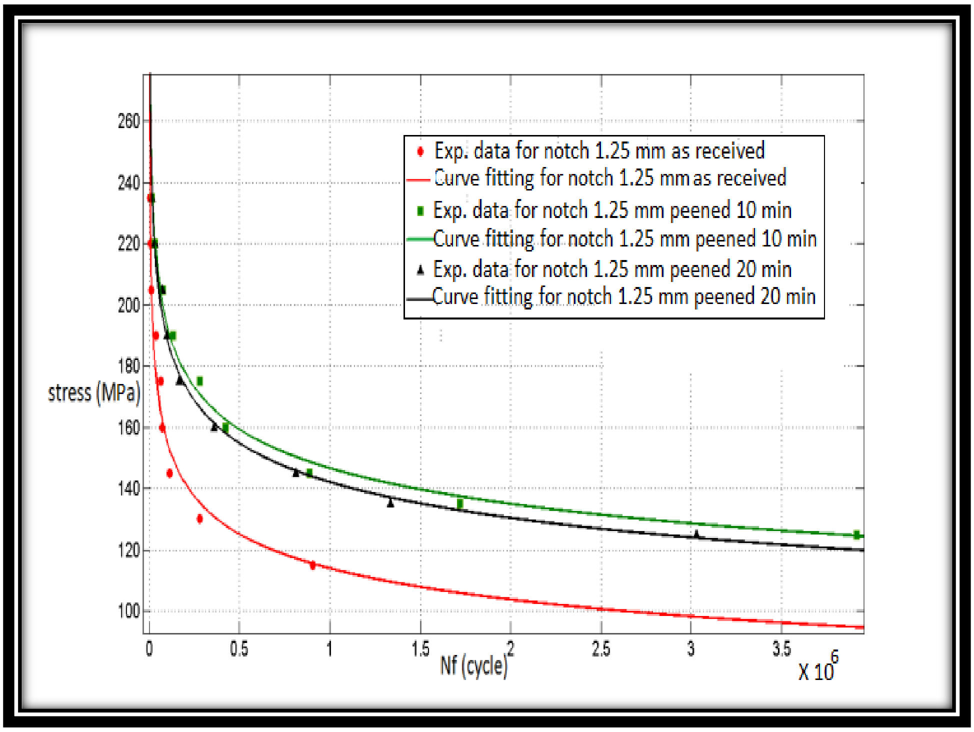


Fig. 12: S-N curves for 1.25 mm notch radius specimens at different SPTs For AA7075-T6

The equations and fatigue strength which describes this curve with an accuracy 95% of data fitting are given in Table 5, while the other results; stress concentration factor (K_t) , strength reduction factor (K_f) and notch sensitivity factor (q) are shown in Table 6.

Table 5: All S-N curved equations for AA7075-T6

Group	Equation	Fatigue strength (MPa)
A	$\sigma_l = 1559 * N^{-0.1637}$	162.420
B	$\sigma_l = 3940 * N^{-0.2174}$	195.477
C	$\sigma_l = 3513 * N^{-0.2104}$	191.989
D	$\sigma_l = 684.4 * N^{-0.1312}$	111.715
E	$\sigma_l = 785.4 * N^{-0.1231}$	143.381
F	$\sigma_l = 806.4 * N^{-0.1269}$	139.685
G	$\sigma_l = 738 * N^{-0.1353}$	113.830
H	$\sigma_l = 766.9 * N^{-0.1197}$	146.737
J	$\sigma_l = 789.9 * N^{-0.1242}$	142.027

Table 6 : Values of (K_f , K_t , q , ρ) for AA7075-T6

SPT (min)	Smooth strength σ (MPa)	Notch strength σ (MPa)	Notch Radius (mm)	K_f	K_t	q	Variation % q	Neuber length $\rho(mm)$
0	162.420	111.715	1	1.454	1.73	0.622	received	0.369
10	195.477	143.381	1	1.363	1.73	0.497	-20.1	1.024
20	191.989	139.685	1	1.374	1.73	0.512	-17.68	0.908
0	162.420	113.830	1.25	1.427	1.62	0.689	received	0.255
10	195.477	146.737	1.25	1.332	1.62	0.535	-22.35	0.944
20	191.989	142.027	1.25	1.352	1.62	0.568	-17.56	0.723

From the results of the fatigue test of group B (Table 2) (un-notched specimens shot peening 10 min.), it can be observed that the value of the endurance limit of this group is higher than the value of endurance limit of group A and C, that’s due to the effect of increasing the surface residual stress of group B higher than the other two groups (A, C), as shown in, Figure (10).

The enhancement percentage of the endurance limit is (20.35%) for group B and (18.21%) for group C compared with as received. This enhancement in endurance limit is due to the increasing in the surface compressive residual stress limit which was (369.95%) for group B and (270.12%) for group C, this case caused the difference in fatigue endurance life .

From the results of the fatigue test of group E (notch radii 1mm specimens and shot peening 10 min.), it can be observed that the value of the endurance limit of this group is higher than the value of endurance limit of other group D and F, Figure (11). The enhancement percentage of the endurance limit is (28.35%) for group E and (25.04%) for group F compared with as received, and the variations of reduction in notch sensitivity factor (q) are (20.1%) , (17.68%) while for Neuber characteristic, the increases in length ρ are (177.5%) , (146%) for groups E and F, respectively.

Results of the fatigue test of group H (notch radii 1.25 mm specimens and shot peening 10 min.) showed that the value of the endurance limit of this group is higher than the value of endurance limit of other group G and J, Figure (12). The enhancement percentage of the endurance limits (28.91%) for group H and (24.77%) for group J compared with as received, and the variations of reduction in notch sensitivity factor (q) are (22.35%), (17.56%) whereas for Neuber characteristic, the increases in length ρ are(270.2%) ,(183.5%) for group H and J respectively. The reduction in notch sensitivity factor has taken the advantage to increase the service life and advised to make surface treatment by shot peening for any design like this case.

The relation between un-notch (smooth) specimen as received and notched specimen with radius (1, 1.25 mm) at different shot peening times (0, 10,20 min) for 7075-T6 aluminum alloys is shown in Figure (13) and (14). They show clearly the comparison between the notch specimen with and without shot peening to the smooth as received specimen. The enhancement percentage gained in the strength endurance limit for 7075-T6 aluminum alloy for specimens as-received (with and without notch) to the shot peening specimens showed that the effect of shot peening on the endurance limit with notch radius 1mm. was (62.4%), (55.2%) for SPT 10, 20 min, respectively. And, for notch radius 1.25 mm, the enhancement was (67.7%), (58%) for SPTs 10, 20 min, respectively.

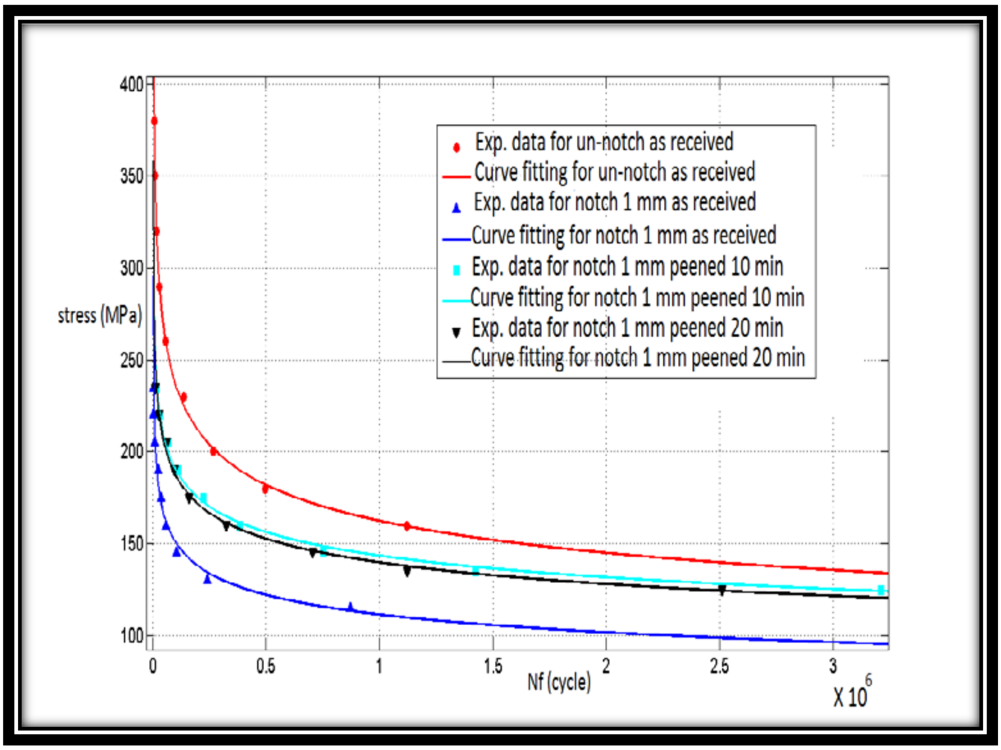


Fig. 13: Smooth and notch radius 1 mm at different SPTs For AA7075-T6

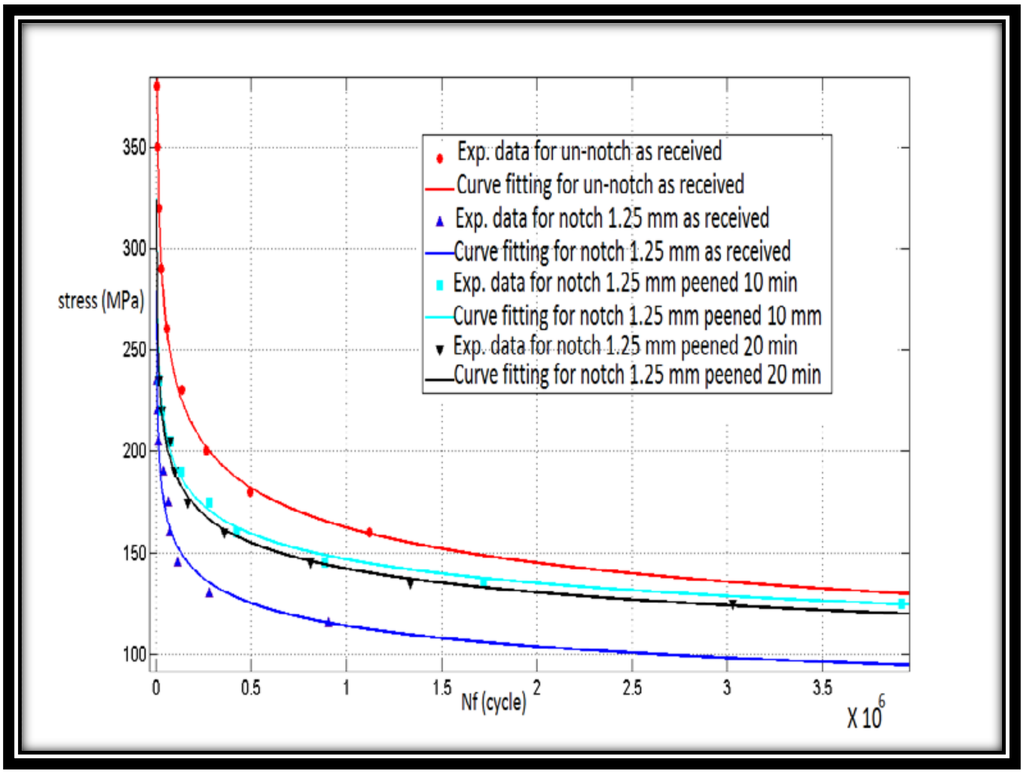


Fig. 14: Smooth and notch radius 1.25 mm at different SPTs For AA7075-T6

6. Conclusions

The main conclusions drawn from this paper on both mechanical properties and their fatigue behavior with considering the shot peening effect are listed below:

1. The maximum enhancement percentage of the endurance limit was (28.35%) for group E and (25.04) for group F compared with as received .
2. The maximum decreasing in notch sensitivity factor (q) was (22.35%) at notch radius 1.25 mm and at 10 min SPT , this reduction caused to increase the service life.
3. The maximum increasing in Neuber characteristic length (ρ) were 270.2% and 183% for groups H and J, respectively.
4. A small increasing was carried out in ultimate tensile stress (σ_u) due to shot peening which was (1.79%)

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