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Effect of Oil – Corrosion on Tensile and Fatigue S-N Curve Properties of AA6061-T6

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K E Y W O R D S

AA6061-T6, mechanical properties, hardness, fatigue, oil corrosion, shot peening.

A B S T R A C T

The present study described the effect of shot peening on mechanical properties and rotating corrosion –fatigue behavior (strength and life) of AA6061-T6. Ultimate tensile strength (UTS) and yield stress (YS) were reduced by 4.6% and 1.24% when immersing the tensile samples in crude oil for 60 days. The values of (UTS) and (YS) were raised from 307 to 316 MPa and from 248 to 254 MPa respectively when treated for 10 min. shot peening (SP). Hardness of oil corrosion samples dropped due to pitting corrosion and slightly raised for SP prior to corrosion samples. Oil corrosion reduced the fatigue strength by (-1.25%). This percentage was enhanced due to SP to 2.377%. SP significantly increased the rotating fatigue life by a factor of 1.19 and 1.3 at (UTS) and (Ys) loads respectively. (SP) technique improved corrosion-fatigue resistance due to producing compressive residual stresses at surface layers.

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1. Introduction

Corrosion fatigue is a process occurs under simultaneous corrosion and cyclic loading at low and high stress levels. Corrosion can be defined as a degradation of material due to a reaction with its environment. For example, mild steels are susceptible to general corrosion and aluminum alloy exhibits and oxide layer. The corrosion takes many forms like pitting, crevice corrosion and stress-corrosion crack.[1][2].

Saba F.N. [3] studied the mechanical and corrosion fatigue of 6061-T6 subjected to corrosive environment of 3.5% Nacl solution for 77 days. It was obtained that the fatigue strength constant S-N curve reduced by 4.5% and after applying ultrasonic impact peening this percentage was reduced to

2.2%. Daavari and Sadough [4] tested welded steel pipes subjected to corrosion –fatigue and it is observed that the mechanical and fatigue properties were significantly reduced. They used ultrasonic impact peening to improve the mechanical properties and fatigue behavior. It was observed that the mentioned properties are clearly increased.

2. SHOT PEENING (SP)

SP is a process causes a layer of compressive residual stress and strain hardening at the surface. This technique has a positive results regarding corrosion-fatigue. SP is a cold working which small spherical shots at different velocities are fired against a target surface. SP is commonly employed to create layers of compressive residual stress at the surface subjected to tensile, fatigue or corrosion fatigue.

The compressive residual stresses at the surface resulted from SP) have proven that the (SP) process is extremely beneficial to corrosion – fatigue resistance of aluminum alloy. Zupanc and Grum [5] tested high - strength aluminum alloy 707-T651 subjected to (SP). The experimental results indicated that (SP) treatment improved the fatigue and corrosion – fatigue life nearly doubled the cycles of unpeened samples. Muna K.[6] investigated the influence of (SP) time using steel ball of 1.25 mm diameter on fatigue strength of 1020AISI. The results observed that the best fatigue strength has been achieved when using 20 minutes (SP). The shot peening device, shot peening parameters, dimensions of steel balls can be seen in Ref. [7].

The present paper focuses on improvement and evaluation of mechanical and fatigue properties of AA6061-T6 subjected to oil corrosion and use shot peening technique for enhancement these properties.

3. EXPERIMENTAL WORK

I. Material selection

Aluminum is denoted as a young metal as compared to other metals used today. Aluminum alloys are used more than non-ferrous metal like copper, tin, lead and zinc due to processes low specific weight, high corrosion resistance, good electrical conductivity and good heat conductivity. About 85% of aluminum is employed for rolled plate, sheet, rod, bar, extrusion and wire. The material selected in the present study is AA6061-T6 Aluminum alloy which has good formability, machinability and fair resistance to atmospheric corrosion [1].

This alloy has a wide range of structural applications and welded assemblies including pipelines, aircraft, electrical and electronic application [2].

II. Chemical analysis

Chemical analysis of the selected material (AA6061-T6) is done in the (SCIER) state company for inspection and engineering rehabilitation in Iraq. The results are compared to American standard ASTM B-211, which are tabulated in Table I.

TABLE I: chemical analysis of AA6061-T6, wt%

Element wt%	Fe	Mn	Cr	Ti	Si	Cu	Zn	Si	Al
Experimental	0.46	0.12	0.17	0.1	0.57	0.28	0.18	0.6	Balance
Standard ASTM-211	0.4-0.8	Max. 0.15	0.04-0.35	Max. 0.15	0.4-0.8	0.15-0.4	Max. 0.25	0.4-0.8	Balance

III. Mechanical properties

Tensile test is carried out using tensile machine type (DWW 50). The specimens are fabricated according to (ASTM 370). The profile and dimensions of tensile specimen is illustrated in Figure 1.

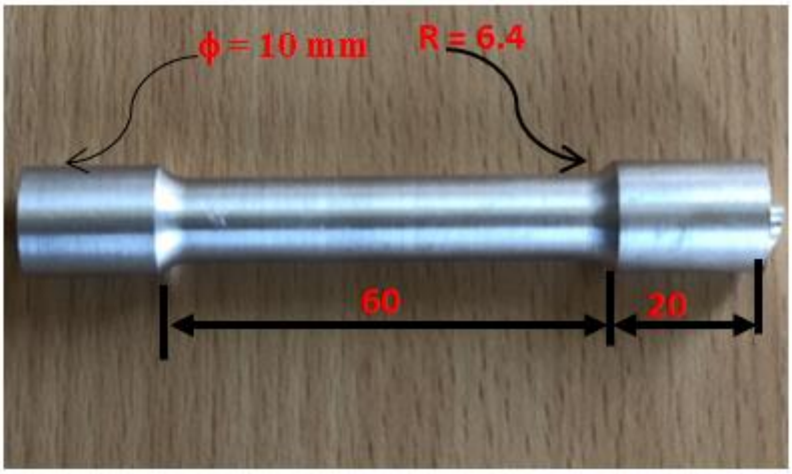

Figure 1: Tensile Specimen with Dimensions in (mm) according to ASTM370

The tensile test specimens (3 specimens) have been fixed in the tensile testing and the test have been done at room temperature (RT), and compared to the standard properties (tensile strength (UTS) yield strength (YS) ductility and modulus of elasticity E) have been obtained as shown in Table II.

TABLE II: Mechanical properties of AA6061-T6 at (RT) with standard

Properties	UTS (MPa)	Ys (MPa)	E (GPa)	Ductility
ASTM370	310	276	68.9	17
Experimental	322	265	71	16.6

IV. Rotating bending specimen

The samples of AA6061-T6 were cut from rod of 1 m in length and 12 mm in diameter. All samples were fabricated using programmable CNC machine using a suitable program then the samples were ground by means of abrasive paper followed by rotating disc cloth polishing. The test specimen is shown in Figure 2.

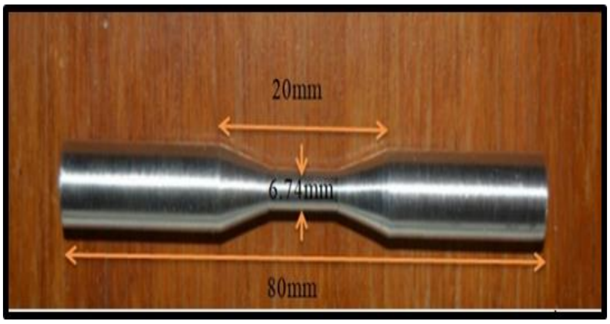

Figure 2: Rotating bending fatigue specimen

V. Fatigue testing machine

The fatigue tests were done using rotating bending fatigue test type SCHENC PUNN The sample was subjected to applied load developing a bending moment (M). Therefore the specimen surface is under tension and compression stresses when rotating the specimen. The bending stress as calculated from the relation below:

$$\sigma_{bending} = \frac{125.7 \times 32\, F\,(N)}{\pi\, d^3} \qquad (1)$$

Where 125.7 is the arm of the force (F) in (N) and d is the minimum diameter of fatigue specimen in (mm).

The fatigue test machine is equipped with a counter to record the cycles during testing. The machine stops arbitrary from rotating due to electrical circuit cut which is attached by a micro switch. Figure 3 shows the fatigue test machine.

VI. Corrosion test

The samples of tensile and fatigue were immersed in crude oil for (60) days and then applying tensile and fatigue tests after cleaning the samples from oil.

VII. Shot Peening process

The shot peening machine used was shot tumbles control model STB-OB No.a3008 05 type with ball steel of 2.75 mm diameter and 55HRC hardness. The time to be shotted was selected to 10 min. based on previous study [8]. The distance from specimen and nozzle was kept constant and of around 110m.

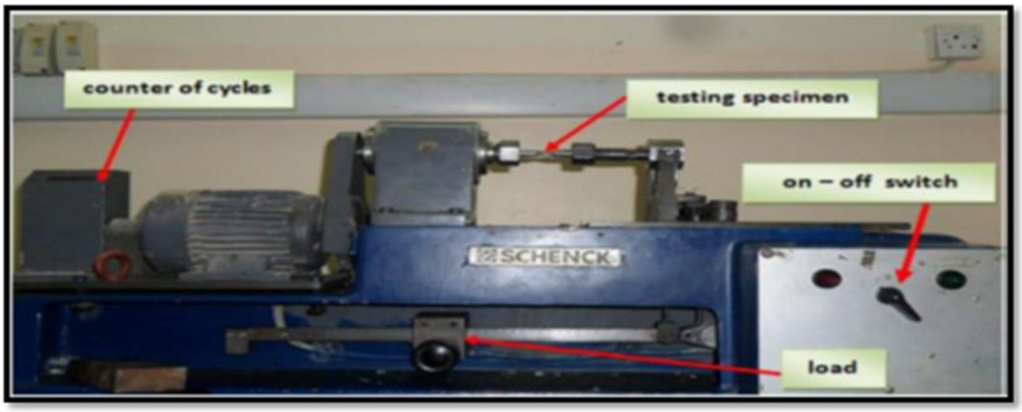

Figure 3: Fatigue rotating bending test machine type SCHENC

4. EXPERIMENTAL RESULTS AND DISCUSSION

I. Tensile test results

The mechanical properties results (UTS), (Ys), (E), and ductility for three cases obtained from stress-strain curves while the hardness was measured by BH technique for the samples of three cases i-e (as received (RT) oil corrosion and SP prior to corrosion). The results of the above three cases are summarized in Table III.

TABLE III: Mechanical properties and hardness AA6061-T6 at different cases of working conditions

Properties	UTS (MPa)	Ys (MPa)	E (Gpa)	Ductility	BH
Experimental (RT)	322	265	70	17	68
60 (days) oil corrosion	307	248	68	18.2	64
SP + corrosion	316	254	68.5	17.4	66

AA6061-T6 has less ductility (around 16%) and has high yield stress compared to AA6061-T4. The focusing on the aluminum alloy coming from the 6XXX series are Al-Mg-Si alloys that have extensive applications structural members, aerospace industry and light weight automotive bodies [9].

Results of Table III indicate that the UTS reduced by 4.6 % due to oil corrosion but this percentage is improved to 1.24% when applying the shot peening (SP).

The YS reduced from 265 MPa to 248 MPa at oil corrosion case and then raised to 254 MPa due to SP process showing 6 MPa stress resulting from compressive residual stresses at the surfaces. Figure 4 indicates the change in mechanical properties from RT to oil corrosion and SP + corrosion.

The mechanical properties of the samples tested in oil corrosion indicated that the corrosion reaction has occurred in these samples. The influence of shot peening on corrosion resistance is clearly illustrated in Figure 4 and the experimental results show an increase in UTS and YS after (SP) and the main reasons is coming from increase the surface hardening of surface layer induced compressive residual stresses lead to enhancement the mechanical properties.

It is clear that Figure 4, the AA6061-T6 showed discernible change in (UTS) and (YS) after SP for the samples subjected to oil . The tensile and yield stress increased from 307 to 316 MPa and from 248 to 254 for (UTS) and (YS) respectively.

It is established that the SP can produce high dislocation densities with attendant effects on mechanical properties [10]. Table III refers to an improvement in UTS and YS of AA6061-T6 due to treating the surface by shot peening. Figure 5 gives the BH value at three conditions of testing.

For AA6061-T6 at (RT), peak hardness of 68 was recorded, but the peak hardness was reduced to 64 when tested at oil corrosion and then raised to 66 when treated with SP prior to oil corrosion.

The reduction percentage in hardness was reported to be 2.85% due to 60 days oil corrosion but this percentage was reduced to 2.14%, due to compressive residual stresses created at specimen surface resulted from shot peening process. Paul [11] reported that shot surface are compressive residual stress and extremely high dislocation densities in layer near to surface leading to additional surface hardening. An enhancement of hardness in AA6061-T6 could be attributed to higher dislocation in density. The hardness of samples treated with SP prior to corrosion is greater than the samples treated with oil corrosion. The enhancement ratio is 3.12%. Finally, the hardness of

oil corrosion samples drops due to pitting corrosion and slightly raised for SP prior to corrosion samples as shown in Figure 5.

It is clear from Table III that the ductility of oil corroded samples is higher than that of samples tested at (RT). The higher ductility could be attributed to the fact that pitting corrosion reduced hardness and dislocation density resulted in raising the ductility.

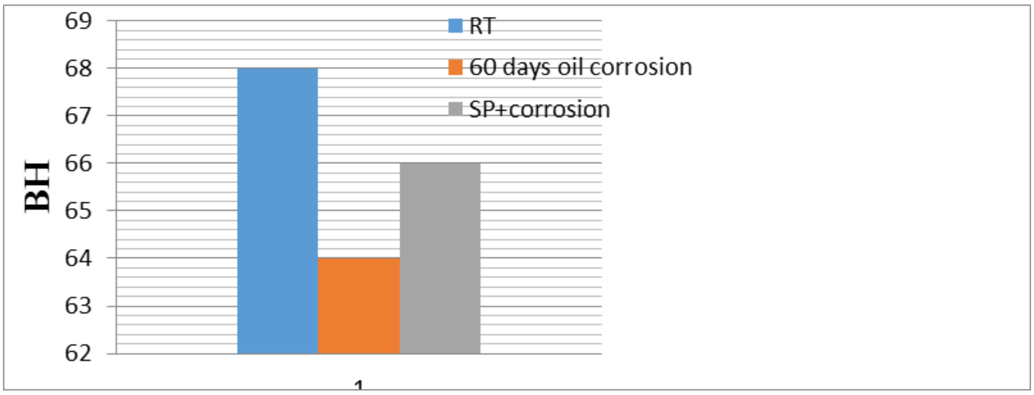

Figure 4: BH hardness values for three cases of testing

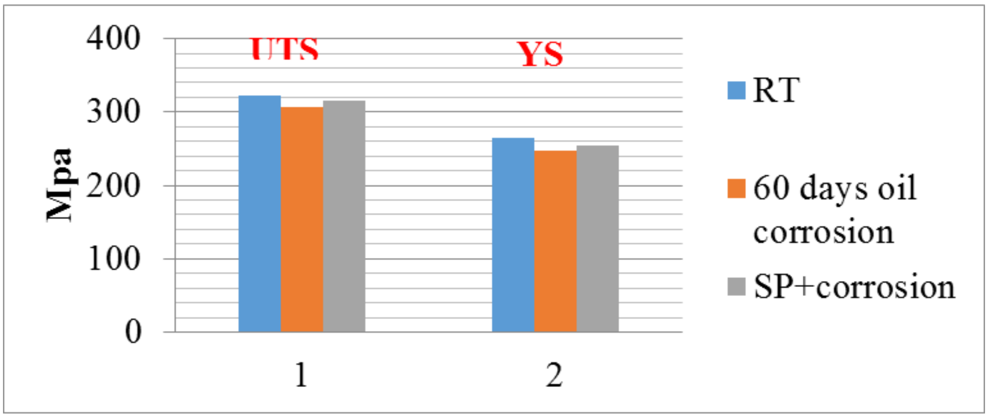

Figure 5: BH hardness values for three cases of testing

II. Constant fatigue behavior

The fatigue tests were performed using fatigue testing machine type (PUNN rotating bending) with stress ratio R = -1 and 25 Co room temperature (RT). The results are tabulated in Table IV. Table IV gives the constant S-N curves fatigue results.

TABLE IV: S-N curve Fatigue results at (RT), 60 days of oil corrosion, SP prior to corrosion

Condition	Specimen No.	Applied stress (MPa)	N_f (cycles)	N_f average	R^2	S-N curve equation
RT	1,2,3	221	20000,26000,18000	21333	0.9996	$\sigma_f = 1930Nf^{-0.217}$
	4,5,6	190	33000,41000,56000	43333		
	7,8,9	158	92000,111000,87000	96666		
	10,11,12	126	28000,301600,268000	28606		
60 days oil corrosion	13,14,15	221	1160,16000,12800	13467	0.99	$\sigma_f = 1648Nf^{-0.208}$
	16,17,18	190	26600,21800,24600	24333		
	19,20,21	158	82000,72800,80800	78533		
	22,23,24	126	210600,198000,186200	198267		
SP prior to corrosion	25,26,27	221	17600,16000,19600	17733	0.9912	$\sigma_f = 1479Nf^{-0.19}$
	28,29,30	190	29600,24000,30800	28133		
	31,32,33	158	84600,90000,81800	28133		
	34,35,36,	126	230000,241800,237000	236266		

The fatigue tests were carried out for three cases mentioned before and for each stress level there are three specimens were examined with different applied stress based on the results of mechanical properties (UTS). The applied stresses were selected to be 0.7 UTS, 0.6 UTS, 0.5 UTS and 0.4 UTS. The results have been graphically displayed in the form of S-N curve. This curve is obtained by curve fitting, the experimental data in the above table. The power law regression is given by [12].

$$\sigma_f = AN_f^{\alpha} \qquad (2)$$

Where σf is applied stress amplitude (MPa), Nf is the number of cycles to failure. A and α are the fitting parameters (material constant). The correlation parameter (R2) which is given in above table indicated that the experimental data are explained well or not by power law formula. R2 is a band measure of the goodness of fit.

It is clear that shot peening significantly increased the rotating fatigue strength (σE.L) from 57.67 MPa to 69 MPa resulting in a factor of 1.19. Shot peening is a cheapest and available method to improve the corrosion-fatigue strength and life at low service loads.

The beneficial effect of (SP) in enhancing the corrosion – fatigue life was clearly evident in both (UTS) and (YS) applied loads. (SP) localized plastic flow causing work hardening, general roughening and generation of compressive residual stresses. All these effects are expected to influence the mechanical properties hardness, and fatigue properties

III. Fatigue analysis

The low and high cycle fatigue studies are performed by taking a stress ratio ® of (-1). Table IV present the fatigue cycle to failure for (RT) , 60 days oil corrosion and SP prior to corrosion while Figure 6 describe the applied alternating stress verses the number of cycles to failure for the above three cases.

The fatigue strength at 107 cycles (fatigue endurance limit σE.L) is found to be 58.4, 57.67, and 69 MPa for (RT), 60 days oil corrosion and SP prior to corrosion respectfully. From the results presented in Table IV and Figure 6, it is seen that there is a significant improvement in fatigue strength. In case of 60 days oil corrosion fatigue strength reduced from 58.4 to 57.67 MPa exhibiting 1.25% reduction while this percentage improved to 1.64% due to SP prior to corrosion. The fatigue life for the cases can be obtained from the experimental S-N curve equations and alternating stress of (UTS) and (YS) as seen in Table V.

Corrosion – fatigue is one of the most important aspects of aircraft structure design [12]. In particular, developing and verifying a method for predicting corrosion – fatigue life of typical structures is importance. The corrosion – fatigue life and strength can be enhanced by the use of controlled cold working methods. SP is one such process which induces residual compressive stresses (RCS). The RCS reduce the tensile mean stress due to the aplied loads and manufacturing thereby it incresae the fatigue strength and life.

It is clear that SP process improves the fatigue life from 2565 to 3053 cycles after SP prior to corrosion under (UTS) applied load and from 6545 to 8514 under (YS) applied load. The improvement factor was 1.19 and 1.13 in the ondition of (UTS) and (YS) applied load respecrively.

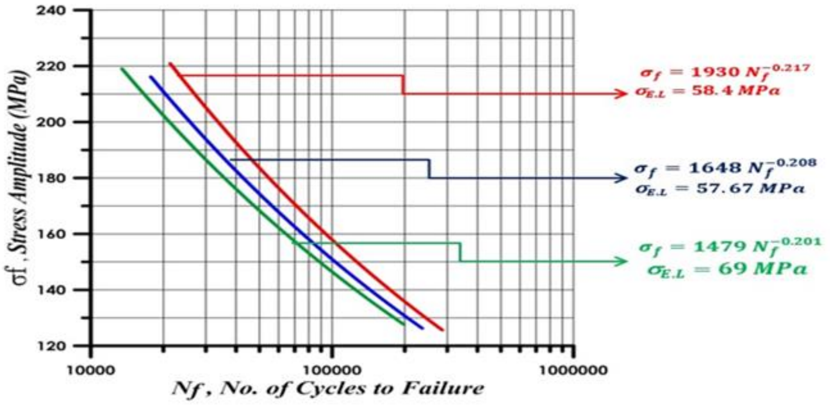

Figure 6: S-N curves for three different conditions of testing

TABLE V: Fatigue life predication at (UTS) and (YS)

Conditions	S-N curve equation	Fatigue life at (UTS)=322 MPa	Fatigue life at (Ys)=256 MPa
RT	$\sigma_f = 1930 Nf^{-0.217}$	3836	9414
60 days oil corrosion	$\sigma_f = 1648 Nf^{-0.208}$	2565	6545
SP prior to corrosion	$\sigma_f = 1479 Nf^{-0.19}$	3053	8514

5. Conclusions

Based on the experimntal results of corrosion fatigue and shot peening process given in this study, the following preliminary conclusions coud be drawn.

1. Shot peening method can be used as one of the cheapest and best techniques to enhance the mechanical properties and corrosion.
2. Shot peening improved corrosion-fatigue resistance due to produceing compressive residual stress at surface layer.
3. Ultimate tensile strength (UTS) and yield stress (YS) have been reduced by 4.6% and 6.4% when immersing the tensile samples in croud oil for 6 days and then these values were reduced to 2.84% and 2.36% due to applying shot peening.
4. Oil corrosion hardness samples droped from 68 to 64 and slighitly raised when applying shot peening process.
5. Fatigue strength (σE.L) reduced due to oil corrosion from 58.4 MPa tu 57.67 MPa and fatigue life reduced from 3836 cycles to 2565 cycles and from 9414 to 6545 cycles at (UTS) and (YS) applied load resprctively.
6. Shotpeening process signifcantly improved the rotating fatigue strength by a factor of 1.199 and fatigue life by 1.19 at (UTS) applied load also it enhanced the fatigue life of (YS) applied load by a factor of 1.3.

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