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Ultrasonic impact peening technique for improvement the constant amplitude corrosion-fatigue interaction

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Abstract
The fatigue behavior of 6061-T6 aluminum alloy under constant amplitude loading was investigated in air for as-received and pre-corroded specimens in 3.5% NaCl corrosive solution for 77 days. Constant corrosion-fatigue tests have been done with and without ultrasonic peening treatment under rotating bending load at stress ratio (R= -1) and room temperature (RT= 25 °C). The experimental results presented that the tests of fatigue life on pre-corroded specimens with and without ultrasonic peening revealed a significant reduction in life related with the presence of corrosion defects before cyclic loading. In state of unpeened specimens the constant S-N fatigue strength curve was decreased by 4.5% due to immersed the specimens in corrosive 3.5% NaCl solution for 77 days, while in state of ultrasonically peened specimens the reduction of S-N curve decreased to 2.2% due to the beneficial effect of this treatment for increasing the corrosion-fatigue life. The improvement of fatigue life and corrosion-fatigue life of specimens when applying of ultrasonic peening treatment was 8.69% and 2.3% respectively.

Keywords: Corrosion-Fatigue; 6061-T6 Aluminum alloy; Ultrasonic peening treatment; Aluminum alloy.

1. Introduction

The process by which fracture occurs prematurely under conditions of simultaneous corrosion and repeated cyclic loading at lower stress levels or fewer cycles than would be required in the absence of the corrosive environment known as corrosion-fatigue [1]. Nowadays aluminum alloys represent an important material category because their good weight/strength ratio and high corrosion resistance. Wrought Al alloys in particular have been widely used in the automotive, marine, aircraft, and construction industries. However, despite the general high corrosion resistance of aluminum alloys in chloride environment localized corrosion often occur. In this aspect, additional surface treatment and protection is necessary to prolong the work life of machine parts. In recent years, ultrasonic impact treatment has been attracted global interest due to its ability to improve both mechanical properties and corrosion resistance [2]. The ultrasonic peening (UP) is one of the new and promising methods for improvement of fatigue life of materials, structures and alloys. During the different stages of its development the UP methode was also known as ultrasonic treatment (UT), ultrasonic impact peening (UIP), and ultrasonic impact treatment (UIT). The beneficial effect of UP is achieved mainly by eliminating of harmful tensile residual stress and introducing of compressive residual stress into surface layers of material, decreasing of stress concentration in weld toe zones and enhancement of mechanical properties of surface layers of material [3]. Daavari and Sadough

[4] investigated the influence of UIT on behavior of corrosion fatigue of welded steel pipes. The tensile residual stresses caused by different manufacturing methods that were the main reason of reducing the structures lives under conditions of cyclic loading and corrosive environment. The application of UIT was one of influential and promising processes for developing the fatigue performance of materials. Furthermore, it had some positive action on the corrosion resistance of metals, which was included: closing of surface crack, introducing of compressive residual stresses, enhancement of corrosion resistance due to reducing of residual stresses. Alalkawi et al. [5] studied the effect of UP technique has been used as surface treatment of 2017A-T3 Al-alloy to improve the mechanical properties and fatigue life. The mechanical properties and constant fatigue test have been performed at the room temperature and stress ratio (R= -1). Three kinds of surface treatment UP were accomplished, one line 1UP, two lines 2UP, three lines 3UP at the specimen surface. The results showed that the all three kinds of UP developed the mechanical properties but by different rate. The best improvement was achieved from the 1UP. The increase rate of mechanical properties reduces progressively as the number of peening line increase. Fatigue strength was enhanced through ultrasonic peening, an increase of 61% for 1UP, 53% for 2UP, and 47% for 3UP. Gou et al. [6] applied the UIT to control on the residual stress of 6005-T6 aluminum alloy of welded joints. The results of experimental tests concluded that the UIT could produce compressive transverse and longitudinal residual stress in the welded joints, increase the tensile strength and harden the surface. The tests of corrosion (salt water of 5wt. %NaCl at 35 °C) were done for both an as-welded sample and an ultrasonically treated sample. The treated sample has lower tensile residual stress and higher strength in comparison with untreated sample during corrosion test. So, UIT was an effective process to develop the stress corrosion cracking resistance of welded joints of 6005-T6 aluminum alloy due to stress corrosion cracking was one of the major problems for welded joint of the mentioned alloy.

2. Experimental work

This work starts firstly by analysis the chemical composition of the selected material (6061-T6 Aluminum alloy) and then tensile test is done at room temperature to determine the mechanical properties. Secondly, aqueous solution of (3.5wt % NaCl in tap water) is used for corroding the aluminum alloy. Thirdly, the aluminum alloy is subjected to the corroded media to determining the influence of this corroded media on the fatigue strength and fatigue life under constant amplitude loading. Finally, to find how the ultrasonic peening technique improves the behavior of fatigue and corrosion-fatigue life of this alloy as mentioned above.

2.1 Material

The material included in this study is an aluminum alloy 6061-T6 and was received as rod of 19 mm diameter. This alloy has good formability, weldability, corrosion resistance. Good general purpose alloy used for a wide range of structural applications and welded assemblies including truck components, railroad cars, pipelines, marine applications, agricultural applications, aircrafts, architectural applications, automotive parts, building products, chemical equipment, electrical and electronic applications, fan blades, general sheet metal, hospital and medical equipment, machine parts and storage tanks [7]. Chemical analysis of this alloy (6061-T6 Al alloy) is done at (Iraq Geological survey, Ministry of Industry and Mineral, Baghdad, Iraq). The results are compared with American standard ASTM B-211 [8], which are listed in Table 1 below. The experimental mechanical properties results are also compared with standard that are presented in Table 2.

Table 1. Standard and experimental chemical composition of 6061-T6 Al alloy in wt.

Alloying element %	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Standard ASTM B-211	0.4-0.8	Max.0.7	0.15-0.4	Max.0.15	0.8-1.2	0.04-0.35	Max.0.25	Max.0.15	Bal.
Experimental	0.55	0.36	0.26	0.11	1.07	0.12	0.19	0.09	Bal.

Table 2. Standard and experimental mechanical properties of 6061-T6Al alloy.

Property	Ultimate tensile strength σ_u (MPa)	Yield strength σ_y (MPa)	Elongation %	Modulus of elasticity GPa
Standard ASTM B-211	310	276	17	68.9
Experimental	316	268	16.5	70

2.2 Tensile test

This test is performed at room temperature by using tensile test rig type (WDW-50) as presented in Figure 1 at the (Materials Engineering Department, University of Technology, Baghdad, Iraq) to get of the mechanical properties as mentioned before of selected material (6061-T6 Al alloy).

The specimen of tensile test is fabricated in a round cross section with the required dimensions according to the standard ASTM (A370-11) as illustrated in Figure 2.

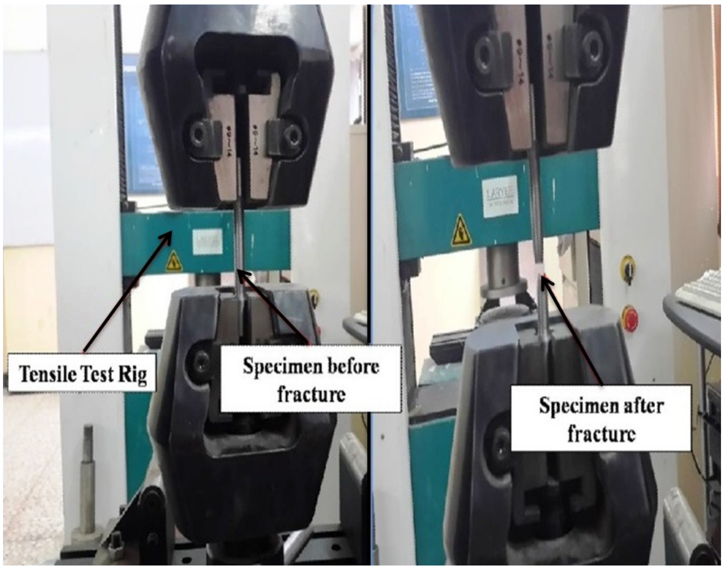

Figure 1. Tensile test machine WDW-50.

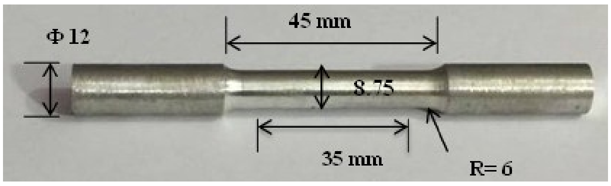

Figure 2. Dimensions of tensile test specimen in (mm) according to ASTM (A370-11).

2.3 Roughness test

After preparing the specimens, roughness test is accomplished at (Production and Metals Engineering Department, University of Technology, Baghdad, Iraq) by (Pocket surf Mahr Device), as shown in Figure 3. The results are tabulated in Table 3 for ten selected specimens.

2.4 Fatigue test

This test is done in (Department of Electromechanical Engineering, University of Technology, Baghdad, Iraq) by using fatigue machine of rotating bending of type (SCHENCK PUNN) as shown in Figure 4 to test specimens of (6061-T6 Al alloy) under different stresses. Shape and dimensions of fatigue specimen are manufactured according to standard specification of (DIN 50113) as illustrated in Figure 5.

Figure 3. Roughness surface apparatus test.

Table 3. Surface roughness results for ten selected specimens of aluminum alloy (6061-T6).

Spec. No.	Min. diam. (mm)	Average roughness Ra (μm)	Peak roughness Rt (μm)
1	6.70	0.92	1.25
2	6.69	0.85	1.71
3	6.65	0.77	1.82
4	6.70	1.07	2.08
5	6.73	1.09	1.92
6	6.72	0.88	1.72
7	6.70	0.79	1.45
8	6.65	0.82	1.90
9	6.75	0.97	2.17
10	6.71	1.1	2.51

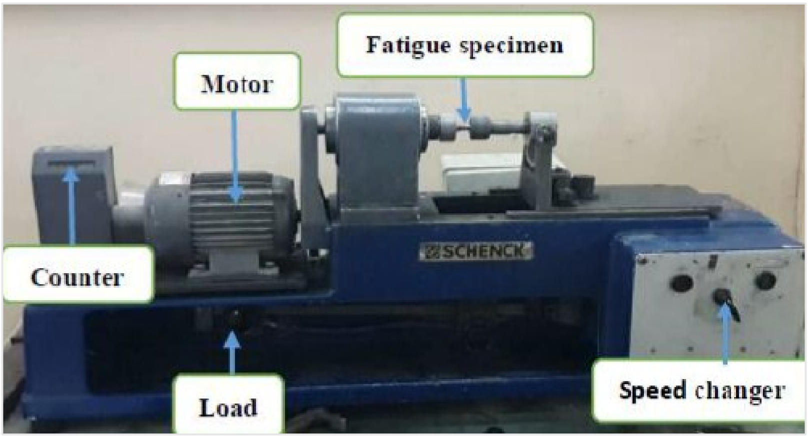

Figure 4. Fatigue rotating bending machine (PUNN SCHENCK).

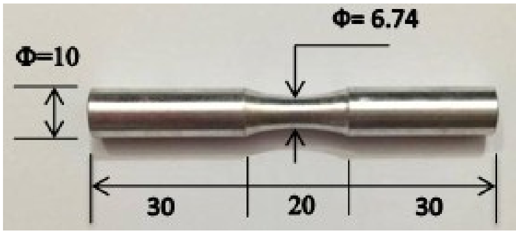

Figure 5. Dimensions of fatigue test specimen in (mm) according to standard specification of (DIN 50113).

2.5 Ultrasonic peening (UP) process

Ultrasonic peening device introduces the ultrasound energy into metal through surface impulse contact. This energy is introduced into the metal by converting the harmonic, resonant oscillation of an acoustically tuned body to mechanical impulses on a surface. The main technical parameters of UP device are given below [9]:

Brand Name: HC, mode Number: HC-S-1
Frequency: 20KHZ, Voltage: 220v, power: 500w
Type: portable
Length of gun: 450mm and weight of gun: 4 kg
System weight: 15kg
Shape of gun: The impact of the needle or impact rod
The size of generator: 195*270*430 mm and the weight of generator: 8 Kg
Working mode: impact the surface
Applicable materials: Aluminum alloy, low carbon steel, high strength steel, etc.
The ultrasonic impact treatment is done at (Electromechanical Engineering Department, University of Technology, Baghdad, Iraq) by using ultrasonic device, as presented in Figure 6.

Example of the fatigue specimens with and without ultrasonic peening after fatigue testing illustrated in Figures 7 and 8.

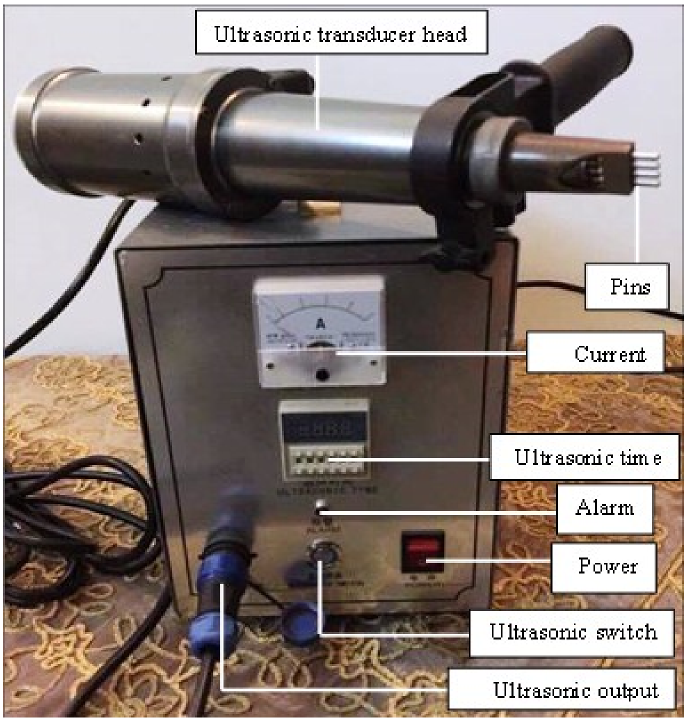

Figure 6. Ultrasonic peening device type (HC-S-1).

Figure 7. Fatigue specimens with UP after fatigue failure.

Figure 8. Fatigue specimens without UP after fatigue failure.

2.6 Corrosion test

The specimens were immersed in aqueous solution of 3.5% NaCl (mixture of tap water and sodium chloride NaCl salt) for 77 days and then applying constant fatigue test after removing the specimens from the saline solution. Figure 9 shows example of fatigue specimens submerged in corrosive NaCl aqueous solution.

Figure 9. Example of fatigue specimens submerged in corrosive NaCl aqueous solution.

3. Experimental results and discussion

The first series of constant amplitude fatigue tests was carried out for 24 specimens (dry fatigue) used eight stress levels (80,100,120,140,160,180,200 and 220 MPa) and 15 specimens for (corrosion-fatigue) used five stress levels (80,120,160,200 and 240 MPa), when these specimens were submerged in saline solution of 3.5% NaCl for 77 days. The second series of tests was done for one line of ultrasonic peening using 24 specimens (dry fatigue) and 15 specimens (corrosion-fatigue). This series used the same conditions and stress levels of the first series. The results of these two series are presented in Table 4 including the number of specimens, applied stresses (MPa), the number of cycles to failure of the specimens (N_f) achieved from the test and their average (N_f av).

The Basquin law may be used to express the relationship between the fatigue strength and fatigue life of the material. This law can be expressed by the following equation [10].

$$\sigma_f = AN_f^{\alpha} \tag{1}$$

where (σ_f) is the cyclic stress amplitude at failure, (N_f) is the number of cycles to failure and (A), (α) are material constants which are the fitting parameters. The above data are plotted according to Basquin equation in Figure 10 which illustrates the fatigue life behavior. From the results of Table 5, it is shown that the fatigue life of metal used is sensitive to the corrosive media. In addition, the material had the longest fatigue life in air but the lowest in salt water. However, as the applied stress increases, the corrosive environments become less influence on the fatigue life of material. When the number of cycles increase, the corrosive environment become more effective on the fatigue strength.

(R^2) known as the correlation factor, which is used to confirm if the experimental data are well described by power formula. The value of (R^2) in the Figure 10 is calculated by equations that are presented in Ref [11]. As (R2) is closer to unity, the relationship between stress at failure (σ_f) and average number of cycles to failure (N_f av.) is stronger. Figure 10 shows the S-N curves for four conditions included dry and pre-corroded fatigue specimens for 77 days with and without one line ultrasonic peening. As shown in the Figure 1 the behavior of fatigue life of pre-corroded specimens without ultrasonic peening reduced down and of pre-corroded specimens with prior ultrasonic peening decreased slightly as compared with specimens tested in dry condition.

Table 5 presented that the fatigue strength of pre-corroded specimens for 77 days in salt solution was (44 MPa) showing (4.5%) decreased and that of pre-corroded specimens of 77 days with prior one line of UP was (45 MPa) showing (2.2%) decreased as compared with the fatigue strength of dry specimens which was (46 MPa). an approximately (60%) decrease in fatigue strength of 7075-T6 Al-alloy was determined by Genel [12] when he used the same conditions of the present work, but the corrosive time was 3 years.

Also The fatigue strength of dry fatigue specimens with one line UP was (50 MPa) showing (8.69%) improvement as compared with that of dry fatigue specimens without UP, while the fatigue strength of pre-corroded specimens for 77 days with one line UP was (45 MPa) showing (2.3%) improvement as compared with that of pre-corroded specimens without UP, as illustrated in table (6). This conclusion is agreed well with what Alalkawi et al. [5] concluded. They studied the effect of three type of ultrasonic peening i.e. one line, two lines and three lines surface modification on the mechanical and fatigue properties of (2017-T3 Al-alloy). The experimental results exhibited that the best type of ultrasonic peening was the one line, which gave an improvement about 61% for 1UP, 53% for 2UP and 47% for 3UP as compared to endurance fatigue limit of untreated specimens.

Table 4. Constant fatigue results for four conditions of testing with and without UP.

Specimen No.	Applied stress (MPa)	N_f Cycles	N_f av.
Dry fatigue condition			
1,2,3	80	810600,902000,929000	880533
4,5,6	100	510800, 525600,534000	523467
7,8,9	120	298000,307000,313000	306000
10,11,12	140	239000,244000,281000	254666
13,14,15	160	84000,92000,107000	94333
16,17,18	180	65000,77000,88000	74667
19,20,21	200	40000,45000,52000	45666
22,23,24	220	18000,22600,25000	21867
Corrosion-fatigue condition for 77 days			
25,26,27	80	600300,686000,643200	643167
28,29,30	120	206000,218000,212800	212266
31,32,33	160	70600,82000,76600	76400
34,35,36	200	36500,33000,40000	36500
37,38,39	240	6800,8000,7600	7467
Dry fatigue with prior one line UP			
40,41,42	80	994600,1080000,1182000	1085533
43,44,45	100	729000,668000,820000	739000
46,47,48	120	394000,417000,428600	413200
49,50,51	140	254800,270900,282000	269233
52,53,54	160	88000,94000,104000	95333
55,56,57	180	72000,81000,96000	83000
58,59,60	200	56000,60800,66000	60933
61,62,63	220	31600,28000,21600	27067
Corrosion-fatigue condition for 77 days with prior one line UP			
64,65,66	80	727600,752000,739200	739600
67,68,69	120	244000,235000,238800	239267
70,71,72	160	85600,78000,82000	81867
73,74,75	200	42600,48800,46000	45800
76,77,78	240	7800,10600,9800	9400

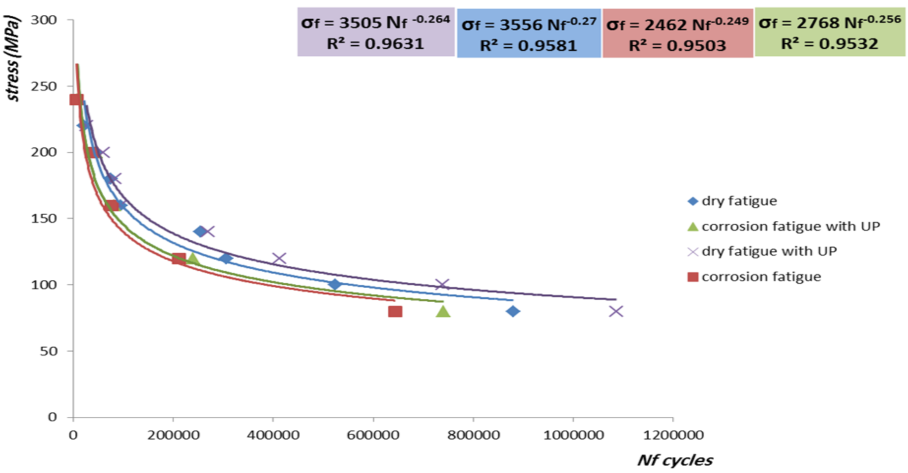

Figure 10. Experimental S-N curves of constant amplitude for four conditions.

Table 5. Fatigue endurance limit at 10^7 cycles and reduction factor.

Condition	Basquin equation	Endurance limit at 10^7 cycles	Reduction factor
Dry fatigue	$\sigma_f = 3556\ N_f^{-0.27}$	46 MPa	
Corrosion fatigue without UP	$\sigma_f = 2462 N_f^{-0.249}$	44 MPa	4.5%
Corrosion fatigue with UP	$\sigma_f = 2768\ N_f^{-0.256}$	45 MPa	2.2%

Table 6. Fatigue endurance limit at 10^7 cycles and improvement factor.

Condition	Basquin equation	Endurance limit at 10^7 cycles	Improvement factor
Dry fatigue with UP	$\sigma_f = 3505\ N_f^{-0.264}$	50	8.69%
Dry fatigue	$\sigma_f = 3556\ N_f^{-0.27}$	46	
Corrosion fatigue with UP	$\sigma_f = 2768\ N_f^{-0.256}$	45	2.3%
Corrosion fatigue without UP	$\sigma_f = 2462\ N_f^{-0.249}$	44	

4. Conclusions

From the present work, the effect of corrosive environment and ultrasonic peening on the fatigue life of aluminum alloy (6061-T6) are investigated under stress ratio (R= -1). The following remarks can be derived:

1. Constant fatigue life was reduced under corrosion media and the fatigue strength decreased by a factor of about 4.5%.
2. Fatigue strength of pre-corroded specimens with prior ultrasonic peening decreased slightly by a factor of approximately 2%.
3. The improvement percentage of fatigue strength by ultrasonic peening was approximately (9) for dry condition while it was (2) for 77 days corrosion in 3.5% NaCl solution.

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