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Investigation the Creep-Fatigue Behavior and A.C. Electrical Conductivity of AA 6061 Under Ultrasonic Peening

Abstract- *Ultrasonic peening is an innovative surface improvement process used to increase the resistance of aircraft metals and enhance high cycle fatigue life. The process creates residual compressive stresses deep into part surfaces. These compressive surface stresses inhibit the initiation and propagation of fatigue cracks. Aluminum alloys are relatively new materials used in aerospace, marine, automobile, and bridges due to low weight, which has significant advantages compared to the other materials. A major concern in the design of Aluminum alloys subjected to variable loads is fatigue strength and life. In this paper mechanical properties, fatigue strength, fatigue life and A.C.. electrical conductivity were studied for AA6061-T6 to assess the effects of ultrasonic peening (UP) on mechanical properties, fatigue at room temperature (RT), creep-fatigue (CF) at 250°C and A.C.. electrical conductivity. Test results showed that after UP, the mechanical properties; ultimate tensile strength (UTS) and yield stress (Ys) were noticeably improved. The improvements in UTS and Ys were enhanced by 5.7% and 1.5% respectively while the ductility was reduced from 16.5% to 15.7%. Fatigue strength was enhanced by 8.37% compared to strength at RT. The results of UT before creep-fatigue CF showed increasing in fatigue strength 147 MPa at CF 250 °C and improved to153 MPa after applying UP, indicating 4% improvement in strength. The fatigue life was improved after UP for both RT and CF. It was found that the A.C. electrical conductivity increase as the frequency increase for all the cases above.*

Keywords- *Creep-Fatigue, Aluminum Alloy, Ultrasonic Peening, Electrical conductivity.*

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1. Introduction

Aluminum and its alloys widely employed as materials in transportation (marine, automobile) engine components, structural applications and aerospace [1]. Fatigue properties have been investigated on several pure metals and alloys in the Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF) regions. Fatigue behavior is often characterized by a curve that describes the applied stress, stress at failure (σ_f), versus number of cycles to failure (N_f). This curve is typically presented in log-log coordinates or semi-log. Also is known to have two distinct regions; region (I) corresponds to LCF (up to 10^4 cycles), and region (II) is the HCF (10^5 - 10^7 cycles) and often expressed in the power law formula which describes the fatigue behavior, and it is correlation factor (R^2) [2]. Studies of the electrical properties of Aluminum and its alloys have increased importance because of its applications in electrical and electronics engineering [3]. Ramos et al. [4] investigated the effect of Ultrasonic Treatment (UT) and Shoot Peening (SP) on the fatigue behavior of the 7475-T351 aluminum alloy. It was found that the fatigue life of (HCF region) improved and the fatigue strength enhanced by 35% compared to the base metal.

Alalkawi et al. [5] studied the influence of (UT) on dry fatigue and fatigue–corrosion life AA6061-T6 under controlled stress (R= -1) and room temperature (RT). They concluded that the fatigue of dry specimens was improved by 8.69%, and for corrosion–fatigue was 2.3% when applying Ultrasonic Treatment (UT).

Shaker et al. [6] studied the influence of ultrasonic treatment (UT) for fatigue life improvement of sheet specimens 6061-T6 aluminum alloy. They concluded that the fatigue life and strength enhanced by using (UP) due to the surface hardening. This enhancement can be denoted as a safety factor that reaches to 1.42 when using this treatment (UT).

Daavari et al. [7] investigated the effect of ultrasonic impact treatment (UIP) of welded steel pipe (A106-B) in order to enhance the corrosion fatigue when these pipes work under corrosive environment and cyclic loading. They concluded that corrosive fatigue life increased by increasing the hardness of the surface due to increasing the

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density and reducing the possibility of cracking when the weld toe angle and radius are modified. The corrosion resistance has improved due to the reduction of tensile residual stresses.

Dong [8] studied the effect of creep-fatigue interaction CFI on a TiAl alloy at 750 ℃ and 800℃ in the air to explore the effect of dwell time on fatigue life. They concluded that fatigue life decreased with increasing minimum strain rate and decreased when time increasing dwell. Two life models were proposed to predict LCF, creep, and CFI life based on dwell time and minimum strain rate. The predicted life of both models agreed very well with the experimental life of the alloy at high temperatures.

Sabah [9] studied the influence of aluminum oxide nanoparticles on dielectric properties of polyvinyl alcohol (PVA) nanocomposites. The results exposed that the dielectric properties (dielectric loss, dielectric constant and A.C electrical conductivity) of PVA raised by increasing the concentrations of nanoparticles. The dielectric characteristics are varied with increasing frequency used in the electrical area.

Basher et al. [10] synthesized polypyrrole PPY-Fe_2O_3 nanocomposites using the in-situ chemical oxidative polymerization technique the amount of filler was taken to be 10-50wt% of PPY. The electrical conductivity of the specimens was done using the vibrating sample magnetometer (VSM) and two probe methods. It’s found that the electrical conductivity increased up to 20% of filler then decreased with increasing the amount of filler.

The A.C. electrical conductivity $\sigma_{a.c}(\omega)$ can be calculated from the empirical formula $\boldsymbol{\sigma_{a.c}}\,(\boldsymbol{\omega}) = \boldsymbol{A}\,\boldsymbol{\omega^{S}}$, where ω is the angular frequency, $\boldsymbol{A}$ is material constants and $\boldsymbol{s}$ the frequency exponent.

Abdallah et al. [11] electrically tested metal fiber polyester composite, and they found the AC electrical conductivity ($\boldsymbol{\sigma_{a.c}}$) increased with increasing the frequency and the exponent (s) decreased when increasing the frequency.

The aim of this work is to determine the effect of ultrasonic treatment (UT) on mechanical, fatigue at RT, creep-fatigue properties, and A.C. electrical conductivity of AA6061-T6 and to compare between the above cases.

2. Experimental Work

Alloy AA6061-T6 is the material used in this paper. This alloy has good characteristics such as weldability, formability and corrosion resistance. The alloy used for a wide range of welded assemblies and structural applications including railroad cars, truck components, marine applications, pipelines, aircrafts, automotive parts, architectural applications, building products, chemical equipment, electrical and electronics applications, fan blades, all-purpose sheet metal, medical equipment, machine parts and storage tanks [12]. This research starts firstly by analysis the chemical composition of the Aluminum alloy (AA6061-T6), and the results are compared with American standard ASTM B-211, and illustrated in Table 1.

I. Tensile Properties

The tensile mechanical properties were obtained from the stress-strain curves done using the tensile test machine (WDW-50), and the details of the tensile specimen is formed in dimensions according to the standard ASTM (A370-11) as shown in Figure 1.

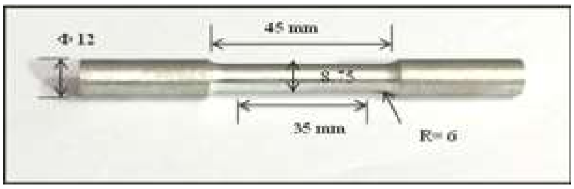


Figure 1: Dimensions of tensile specimen in (mm) according to ASTM (A370-11).

II. Fatigue Testing

A fatigue is a failure of material or process due to the action of repeated or fluctuated stress for some number of cycles. Fatigue failure gives no visible warning and it has suddenly happened and dangerous. Machine parts are found to have failed under the action of repeated or fluctuating stress. Careful analysis reveals that the actual maximum stresses were below the ultimate strength of the material and quite frequently even below the yield strength. Hence, the failure due to these stresses is called (fatigue failure) [13]. Fatigue tests were achieved in (Department of Electromechanical Engineering, University of Technology, Baghdad, Iraq) by using fatigue testing machine of rotating bending type (SCHENCK PUNN rotating bending) as shown in Figure 2.

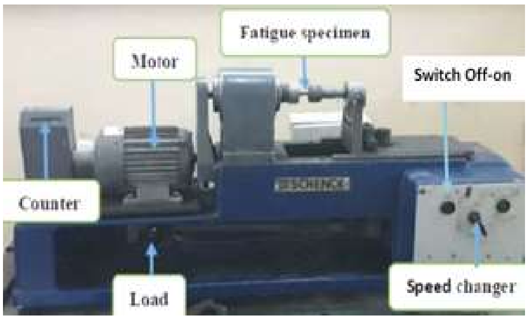


Figure 2: Fatigue rotating bending machine (SCHENCK PUNN).

Table 1: Chemical analysis of AA6061-T6.

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.

III. Fatigue Specimen Preparation

Preparing the fatigue specimens from rod of 14 mm diameter and 1 meter in length. The fatigue specimens are manufactured by using modern CNC lathing machines related to standard specification of (DIN 50113) as illustrated in Figure 3.

IV. Creep–Fatigue Interaction (CF at 250℃

Creep and fatigue are complex mechanisms that include various types of decetructive processes. Creep produces intergranular cavitation harm, while fatigue helps to propagate cracks through transgranular paths with surface striations and wide surface cracks. Hales [14] has a pertinent work on mapping this interaction and reviewed by Yan lately et al. [15]. The precise estimation of creep-fatigue interaction is a severe matter for industrial parts working with considerable cyclic thermal and mechanical loads. In order to achieve creep-fatigue results, a small furnace was attached to the fatigue-testing machine with a digital thermal control unit board. An electrical heater of (2000W) was fixed inside the furnace with a K-type thermocouple to control the heating temperature inside the furnace [16]. The furnace fixed on the testing machine with a control board is shown in Figure 4.

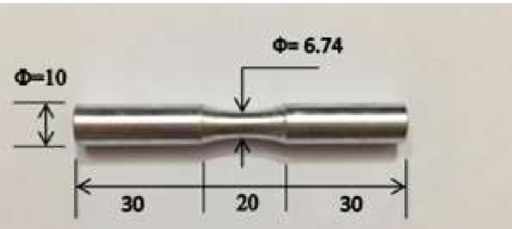


Figure 3: Fatigue test specimen in (mm) according to standard specification of (DIN 50113)

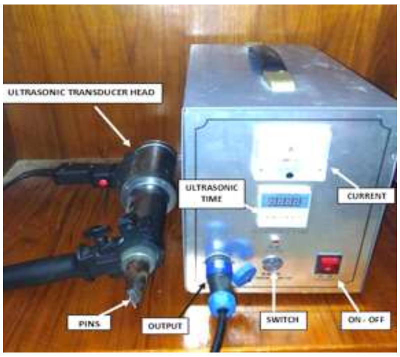


Figure 4: SCHENCK PUNN rotary bending fatigue - creep machine

V. Ultrasonic Peening (UP)

The ultrasonic peening (UP) is almost a new technique used to enhance the fatigue life of material, structure, and alloy. The UP technique sometimes called ultrasonic impact treatment (UIT), ultrasonic treatment (UT), and ultrasonic impact peening (UIP). The beneficial influence of UP is carried out mainly by enhancement of the mechanical properties of surface layers of materials. The UP is the most efficient enhancement treatment when compared with other technologies like laser peening (LP), hammer peening (HP), heat treatment (HT) and shot peening (SP). The UP device transfers the ultrasound energy into metal by the surface impulse contact. Transferring the energy into the metal by converting the harmonic, resonant oscillation of an acoustically tuned body to mechanical impulses on a surface. The technical features of the UP device can be seen in reference [17]. The main items and details of the UP device are shown in Figure 5.

Figure 5: UP Device type (HC-S-1).

3. Results and Discussion

I. Tensile Results

The mechanical properties tests of AA6061-T6 were done at four conditions; room temperature (RT), ultrasonic peening (UP), creep-fatigue interaction (CF) at (250 ℃) with and without UP given in Table 2. The above data are obtained from the experimental stress-strain tests of AA6061-T6 at RT, Ultrasonic peening (UT), creep-fatigue (CF) interaction 250 ℃ and CF treated with UP. Since the results are drawing, as shown in Figure 6. It has observed from Table 2 and Figure 6, the modulus of elasticity (E) decreases slightly for CF and (CF+UP) testing compared to RT testing. The percentage of reduction is 2.4% and 1.4 % for CF and (CF+UP), respectively.

However, the value of E increased by 0.7% for UP compared with the RT case. As well the ultimate tensile strength UTS of AA6061-T6 primarily increases when treated with UP. Peak UTS of 334 MPa is obtained for AA6061-T6 treated with UP compared with RT of 316 MPa. Beside the UP process gives an improvement of 5.7% in UTS while ductility is reduced from16.5% to 15.7%. Statnikov et al. [18] reported that hardness, wear- resistance, and mechanical properties had been improved after (UP) treatment for Aluminum alloy.

II. Fatigue Results

Four groups of 12 specimens were carried out under stress levels (500, 400, 350 and 250) MPa in order to compare between them. The first group of fatigue tests was performed at room temperature RT. The second group treated with three lines of ultrasonic peening UP. The third group deals with creep-fatigue interaction at 250 ℃. While the forth group examined the three lines of UP prior to creep-fatigue interaction at 250 ℃. Table 3 gives the results of these four groups including applied stresses (MPa), the number of cycles to failure of the specimens (Nf) and their average cycles (Nf av).

The data in Table 4 can be fitted by the power-law dependence

$$\sigma f = A\, Nf\, \alpha \quad (1)$$

Where A and α as material constants are listed in Table 4 with correlation coefficient R2.

The present data when using UP effects on fatigue life is based on the experimental data obtained using the criteria of the S-N curve. For different conditions of testing, fatigue at RT, fatigue with UP, CF interaction at 250 ℃ and UP before creep-fatigue interaction can be observed as S-N equations with correlation coefficient R^2 in Table 4. A relationship between the applied stress and fatigue life for the above cases can be seen in Figure 7.

Table 2: Mechanical properties of AA 6061-T6 at different conditions

Condition	UTS (MPa)	Ys (MPa)	E(GPa)	Ductility %	Failure strain
RT(25 °C)	316	268	70	16.5	0.52
UP	334	272	70.5	15.7	0.62
CF (250 °C)	264	222	68.3	17.3	0.48
CF+UP (250 °C)	275	234	69	17	0.46

Table 3: Fatigue results of four conditions of testing with and without UP.

Specimen No.	**Applied stress (MPa)**	**N_f Cycles**	**N_f av. (Cycles)**
	Fatigue Condition (RT)		
1, 2, 3	500	4000, 4800, 3600	4133
4, 5, 6	400	14000, 18000, 12000	14666
7, 8, 9	350	78000, 82000, 93000	84333
10, 11, 12	250	1750000, 1500000, 1360000	1536666
	Ultrasonic peening 3 lines (UP)		
13, 14, 15	500	5000, 4500, 5600	5033
16, 17, 18	400	22000, 21800, 18600	20800
19, 20, 21	350	102000, 112800, 94600	103133
22, 23, 24	250	2028000, 1760000, 1890000	1892666
	Creep-fatigue at 250 °C (CF)		
25, 26, 27	500	1200, 980, 1000	1060
28, 29, 30	400	7200, 6000, 8200	7133
31, 32, 33	350	44000, 35600, 39800	39800
34, 35, 36	250	105000, 98600, 111200	104933
	Ultrasonic Peening UP prior to Creep-Fatigue at 250 °C (CF+UP)		
37, 38, 39	500	2000, 1600, 1580	1726
40, 41, 42	400	11600, 14800, 10000	12133
43, 44, 45	350	56800, 64000, 51200	57333
46, 47, 48	250	122000, 132600, 114800	123133

Table 4: S-N curve equations

Type of testing	**A**	**α**	**R^2**	**S-N Curve equations**
RT	1234	-0.112	0.9856	$\sigma_f=1234\ N_f^{-0.112}$
UP	1380	-0.114	0.9915	$\sigma_f=1380\ N_f^{-0.114}$
CF	1338	-0.137	0.9135	$\sigma_f=1338\ N_f^{-0.137}$
CF+UP	1584	-0.145	0.9	$\sigma_f=1584\ N_f^{-0.145}$

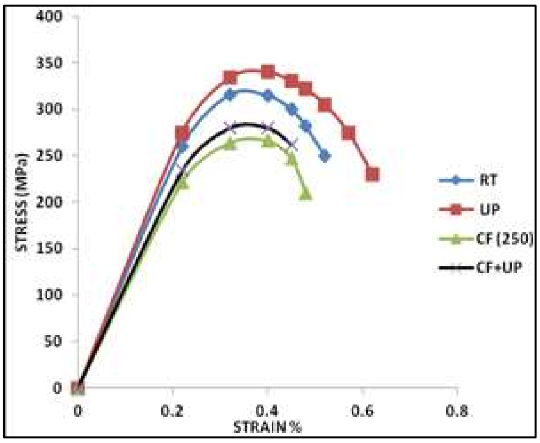


Figure 6: Experimental stress-strain curves in four conditions of testing.

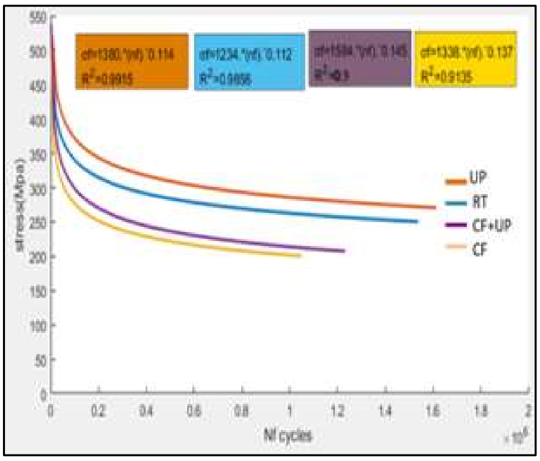


Figure 7: Fatigue life as a function of applied stress of AA6061-T6 at different conditions.

The plot of fatigue life versus the applied stress in Figure 7 indicates that the fatigue life of AA6061-T6 is sensitive to applied stress at high cycle fatigue (HCF) region while at (LCF) region is almost not sensitive. The presented curves are well described by power-law dependence and this appears from the values of R^2 (0.9 to 0.99). In-state of the RT the fatigue strength at 107 cycles was increased from 203 MPa to 220 MPa which gives an improvement percentage of 8.37% when applying of UP. Alalkawi et al. [5] tested AA6061 under constant fatigue life using ultrasonic peening UP, and they found that the S-N curve improved by 8.69% while the cumulative life was improved by (2.25 - 3) % for high-low and low-high loading sequences. It has been obtained that the fatigue endurance limit increased from 203 MPa to 220 MPa resulted in 8.37% enhancement. While the fatigue endurance limit reduced from (203 to 147), MPa was showing a 27.58% reduction due to creep-fatigue CF at 250 ℃. The results of UP before CF show that the fatigue endurance limit changed from (147 to 153), MPa indicating a 4% improvement in strength due to UP. Figure 8 shows the values of the fatigue endurance limit for four cases.

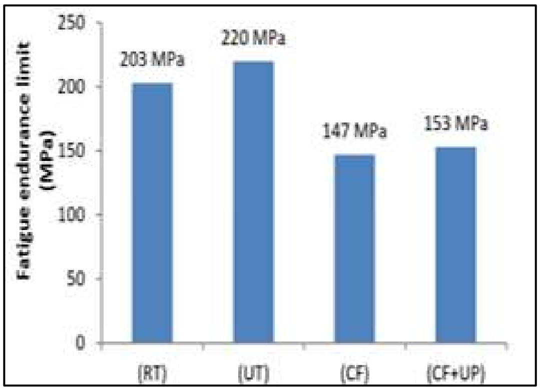


Figure 8: Fatigue endurance limit at 107 cycles for AA6061-T6 at different cases.

III. Mechanical Properties and Fatigue Life

The fatigue life of metals is affected by the values of mechanical properties. Figure 9 shows the fatigue life at **UTS** and **Ys** of four cases of testing.

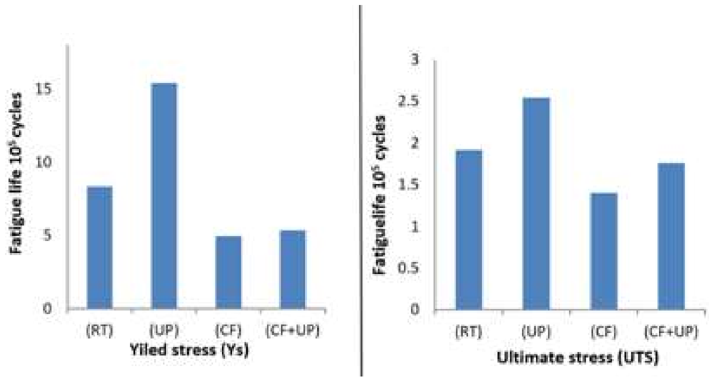


Figure 9: Fatigue life testing of different conditions based on mechanical properties.

Figure 9 Exhibits that the fatigue life increased at UP while it decreased at CF compared to RT. Moreovere the main reason for this increas in fatigue life due to the improvement in mechanical properties; UTS and Ys were increased from (316 to 334) MPa and from (268 to 272) MPa at UP testing condition respectively. The improvement factor was recorded to be 1.325 to 1.843 when comparing the fatigue life under UTS and Ys, applied stresses for RT and UP. Meanwhile, this factor changes to become 1.257 to 1.08 when applying CF at 250℃ and (CF+UP) at UTS and Ys, respectively. Daavari and Sadough [7] concluded that the corrosion-fatigue behavior of welded pipes was clearly improved when applying the UP technique, in-service conditions involving elevated temperature, the thermal stability of residual stresses becomes an important issue. UP process produces several beneficial effects in metals and alloys. Among these is increasing the resistance of materials to surface-related failures such as fatigue, stress corrosion cracking, and creep-fatigue interaction. The key benefits achieved in most applications with UP are significant increases in mechanical and fatigue properties (strength and life).

IV. A.C. Electrical Conductivity

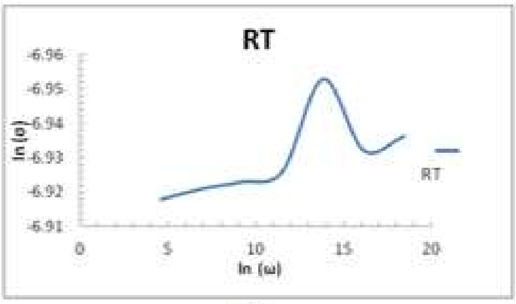
The A.C. electrical conductivity results for AA6061-T6 alloy at different conditions were investigated as a function of frequency (*f*). Table 5 presents the A. electrical conductivity results for three cases.

Table 5: A.C. electrical conductivity results for AA6061-T6 alloy with different conditions

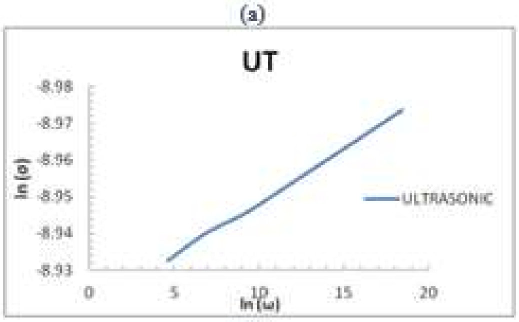
(*f*) Hz	AA6061-T6 (RT)	(UP) Ultrasonic	(CF) at 250 ºC
10^2	$9.9 * 10^{-4}$	$1.32 * 10^{-4}$	$1.38 * 10^{-4}$
10^3	$9.87 * 10^{-4}$	$1.31 * 10^{-4}$	$1.37 * 10^{-4}$
10^4	$9.85 * 10^{-4}$	$1.303 * 10^{-4}$	$1.369 * 10^{-4}$
10^5	$9.82 * 10^{-4}$	$1.294 * 10^{-4}$	$1.361 * 10^{-4}$
10^6	$9.56 * 10^{-4}$	$1.285 * 10^{-4}$	$1.354 * 10^{-4}$
10^7	$9.76 * 10^{-4}$	$1.276 * 10^{-4}$	$1.346 * 10^{-4}$
10^8	$9.72 * 10^{-4}$	$1.267 * 10^{-4}$	$1.339 * 10^{-4}$

According to the formula $\sigma_{a.c}(\omega) = A\,\omega^s$, the A.C. electrical conductivity increased with increasing frequency. However it was found that the A.C. conductivity reduced when frequency increase for pure AA6061-T6 alloy, ultrasonic, and creep-fatigue interaction at 250 °C.

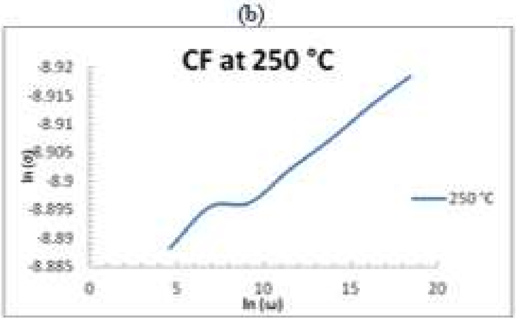
Figures 10 - a, b and c show the relationship between ln(σ) and ln(ω) for three cases; AA6061-T6 at RT, AA6061-T6 treated with UP and AA6061-T6 tested with CF at 250 ℃. The figure has revealed that electrical conductivity $\sigma_{a.c}$ increased with increasing frequency. This finding is agreed well with that concluded by Donnelly and Varlow [19] who concluded that the $\sigma_{a.c}$ increases when the frequency increase and they proposed two factors affected on the A.C. conductivity, ions motion and main chain or the backbone motion. In addition, it has found the $\sigma_{a.c}$ proportional to the frequency at high values of frequencies according to equation $\sigma_{a.c}(\omega) = A\,\omega^s$.



(a)



(b)



(c)

Figure 10 - a, b and c: The relationship between ln(σ) and ln(ω) for different cases

4. Conclusions

Followings are the major findings of the present investigation:

1) Aluminum alloy AA6061-T6 was successfully treated with UP under RT and CF.

2) Tensile test results revealed that the UTS and yield stress Ys were increased by 5.7% and 1.5% respectively when applying UP technique.

3) Applying the UP method reduced the ductility of AA6061-T6 from 16.5% to 15.7%.

4) An exponential equation of the $\boldsymbol{\sigma}_{\mathbf{f}} = A\ N_f^{\alpha}$ has been effectively used to predict the constant fatigue life for the above cases.

5) The fatigue strength was improved by 8.37% when using the UP method compared to fatigue strength at RT.

6) Fatigue life of AA6061-T6 was improved by a factor of 1.325 to 1.843 when applying RT and UP but this factor was recorded to be 1.257 to 1.08 under applying CF and (CF+UP) at UTS and Ys applied stresses respectively.

7) It was found that the electrical conductivity increases with increasing the frequency according to equation $\boldsymbol{\sigma}_{\mathbf{a.c}}\,(\boldsymbol{\omega}) = A\ \boldsymbol{\omega}^{s}$ for all the samples tested.

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