In this research work a direct extrusion unit has been designed and manufactured for circular section using the theoretical die design concepts for designing of the die profile, as constancy of the ratio of successive generalized homogeneous strain increment (CRHS). This was carried out by studying the final mechanical properties of the direct extruded products through dies with theoretical concept (ACRHS) and (UCRHS). Commercial alloy AA1100 round section billets was subjected to uniform extruded compressive load using two types of extrusion dies i.e. (ACRHS) and (UCRHS) at room temperature. The product of these dies with as received were conducted to testing under tensile and fatigue tests without corrosion and with corrosion of 90 days fully submersed in 0.35 % NaCl solution. The experimental results show that the reduction percentage (RP) in the main mechanical properties, UTS, YS and BHN due to corrosion were 14.28 %, 5.88 % and 12.12 % for as received samples, 2.74 %, 5.08 % and 6.12 % for the ACRHS samples and 7.79 %, 6.86 % and 8.88 % for UCRHS samples respectively. It was concluded that the less reduction percentage was occurred in the ACRHS samples compared to other samples. Corrosion fatigue testing of the above three samples were made and compared to the same samples without corrosion. The testing results revealed that the corrosion is significantly reduce the fatigue strength at 10^7 cycles from 40 to 33.65 MPa for as received samples, from 49.47 to 46.73 for ACRHS samples and from 49.5 to 45.89 MPa for UCRHS samples. The results may be lead to the best mechanical and fatigue properties under corrosion action are the ACRHS samples. The obtained results show that the extrusion die (ACRHS) is the most efficient die design

Keywords: extrusion, die design, mechanical properties, reduction percentage, fatigue strength, corrosion

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USING MODERN CONCEPTS IN THE DESIGN OF EXTRUSION DIES TO IMPROVE THE MECHANICAL EXTRUSION AND FATIGUE PROPERTIES FOR AA1100

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1. Introduction

The cause of failure in engineering parts is fatigue, for example, shaft, connecting rods, turbine blades, connections and supports of bridges. Also in parts of ships, trains and aircrafts. Therefore, this type of failure is the most common, representing 90 % of the failure of engineering parts in practice.

Therefore, it has become necessary to study the factors that improve the mechanical and fatigue properties of metals and that prevent or delay the fatigue failure of these parts.

2. Literature review and problem statement

Most of the airframe parts are made of aluminium alloy, and most of the failure of those parts is due to exposure to high loads and due to fatigue. The failure of these parts is very expensive cost for aircraft manufactures. For the purpose of preventing failure by improving the mechanical and fatigue properties of AA1100 alloy used in the manufacture of those parts. The dies designed according to modern concepts were used and the mechanical and fatigue properties of extrusion metal were compared with those of as received metal.

Aluminium extrusion is a modern technique in which billets of aluminium are pushed through a die opening shape with an angle to modify the properties of the new shape and create different sizes to fulfil a specific needs of the users. The extrusion drawing process has many factors that influence the formed bars or tubes, like drawing speed, reduction ratio and die angle.

The effect of die angle in extrusion process on the deformation behaviour and properties of energy absorbing of AA6063 Al-mg-Si alloy was studied. The response of this alloy, tool steel die angle of 15°, 30°, 60° and 75° were used. AVERY DENISON machine was used to supply Compressive load to the punch. In manufacturing process the extrusion die geometry has a great effect on the flow of material. The force required to reduce a certain cross section will depends to the die angle used. The friction between the work piece and die interface will be very high with lower angle [1].

AA100 Samples were anodized into gallic-sulfuric baths to discover the corrosion behaviour. Scanning electron microscopy, linear polarization, and electrochemical spectroscopy was used to observe the effect of different current density and acid concentration on the anodized aluminium sample properties. The Corrosion resistance for anodized samples in gallic-sulfuric Solution with 10 mA-cm^{-2} was less than that of anodized Samples in sulfuric acid. Also it was noted that corrosion resistances of anodized samples with gallic-sulfuric solution will decrease with increasing the adonization current density [2, 3].

The behaviour of AA 6082 and AA6063 alloys was studied as hollow extruded and processed into intricate shapes under high cycle fatigue. The AA6082 samples of fibrous microstructure show up more enhancement in fatigue behaviour. High temperatures effects and exposure of samples to the solution of NaCl were investigated. Fatigue lives for the samples were moderate reduced at high temperatures, while exposure the samples to salt solution greatly reduced fatigue lives [4, 5].

To study the corrosion susceptible of the annealed and unannealed AA1100 alloys, this material subjected to NaCl spray test. The results obtained for both drop impact and salt spray tests were better than that of monolithic sheet metal. These results were good because no crack and no corrosion was happen [6, 7].

The majority of failures in alloy airframe parts were because these parts are subjected to high load or fail due to fatigue. From the previous research study, it was found that the die angle has a great influence on the mechanical and fatigue properties of the extruded metal. The die angle, the length of the die and the x-area of the die can be expressed by the geometric shape of the die [8].

The previous research focused on the influence of the die angle on the deformation behaviour or on the mechanical and fatigue properties of aluminium alloys. These studies did not address the effect of designing the geometry of the extrusion die designed according to modern design concepts on the mechanical and fatigue properties. The current research will take into consideration the effect of the geometry of the extrusion die designed according to modern concepts on the mechanical and fatigue properties with the presence and absence of chemical corrosion.

3. The aim and objectives of the study

The aim of this research is to improve the mechanical and fatigue properties of AA1100 alloy by using modern concepts in die design.

To reach this aim, the following objectives are accomplished:

– evaluate the tensile properties of the extruded samples using extrusion dies designed according to the concepts of constancy of the ratios of successive generalized homogenous strain increment (two dies, ACRHS and UCRHS);

– evaluate the fatigue properties of the extruded samples using the dies (ACRHS and UCRHS);

– evaluate the fatigue strength (endurance fatigue limit at 10^7 cycles) of the extruded samples using the dies (ACRHS and UCRHS).

4. Materials and methods of research

4. 1. Object and hypothesis of the study

The current research focused on studying the mechanical and fatigue properties of AA1100 alloy. This alloy is widely used in the manufacture of many airframe parts. These parts are subjected to high loads and failure often occurs due to fatigue due to rotation of these parts at high speeds. The current research focuses on improving the mechanical and fatigue properties of this alloy to prevent or delay failure.

4. 2. Chemical analysis

Chemical composition of AA1100 was carried out at (SIER) State Company for inspection. Table 1 shows the Chemical composition of AA1100.

Table 1

Chemical composition of AA1100 wt %

Cu	Si	Mn	Fe	Zn	Mg	Other elements	Al
0.18	0.91	0.032	0.62	0.03	0.005	0.014	balance

AA1100 is used in applications where the resistance of corrosion is more important than strength [9] and also used for the same aircraft plants.

4. 3. Tensile test

The mechanical properties were obtained using tensile test rig designed for testing the material (different metals and materials at room temperature (RT) and at elevated temperature (ET) [10]. The tensile test sample is selected according to the ASTEM 370.

The strength of the sample used was measured using the tensile test machine. Loading of the sample was achieved through a double screw mechanism, the load at any instant being shown on continues curve.

4. 4. Extrusion dies

Most researches for extrusion die geometry was depend on the theoretical concept as constancy of the ratio of successive generalized homogenous strain increment (CRHS). This concept assumed that, the ideal extrusion die geometry depends on the homogenous strain only and ignored the non-homogenous strain. This ideal die geometry will not produce shear deformation inside the formed samples and this is the main aim for any extrusion die design.

The engineering shape of the die was considered the main parameters for designing the die according to the deformation rates which denoted by S (deformation rate).

The constancy of the ratio of homogenous strain can be reached by using the theoretical formula:

$$\frac{\varepsilon_{H2}-\varepsilon_{H1}}{\varepsilon_{H1}-\varepsilon_{H^{\circ}}}=\frac{\varepsilon_{H3}-\varepsilon_{H2}}{\varepsilon_{H2}-\varepsilon_{H1}}=\frac{\varepsilon_{Hn}-\varepsilon_{Hn-1}}{\varepsilon_{Hn-1}-\varepsilon_{Hn-2}}=S,$$

where ε_{Hn} – homogenous strain at any section in the deformation path, S – rate of deformation.

The value of S can be unity, its mean that the rate of deformation is uniform (UCRHS), when the value of S more than 1 the deformation is called accelerated deformation (ACRHS), also when the value of S less than 1 the deformation called decelerated deformation (DCRHS) [11].

$$\varepsilon_{Hn} = \ln\left(\frac{R_\circ}{R_n}\right)^2 = \ln(Z_N),$$

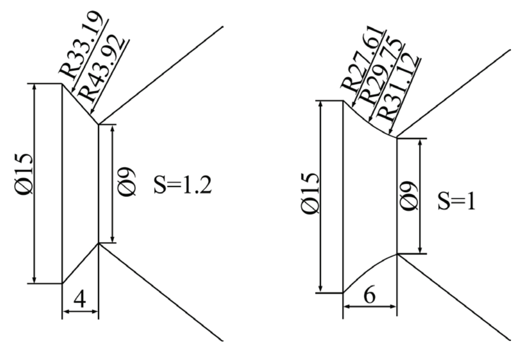
where Z_N – physical dimensions of the samples.

$$Z_n = \left(\frac{R_\circ}{R_n}\right)^2,$$

where $R_\circ$ – original die radius, R_n – die radius at any section.

The die geometry can be seen in Fig. 1.

The punch was made of X210Cr12/G metal because it has a high strength due to the force it is exposed to during the extrusion process.



a *b*

Fig. 1. Extrusion die Geometry: *a* — according to UCRHS; *b* — according to ACRHS

4. 5. Corrosion test

Aluminium alloy tend to pit in general or 3.5 % NaCl. Pitting pit corrosion is a cavities or holes and this type is considered to be more dangerous than the corrosion of uniform manner. Pitting corrosion occurs in the material areas under rapid attack. Corrosion pits is harmful due to stress concentration. Corrosion cracking and Fatigue start at the pits of corrosion [12].

The corrosion test can be described by putting the tensile and fatigue samples in 3.5 % NaCl corrosion Solution for 90 days. Many aircraft parts are subjected to chemical corrosion. The main purpose of this test is to know the effect of corrosion in mechanical and fatigue properties of extruded metal.

4. 6. Fatigue Test

Fig. 2 showed the sample used in fatigue test. The sample dimensions were chosen as that of ASTM (E8/E8M-09) standard.

Fatigue test was carried out for rotating bending cantilever beam at constant and a variable loads. Bending stress was evaluated by using the equation below:

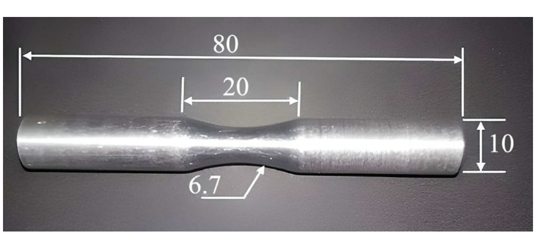


Fig. 2. Dimensions of Fatigue samples (mm)

$$\sigma_b = \frac{32P(125.7)}{\pi d^3},$$

where σ_b – bending stress measured in MPa;

P – applied load measured in N;

d – fatigue sample diameter (6.74 mm).

The force arm was 125.7 mm and the r.p.m. used was 1420.

The fatigue test was carried out using a rotary bending fatigue tester. The operating basis of the device is at frequency of 5600 r. p. m., during which a bending stress is produced in the form of a sin wave with a constant amplitude and an average stress of zero value. A Schenck PUNN type fatigue test rig was used to test all the fatigue samples under rotating bending loading. The sample is clamped on both ends and loaded with rotating about its own axis by a motor. After a specific number of cycles the specimen undergoes failure due to cyclic fatigue. The number of cycles at failure is recorded by a counter while keeping the stress applied constant.

5. Results of the study of mechanical and fatigue properties before and after corrosion

5. 1. Tensile test results

The tensile properties of the extruded samples using extrusion dies designed according to the concepts of constancy of the ratios of successive generalized homogenous strain increment (two dies, ACRHS and UCRHS). The mechanical properties values (UTS, YS and BHN) were examined for the extruded samples before and after corrosion.

Three samples of tensile test were examined under (RT) and humidity (35) with speed rate of 1 mm/min. Table 2 showed the experimental results.

Table 2

Mechanical properties results as a function to extrusion die shape

Type of sample	UTS, MPa	YS, MPa	BHN	Ductility, %	*E*, GPa	Percentage difference based on as-received for UTS
	Without corrosion (Dry)					
Before extrusion (as received)	126	85	33	7.5	69	30.7%
After extrusion (ACRHS)	182	118	49	6.0	71	
After extrusion (UCRHS)	154	102	45	7.0	70	18.18%
With corrosion (90 days in 3.5 % NaCl						
As received	108	80	29	8	68	14.28%
After extrusion ACRHS	177	112	46	7.5	70	28.8%
After extrusion UCRHS	142	95	41	7.8	68	11.26%

The above results are plotted in Fig. 3 to obtain the stress – strain curves.

Fig. 3 show that the tensile strength values of samples extruded through (UCRHS) dies and those before extrusion. Also, the results confirmed that the tensile strength values decrease in the presence of chemical corrosion for all samples.

The reduction percentages (*RP*) in mechanical properties due to corrosion may be defined as:

$$RP = \frac{\text{property}(\text{Dry}) - \text{property}(\text{Corrosion})}{\text{property}(\text{Dry})} * 100.$$

Table 3 shows the RP for UTS, YS and BHN for AA1100 after extrusion.

The reduction percentages for the above samples can be seen in Fig. 4.

Table 3

Reduction percentages values for main mechanical properties with different extrusion dies

Sample type	RP		
	UTS	YS	BHN
As-received	14.28	5.88	12.12
After ACRHS	2.74	5.08	6.12
After UCRHS	7.79	6.86	8.88

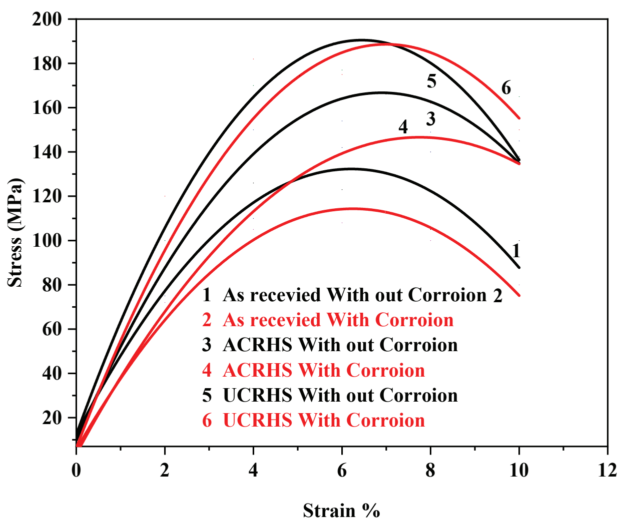


Fig. 3. Stress – Strain curves before and after corrosion for three types of samples

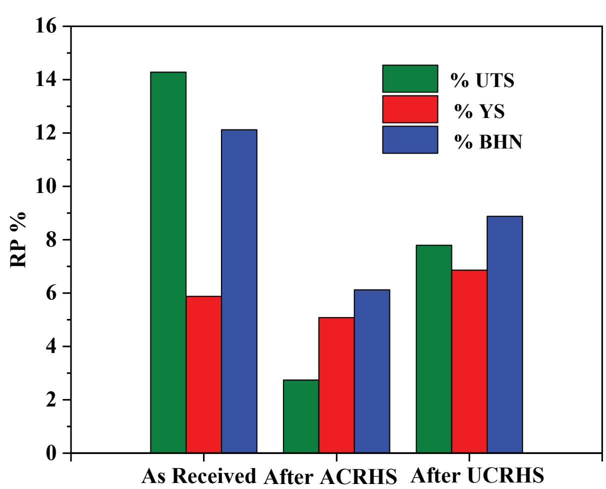


Fig. 4. Reduction percentages in mechanical properties due to corrosion for three types of samples

Fig. 4 show the decrease in *RP* of the mechanical properties of the extruded metal when using dies designed on the basis of the modern concepts compared to as received dies due to corrosion. The *RP* of mechanical properties of the metal extruded through the die were the lowest after corrosion.

5. 2. Fatigue test results

The behaviour of constant *S–N* curves at three different cases can be listed in Table 4, All tests are done at Stress ratio (R=–1) and temperature 30 °C.

The performance of AA1100 under constant Fatigue loading before corrosion can be seen in Fig. 5.

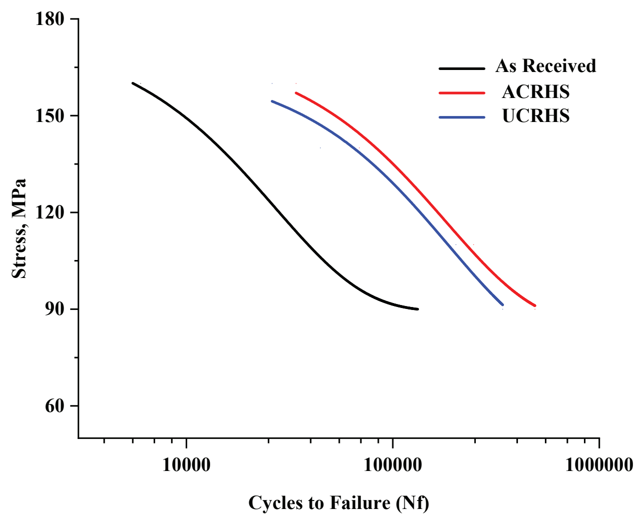


Fig. 5. The behavior of applied stress with the number of cycles to failure (N_f) for as received, Uniform Constancy of the Ratios of successive generalized Homogenous Strain increment samples and Accelerated Constancy of the Ratios of successive generalized Homogenous Strain increment samples before corrosion

Table 4

The Applied stress values with number of cycles to failure (N_f) before corrosion

AS – received samples		
Applied stress, MPa	N_f	N_f average of three sample
160	6000, 4200, 6300	5500
140	16000, 12800, 15000	14600
110	35000, 41000, 40400	38800
90	128000, 135000,133000	132000
ACRHS samples		
160	32500, 36000, 33500	00043
140	66800, 69000, 70600	68800
110	240000, 250000,248600	246200
90	485000, 490000, 489000	488000
UCRHS samples		
160	22000, 27500, 28500	26000
140	43000, 46500, 44300	44600
110	199000, 206500, 200500	202000
90	333000, 356000, 332800	340600

The behaviour of constant S–N curves at three different Cases can be listed in Table 5, All tests are done at Stress ratio (R=–1) and temperature 30 °C.

The performance of AA1100 under constant fatigue loading after corrosion can be seen in Fig. 6.

Fatigue life equations for three samples before and after corrosion are tabulated in Table 6.

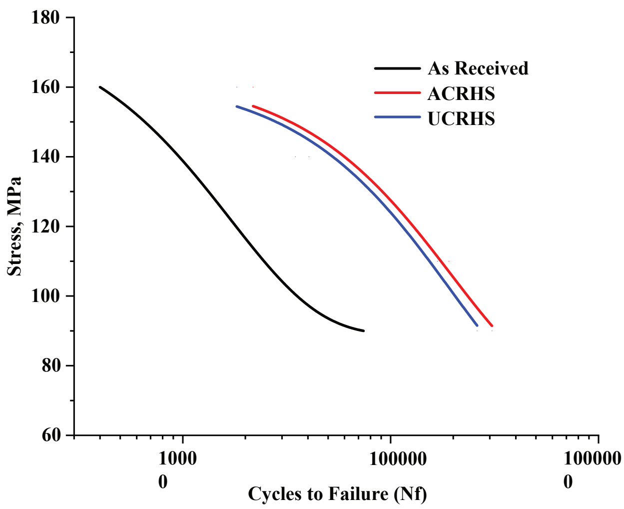


Fig. 6. The behavior of applied stress with the number of cycles to failure (N_f) for as received, Uniform Constancy of the Ratios of successive generalized Homogenous Strain increment samples and Accelerated Constancy of the Ratios of successive generalized Homogenous Strain increment samples after 3.5 % NaCl corrosion

Table 5

The Applied stress values with number of cycles to failure (N_f) after 90 days 3.5 %. NaCl corrosion

AS – received samples		
Applied stress, MPa	N_f	N_f average of three sample
160	3600, 4100, 4300	4000
140	9000, 10100, 9700	9600
110	23630, 25000, 25170	24600
90	70000, 74900, 77100	74000
ACRHS samples		
160	20500, 23000, 21900	21800
140	38600, 42500, 40400	40500
110	188600, 192700, 191100	190800
90	300500, 309900, 310600	307000
UCRHS samples		
160	17900, 19500, 17200	18200
140	32800, 35500, 36100	34800
110	160660, 169500, 173840	168000
90	250500, 265000, 266600	260700

Table 6

Applied Stress-Number of cycles to failure curve equations with (R^2) for three type samples before and after corrosion

Sample type	Before corrosion	After corrosion
AS received	$\sigma_f = 812 N_f^{-0.186}$ $R^2 = 0.9898$	$\sigma_f = 873 N_f^{-0.202}$ $R^2 = 0.9925$
ACRHS samples	$\sigma_f = 1460 N_f^{-0.210}$ $R^2 = 0.996$	$\sigma_f = 1193 N_f^{-0.201}$ $R^2 = 0.9706$
UCRHS samples	$\sigma_f = 1310 N_f^{-0.207}$ $R^2 = 0.975$	$\sigma_f = 1127 N_f^{-0.198}$ $R^2 = 0.9663$

Fig. 5, 6 and Table 6 indicate that the fatigue life of AA1100 decreased when subjected to corrosion.

5. 3. Fatigue strength (endurance fatigue limit at 10^7 cycles)

The endurance fatigue limits for the three samples were reduced by 15.8 %, 5.59 % and 1.48 % for as received, ACRHS and UCRHS Samples [13] tested high strength aluminium alloy and concluded that 60 %, decrease in fatigue Strength at 10^7 cycles was reported for the current work conditions and time of corrosion was one year. The fatigue properties and the endurance limit of the extruded samples using the dies (ACRHS and UCRHS) was examined. The fatigue properties and the endurance limit of the extruded samples were compared with that as received samples before and after corrosion.

Table 7 shows the strength reduction factor (SRF) of the three samples due to corrosion compared to [14] for the same alloy and the same condition of corrosion but the time was 71 days.

Table 7

SRF values compared to [14]

Sample type	(SRF) due to corrosion 90 days	Due to 71 days corrosion
AS received	15.8 %	41 %
ACRHS samples	5.53 %	41 %
UCRHS samples	7.29 %	41 %

The fatigue strength at 10^7 cycles was calculated from the equation of fatigue life results are clarified in Table 8.

Table 8

Fatigue endurance limits before and after corrosion for AA1100

Sample type	Before corrosion, MPa	After corrosion, MPa
AS received	40	33.65
ACRHS samples	49.47	46.73
UCRHS samples	49.5	45.89

The fatigue endurance limit values of ACRHS samples were the highest before and after the effect of chemical corrosion on the samples.

6. Discussion of the results of the mechanical and fatigue properties will be discussed

Extrusion, as in the case of other metal forming processes at temperatures lower than the temperature of recrystallization, leads to a strain hardening of the metal. Strain hardening value depends on the value of the strain, which depends mainly on the reduction in x-area of the metal. Increasing the reduction ratio leads to improving the mechanical properties.

The mechanical properties (ultimate tensile strength, yield strength and hardness) have been greatly improved for the metal extruded through the dies designed on the basis of UCRHS and ACRHS compared to those properties of the metal as received as in Table 2. The extruded metal is subjected to high compressive stresses resulted to high hardness and increasing the bounding between the metal particles. The high Compressive stresses generated from the ACRHS (S=1.2) are greater than the other die sample. The high Compressive stresses lead to raise the mechanical properties such as ultimate and yield strengths [15, 16].

The extrusion die geometry had a significant effect on the improving the fatigue properties. The improvement in fatigue strength and fatigue life was varied according to the varying values of the deformation rates on which the dies were designed. These designs resulted in deferent length and shapes of the forming paths for these dies, and the results were as follows:

– high fatigue strength of metal extruded using the die designed on the basis of accelerated deformation rate compared to the metal extruded for the rest of the dies. The reason is due to the shape of the streamlined die path in a way that the metal flow through it without being obstructed. In addition to the fact that the metal is not exposed to the high friction that may appear in the rest of the dies, which causes the metal to be hampered during extrusion and thus to appearance of extrusion defects in the metal, whose presence is a reason for the decrease in the fatigue strength of metals as shown in Table 8;

– the fatigue life of extruded metal increases as the applied stress decreases when using all the dies as shown in Fig. 5, 6. The fatigue life of extruded metal through the die ACRHS was the highest due to the large ductile region at the top of the crack, which lead to a delay in crack growth, also to the microstructure of the hardened structure that increased the interface barrier, which required the higher stress than the stress required by the metal without extrusion.

The experimental results confirmed that the chemical corrosion negatively affects the mechanical properties, fatigue strength and fatigue life as shown in Table 2 and Fig. 6. The effect of corrosion on the surface could progress to eliminate the material strength i. e. corrosion weakens the surface and resulted in decreasing the strength and hardness and fatigue properties. This finding is in well agreement with that found by [16].

The use of the die designed according to the modern concept ACRHS has appositive effect on the mechanical and fatigue properties of the extruded metal, where the values of ultimate tensile strength, yield strength, hardness, fatigue strength and fatigue life were the highest compared to the other dies.

The limitations of this study are that it relied on the concept of constancy of the ratios of successive generalized homogenous strain increment in design of extrusion dies. This study did not consider the effect of strain rate on mechanical and fatigue properties of the extruded metal. To reduce the effect of strain rate on the mechanical and fatigue properties, it is necessary to design the die based on the stability of the average strain rate through the extrusion die.

In this research, two types of dies designed according to modern concepts were selected UCRHS and ACRHS, but the effect of the die designed on the basis of DCRHS on the mechanical and fatigue properties was not addressed. This is recommended for future work.

7. Conclusions

1. The mechanical properties of the extruded AA1100 improved when using die designed according to the concepts of ACRHS compared to the mechanical properties of the alloy before the extrusion process. The mechanical properties of the alloy decreased under corrosion for the three samples as received, ACRHS, and UCRHS. The decrease in mechanical properties as reduction percentage (RP) of 14.28 %, 2.74 % and 7.79 %, for (UTS), 5.88 %, 5.08 % and 6.88 % for (YS), 12.12 %, 6.12 % and 8.88 % for BHN respectively.

2. The fatigue properties of the extruded alloy improved when using the die designed according to the concept of ACRHS compared to the fatigue properties of the alloy before the extrusion process.

3. The fatigue strength (endurance fatigue limit at 10^7 cycles) for as received, ACRHS, and UCRHS were recorded to be 40, 49.47 and 49.5 MPa respectively. The fatigue strength at 10^7 cycles of the corroded samples were 33.6, 46.73, 45.89 MPa for as received, ACRHS, and UCRHS samples respectively.

Therefore, the fatigue life was decreased in comparison with the same samples tested at air.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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