The Radius Size Variation Effects on Fatigue Strength of AA6061-T6 and AA6061-O Alloys

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Abstract: This research ensured the effects of radius variation on fatigue – life of AA6061-T6 and annealed alloy, AA6061- O. Five different sizes of radius (1, 2, 4, 8, and 16) mm were studied using Neuber notch factor (Kₗ) instead of the theoretical stress concentration factor (Kt). The numerical modeling was adopted using ANSYS Workbench 15 to evaluate the radius size effectiveness on strain and stress distribution, while the experimental procedure carried out to determine the strain-life constants for analytical calculations. The results show that the reduction in the radius leads to increase stress, while the strain remains close to each other with the variations of radius for both alloys. The decrement in stress and strain values for annealed specimens were observed in comparison with base alloy. The transition life (Nₜ) was decreased whenever the radius decreased in both alloys. The fatigue life of annealed specimens increased for all values of radius compared to the specimens without annealed. The comparison of the fatigue life between the experimental and numerical results shows that the experimental results have more than those obtained by numerical estimation and this indicated the validity of the numerical approach.

Keywords: Radius size; Fatigue -Life; Low cycle fatigue (LCF); Stress concentration, Aluminum alloys

1. Introduction

Recently, the fatigue life estimation of components, based on practical experiences that the fatigue failure has coming from cyclic strain rather than from cyclic stress. Local stresses can be exceeding the yield strength of the material due to sharp and curved edge or notches within components and these develop to cause initiation and propagation to the fatigue cracks. Many researchers interested in studying the effect of the sharp or curved edges and notches on the fatigue strength for different mechanical parts.

Katsurou Shingai [1], found the relationship between the tensile cyclic strains and the fatigue life under the range of 10⁴-10⁶ cycles, through employing strain gages to estimate the strains ahead of notches in steel plate specimens. Knop M. et al [2], studied the developed combined method between modern constitutive theory with either Neuber or Glinka approaches to estimate the localized notch strains.

Mcnulty J. C. et al [3], examined the effects of the hole radius size and notches on the fatigue life of an advanced Sylramic™/Sic composite at 815°C. Hurley P. J. et al [4], proposed numerical models for LCF initiation lives estimation in notched Ti 6246 specimens tested in air at room and elevated temperatures by using both Neuber method and non-linear finite element analysis.

Luiz et al[5], applied Taylor's point stress estimated methodology to find the cylindrical contacts fatigue limit under a partial slip regime. Taylor D. et al [6], discussed two new types of approaches
to obtain the useful variable-radius. They concluded that the effects of stress concentration features can be greatly reduced by altering the local curvature. Gao Z. et al [7], employed fatigue stress life prediction approaches for 16MnR steel notched shaft specimens under different fatigue experiments to predict the local fatigue life.

Uygur I. [8], assessed three notch geometries with different stress concentration factors using a critical strain life approach and found that the fatigue lives dramatically reduced due to increasing stress concentration factor. Benachour N. et al [9], investigated empirically the fatigue crack initiation and propagation for 2024 T351 aluminum alloy under constant amplitude loading. They applied NASGRO model in stable propagation stage and local strain approach at the critical notch radius. Joadder B. et al [10], used experimental strain-life relations for plain fatigue of round specimens to predict failure cycles of notched round specimens under strain controlled cyclic loading. They found that the maximum strain appears at notch tip radius and varied from the applied controlled strain.

Susmel L. et al [11], estimated the fatigue lifetime of notched metallic materials based on direct accounting for the degree of multi-axially of the local elasto-plastic stress/strain fields applied to the fatigue process zone. Benachour M. et al [12], estimated the number of cycles for fatigue crack initiation in a notched aluminum alloy plate utilizing a constant amplitude loading based on the tensile residual stress field. Also, studied the loading stress ratio parameter. Ibrahim K. et al [13], examined the influence of notch sensitivity on the fatigue of austempered iron. Also, utilized ANSYS 12.0 software to discover and specify the fatigue strength of the notched ADI samples due to several radii.

Belingardi G. et al [14], generate an experimental program to examine the notch geometry effect on bending fatigue behavior of Twill E-glass/epoxy composite. They found that notched geometry specimens reacted differently because of the variation of curvature radius at the critical loading section of the notch. K. Shingai, Qasim&Emad [15], studied the effect of V shaped notch with various orientations and depths on the fatigue life behavior for High Carbon Steel alloy AISI 1078 beam.

Sargio[16], studied the effect of the stress concentration factor at very high Kt values and the role of different inert or corrosive environment to represent the corrosion fatigue characteristics of Ti-6Al-4V alloy depending on the evaluation of the corrosion fatigue initiation and fatigue mechanisms. Qasim&Emad [17], used experimentally and FEA to analysis results utilized under constant amplitude load in rotational bending through four stress ratios of (R= -0.5, 0, 0.25 and 0.5). The specimens were examined with various radius size geometries and dimensions. Benedetti M. et al [18], produced bending fatigue tests on Al-7075-T651 notched samples under different loading. The residual stress field ahead of the notch has been characterized experimentally and numerically to predict the fatigue resistance.

Telesman J. et al [19], determined and modeled the high temperature dwells effect on notched low cycle fatigue and notch stress rupture behavior for a fine grain LSHR powder metallurgy nickel-based super alloy. Ferro P. et al [20], described the singular residual stresses ahead of the notch tip of V notches and the asymptotic stress field using the notch stress intensity factor.

Made L. et al [21], described the notch support extension depend on the effect of the stress gradient. Several samples with different materials and geometry types are considered to produce more comprehensive validation for the probabilistic LCF model and to establish its wide application range. Anjum N. A. et al [22], evaluated numerically and experimentally the effect of the notch on fatigue strength of aluminum alloy. They analyzed the fatigue failure affect by the notch root radius and depth. The specimens having small root radii showed lesser fatigue strength than those with larger radii.

In this current research, an experimental and numerical investigation for a cantilever beam under symmetrical low cycle bending fatigue have been made for two types of aluminum alloys AA6061-T6 and AA6061-O to find out the effects of radius size variation on the fatigue life and strength.
2. Approach of local strain

Strain life curve can be used to characterize fatigue resistance of metals, in case of fatigue at the notch tip. Local strains are obtained by using the Neuber rule or Glinka describe in the following form [23]:

$\frac{(K_f - \Delta \sigma_a)^2}{4E} = \Delta \sigma \Delta \varepsilon \frac{2}{\epsilon_0} \epsilon$ \hspace{1cm} (1)

Where "$\sigma_a$" is the applied stress and "$\sigma$, $\varepsilon$, and $E$" are the resulting local stress, strain and modulus of elasticity values corrected due to the notch effect. Neuber notch fatigue factor ($K_f$) is used instead of the theoretical stress concentration factor, $K_t$ and it is approximated by using the formula [2]:

$K_f = 1 + \frac{(K_t-1)}{[1+(\frac{a}{m})^2]}$ \hspace{1cm} (2)

Where $a$ is the material constant and it was taken as 0.5969 and 0.635mm for AA6061-T6 and AA6061-O respectively, and $m$ is the notch tip radius [2]. The values of $K_t$ was calculated using the formula of graph illustrated in Fig.1 [24].

In Glinka approach represent the energy equivalence as compared the remote loading conditions as local strains and stresses, illustrated by the following equation [10]:

$\Delta \varepsilon = \Delta \sigma = \frac{\epsilon}{\epsilon} = \frac{\Delta \sigma}{\Delta \varepsilon}$ \hspace{1cm} (3)

$k$ and $n$ are correspond to the material’s cyclic hardening law.

The local strains as a function of local stress range named cyclic stress-strain were determined by coupling the equations (1) and (3), given as:

$\frac{\Delta \varepsilon}{\Delta \sigma} = \frac{\Delta \sigma}{\Delta \varepsilon}$ \hspace{1cm} (4)

The relationship between total strain amplitude, $\frac{\Delta \varepsilon}{\Delta \sigma}$ and failure life, $2N_f$, can be present in the form [2]:

$\frac{\Delta \varepsilon}{\Delta \sigma} = \frac{\sigma_f}{2E}(2N_f)^b + \varepsilon_f(2N_f)^c$ \hspace{1cm} (5)

Where "$\sigma_f$" is the fatigue strength coefficient; "$b$" is the fatigue strength exponent, "$\varepsilon_f$" is the fatigue ductility, "$c$" is the fatigue ductility exponent.

The values of $K_f$ calculated using equation 2 for the two cases of the alloy are illustrated in Table (1).
3. Numerical Modelling:

In this present study, different numerical modelling simulations were expressed due to the radius size of the specimen for the two types of material employing finite element models constructed through the ANSYS Workbench version 15. The pre-processing solutions are provided by selecting the appropriate project model in the analysis system, choosing the static structure. The low cycle fatigue model is a cantilevered solid cylinder specimen fixed from one end and applying a bending symmetrical sinusoidal cyclic mechanical loading at the free end of the specimen perpendicular to the cylinder axis as shown in Fig.2a. During this case study, the main material properties added to the solution types are physical properties, linear elastic properties, experimental stress-strain data (inserted as a table and graph of bending test data), fatigue life (alternating and mean stress-life data inserted as a table and graph of mean stress, cycles and stresses) and strength properties. The geometrical models of the solid cylindrical samples are created by using Solid Works 15, which is easy and having more tools to create models, then imported into ANSYS Workbench 15 software. An automatic free and mapped mesh with medium size is applied to the geometric model that contains the elements by the software. The shapes and the mesh patterns employing a tetrahedral element type due to the irregular geometric model with total number of nodes (2513) and total number of elements (1351), the meshed model is shown in Figure 2b.

Table 1. Values of Kt & Kf

| Radius Size (mm) | AA6061-T6 | AA6061-O |
|------------------|-----------|----------|
|                  | Kt        | Kf        | Kt        | Kf        |
| 1                | 1.637     | 1.470     | 1637      | 1.454     |
| 2                | 1.410     | 1.376     | 1.410     | 1.372     |
| 4                | 1.273     | 1.267     | 1.273     | 1.266     |
| 8                | 1.188     | 1.187     | 1.188     | 1.186     |
| 16               | 1.135     | 1.135     | 1.135     | 1.135     |

Figure 1. Stress concentration factors Kt For Bending of a stepped bar of circular cross section with a shoulder fillet [24].
4. Experimental work
Two types of aluminum alloys, AA6016-T6 and annealed (AA6061-O) were used in this current study as a testing material. Table 2 illustrates the chemical composition of AA6061, and Table 3 contains the mechanical properties of annealed and base alloys. Tensile test has been done according to ASTM B557-84 standard. The LCF specimens are manufactured according to ASTM 606-80 standard as shown in Figure 3. Twelve specimens per radius were employed with different radius size (1,2,4,8,16 mm) for the two alloy types. The apparatus used for fatigue tests is a cantilever type WP 140 with pure reversed bending stress and mean stress equal to zero (R= 1) as shown in Figure 4.

Table 2. Chemical composition of AA6061

| Element Material | %Si  | %Fe  | %Cu  | %Mn  | %Mg  | %Zn  | %Cr  | %Al  |
|------------------|------|------|------|------|------|------|------|------|
| Nominal          | 0.4-0.8 | 0.7 max | 0.15-0.4 | 0.15 max | 0.8-1.2 | 0.25 max | 0.04-0.35 | Balance |
| Actual           | 0.58 | 0.105 | 0.213 | 0.0006 | 0.8 | 0.005 | 0.115 | Balance |

Table 3. Mechanical properties of annealed and base material

| Materials Properties | Engineering Tensile strength (MPa) | Engineering Yield strength (MPa) | Elongation % |
|----------------------|-----------------------------------|----------------------------------|--------------|
| AA 6061-T6 Nominal   | 310                               | 276                              | 12-17        |
| AA 6061-T6 Experimental | 338                       | 300                              | 13           |
| A A6061-O Nominal    | 124                               | 55                               | 25-30        |
| A A6061-O Experimental | 127                     | 73                               | 28           |
5. Results and discussion

5.1. Effects of radius size on the stress and strain
Stress and strain were obtained by numerical modeling depends on the generating experimental data of LCF parameters pointed to the clear effectiveness of radius size. Table 4 illustrates LCF parameters for both two alloys obtained from the strain-life curve as shown in Figure 5 and can be observed the values of $k'$ and $N_T$ affected by the variation of radius more than other parameters. Figure 6 and Figure 7 illustrate samples of stresses distribution according to the radius size of AA6061-T6 and AA6061-O respectively. Table 5 contained the values of max. stress according to radius size. It is observed that the peak stress value increased when the radius size decreased as
shown in Figure 8 and the values of maximum stress for AA6061-O less than AA6061-T6 due to the softening caused by annealing. This result is highly agreed with [1], which is mentioned, that when notched composite material is subjected to bending fatigue loading, the performance is mainly governed by the notch radius size. The local stress is significantly affected by the curvature size of the local radius of the surface, so that increasing the radius size causing decrease in Kt [7]. The results of strain obtained by numerical modeling show that the effects of radius variation are small in comparison with stress. Figure 9 and Figure 10 show sample of strain distribution for AA6061-T6 and AA6061-O respectively. Table 6 contained the values of max. strain due to radius size. The values of strain are very closed to each other in spite of the variation of the radius size, especially for AA6061-O and the same result obtained by [2]. While the value of the strain of AA6061-T6 relatively decreased with increasing of the radius as shown in Figure 11 and this belonging to the reduction of the stress concentration factor. The annealed alloy revealed less value of strain for all radii sizes in comparison with base alloy because of the significant stress relaxation happened through the annealing. In notched specimen, the maximum strain occurs at the notch root and failure of the specimen is appeared due to the value of this maximum strain [11]. This is because the prediction of failure cycles from strain life equation is strongly depends on the accurate evaluation of the maximum strain. Generally, notched or critical radius size geometrical specimens react differently because of the variation of radius of curvature at the critical loading section of the notch [1].

Table 4. Values of LCF parameters

| Parameters size | AA6061-T6 | AA6061-O |
|-----------------|-----------|----------|
| Radius size     |           |          |
| 16mm            | 0.14 -0.509 0.018 -0.122 0.239 595 16240 | 0.27 -0.531 0.068 -0.105 0.197 401 310560 |
| 8 mm            | 0.16 -0.512 0.023 -0.118 0.230 571 11068 | 0.3 -0.512 0.12 -0.118 0.230 389 300000 |
| 4 mm            | 0.21 -0.531 0.027 -0.109 0.205 538 8769  | 0.12 -0.531 0.13 -0.109 0.205 375 280560 |
| 2 mm            | 0.13 -0.526 0.02 -0.121 0.230 490 6120 | 0.17 -0.526 0.074 -0.121 0.230 342 139690 |
| 1 mm            | 0.2 -0.543 0.017 -0.113 0.208 452 2700 | 0.29 -0.543 0.16 -0.113 0.208 318 112540 |
Figure 5. Strain – Life curve sample with radius 16mm for a) AA6061-T6 & b) AA6061-O

Figure 6. Stress distribution samples of AA6061-T6 a) Radius size 1mm, b) Radius size 16mm.

Figure 7. Stress distribution samples of AA6061-O, a) Radius size 1mm, b) Radius size 16mm.
Table 5: Max. stress according to the radii size for AA6061-T6 & AA6061-O

| Radius size (mm) | Max. stress (MPa) | Radius size (mm) | Max. stress (MPa) |
|------------------|--------------------|------------------|--------------------|
| 1                | 439.17             | 1                | 161.86             |
| 2                | 404.6              | 2                | 149.7              |
| 4                | 391.76             | 4                | 144.6              |
| 8                | 381.6              | 8                | 140.61             |
| 16               | 371.88             | 16               | 136.92             |

Figure 8. The Relationship between stress and radius size under LCF

Figure 9. Strain distribution samples of AA6061-T6, a) Radius size 1mm, b) Radius size 16mm

Figure 10. Strain distribution samples of AA6061-O, a) Radius size 1mm, b) Radius size 16mm.
Table 6. Max. strain according to radii size for AA6061-T6 & AA6061-O (FEM)

| Radius size (mm) | Max. strain | Radius size (mm) | Max. strain |
|------------------|-------------|------------------|-------------|
| 1                | 0.00641     | 1                | 0.00236     |
| 2                | 0.00595     | 2                | 0.0022      |
| 4                | 0.00571     | 4                | 0.0021      |
| 8                | 0.00554     | 8                | 0.00204     |
| 16               | 0.00539     | 16               | 0.00198     |

Figure 11. The Relationship between strain and radius size under LCF (FEM)

5.2. The effects of radius size on the transition life (N_T)

The transition life (N_T) is experimentally measured from strain life curve illustrated in Figure 5, which is decreased, whenever the radius decreased for both types of alloys as shown in Table 4. This means that the transition from elastic to plastic state of the alloy is significantly affected by the radius size. This is due to the inelastic behavior of the local strains at the root radius of the notch [11], so when the radius size decreases the transition to a plastic state becomes faster and require less number of cycles. Annealed alloy revealed high transition life (N_T) and large increasing of N_T with increasing the radius size in comparison with the base alloy as shown in Figure 12, and this high difference occurrence is coming out from the plastic state of the softer alloy requires a high number of cycles.

Figure 12. The Relationship between transition life (N_T) and radius size
5.3. The effect of radius size on the fatigue life

The fatigue life obtained by FEM for all specimen models for both alloys with different radii size revealed a good safety. The experimental lives show more than the numerical models and this result pointed to the validity of models proposed by the current study. Equation 5 was used to calculate the strain using the experimental value of $2N_f$ for the same load employed in FEA in order to make a comparison with strain obtained by FEA. Figure 13 and Figure 14 illustrate this comparison and clearly observed that the strain obtained by FEA less than the calculated.

5.4. The effect of radius size on the fracture cross-section

The fracture cross-section is clearly affected by the variation of radius size as shown in Figure 15 and Figure 16. As mentioned above the local strain is inelastic at the root of notches (tip radius size), so when the radius increased the plastic strain at its root lead to encountered the crack propagation because of high density of dislocations and result in the decreased crack propagation area and the increment in fracture area of cross-section of the specimen when the radius size increased and this appeared more clearly with the AA6061-T6 as shown in Figure 15. The annealing of the alloy generally leads to increase the plastic state and its effectiveness became stronger when the alloy subjected to cyclic stress that the microstructure which contains dislocations played a main role as a barrier to prevent the propagation of fatigue cracks and reduced the crack propagation area in the cross-section of the specimen, in addition to the rough and irregular shapes of this region compared to the alloy specimen without annealed is shown in Figure 16.

![Figure 13. Strain obtained by numerical modeling and calculated strain for AA6061-T6](image1.png)  
![Figure 14. Strain obtained by numerical modeling and calculated strain for AA6061-O](image2.png)  

![Figure 15. Fracture cross-section view of AA6061-T6 specimens at different radii size under the same load.](image3.png)
Figure 16. Fracture cross-section view of AA6061-O specimens at different radii size under the same load

6. Conclusions:
In this present research, experimental and numerical methods of studies are applied to study the effects of the radius size on the fatigue strength for two types of aluminum alloys, (AA6061-T6 and AA6061-O) annealed. This research produces a comparison analysis between the experimental work and numerical modelling. The following conclusions drawn out from the research study are:
1. The maximum stress increases when radius size decreased and the values of maximum stress for AA6061-O are less than AA6061-T6 under LCF.
2. The radius size variation has a small effect on the value of maximum strain for AA6061-O. While, this value relatively decreased with increasing the radius size for AA6061-T6.
3. The annealed alloy revealed less value of strain for all radii in comparison with the base alloy.
4. The transition life (N_T) was decreased whenever the radius size decreased for the both two alloys.
5. The crack propagation area at the fracture cross-section was decreased with increasing radius size.

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