Notch Effect on Aluminium Alloy Rod under Rotating Bend Fatigue Load

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Abstract. Aluminium alloys have a wide range of applications, such as the aerospace and automotive industries. The effect of V-notch on fatigue life of cylindrical beam made of aluminium alloys under rotating bending fatigue load has been investigated experimentally and numerically. The experimental work involved the tensile strength, hardness, impact test, and fatigue life behavior at room temperature. The fatigue life test was conducted with a fully reversed cycle with a mean stress ratio (R= -1). The experimental data were compared with the numerical result, and a good agreement was found. The results show that the notch has reduced the fatigue life of aluminum alloy beams.

Keywords. Notch, Aluminium alloy, Rotating bend, Fatigue.

1. Introduction
Strength of fatigue is an important property to be considered in the behavior of mechanical components subjected to static or variable amplitude loading. Fatigue can be defined as "the progressive, localized and parameter structure change that occurs in materials due to subject to repeated or fluctuating strains at nominal stresses that have a maximum value less than the tensile strength of the material" [1]. Metal fatigue is a too complex phenomenon, and many factors affect fatigue life, such as material being used, structure, shape, and temperature changes. There are three stages of fatigue which are crack initiation, crack propagation, and final fracture. Crack is usually starting to be in the high-stress concentration regions located on the component's surface, like cross-sectional change, sharps, corners, scratch, slag inclusions, tool marks, notches, keyways, pits, etc. [2]. The cycle number in the crack stage depends on the magnitude of stress and specimen geometry. If the sample was notched, the crack initiation stage might be very short [3]. The increase in the magnitude of stress leads to the cracks' propagation process across the grains or along the grain boundaries, slowly increasing the crack's size. After initiation and propagation of the crack, the component's ability to carry loads becomes less. Therefore, the fracture will take place when the crack reaches the critical size. The notch is one of the main factors that control structures' fatigue strength, which is hardly avoidable in engineering practice. The failure usually originates in the formation of a crack at a localized point on the notches. Many researchers have investigated the fatigue life of aluminum; for example, Bahaideen et al. [4] studied the behavior of fatigue for specimen made of Aluminium alloy 2024-T4 at a specific temperature. Its result observed that fatigue life cycles are significantly reduced at an elevated temperature when comparative with specimens tested at room temperature as the same applied stress range. Shlyannikov et al. [5] studied temperature effects on the fatigue crack growth.
rate in D16T and B95AT (analogous to 2024 and 7075) aluminum alloys as they apply constant amplitude load. Pablo Wilson et al. [6] investigated the low-cycle fatigue behavior of cast aluminum alloys at ambient and elevated temperatures using an in-situ optical surface crack monitoring, secondary electron microscopy, and X-ray tomography, which are combined to study the fatigue mechanism. The observations highlight the effect of defect distribution and temperature on the crack propagation path and, in particular, the change of the role of eutectic regions as the temperature increases. The resulting fatigue crack initiation model is proposed to consider both temperature and defect effects on the total low-cycle fatigue life and fatigue crack. Mehmood and Hammouda [7] studied the effect of surface treatment on the fatigue life of the 2024 aluminum alloy under constant amplitude loading conditions. The results showed that the surface treatment could be applied to increase the fatigue life of the aluminum alloy under optimum conditions; otherwise, we may not get the appropriate results, and even it may cause adverse effects. Puchi-Cabrera et al. [8] experimentally investigated rotating bending fatigue, both in air and in a 3% NaCl solution, to study the fatigue behavior of a 7075-T6 aluminum alloy coated with a WC–10Co–4Cr cermet by high-velocity oxygen fuel (HVOF) thermal spray, without any grit, blasting before the coating deposition. The result indicated that the coating presence gives a significant increase in the fatigue strength of the substrate. Therefore, the fatigue life of aluminum alloy 7075 is investigated in this paper. The investigation involved two different types of specimens, which are plain and V-notched specimens. The V-notch specimen involved two different V-notch groups: the V-notch with angle (α= 45°) and V-notch with (α= 90°).

2. Experimental work
The experimental work consists of three main parts. The first part includes studying the mechanical properties such as tensile test, hardness test, and impact test. The second part involves the preparation of fatigue test specimens. The third part involves the fatigue test for two group specimens; the first group consists of un-notched specimens, and a second group consisting of V-notch specimens.

2.1. Material selection and chemical composition
The aluminum alloy is more used in engineering structures and components since it has lightweight and corrosion resistance [9]; however, because of the broad uses in aerospace and automotive application, aluminum is considered in this investigation. The chemical composition is essential to know the number of elements that are added to the primary material. The result of the chemical composition of aluminum alloy 7075 is shown in Table 1. The chemical composition device of aluminum alloy has been worked by a spectrometer device, as shown in Figure 1.

| Element     | Al  | Zn  | Mg  | Cu  | Fe  | Si  | Mn  | Ti  | Cr   |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Nominal chemical composition | Basic | 5.1-6.1 | 2.1 | 1.2 | 0.5 | 0.4 | 0.3 | 0.2 | 0.18-0.28 |
| Al alloy    | Basic | 5.27 | 1.44 | 0.29 | 0.42 | 0.25 | 0.28 | 0.10 | 0.23 |

Figure 1. Spectrometer test device.
2.2. Mechanical properties of the material

The tensile test is vital to determine the main mechanical properties of materials, such as the limit of bending, bending resistance (elongation percentage), yield strength, ultimate strength, cutting limit of area, and many properties [10]. Tensile test samples are manufactured according to ASTM-A 370 [11] specifications (50 mm length and 12.5 mm diameter). Figures 2 and 3 show the geometry of the tensile shape and its dimensions. This test is done in the strength lab at the Mechanical Engineering Department at Babylon University, and it is shown in Figure 4. The results of tensile test of specimens are shown in Table 2.

![Figure 2. Tensile test specimens.](image)

![Figure 3. A schematic to test the tensile sample according to specifications (ASTM-A 370).](image)

| Material    | Stander Average value | Specimens Property |
|-------------|-----------------------|--------------------|
| Aluminum    |                       |                    |
| Yield strength $\sigma_y$ (Mpa) | 315 308 310 324 | 311 |
| Ultimate strength $\sigma_{ult}$ (Mpa) | 455 449 452 469 | 452 |
| Modules of elasticity $E$ (Mpa) | 70 72 69 73.1 | 70.3 |
| Percentage Elongation | 17 13 14 19% | 14.6% |

![Figure 4. Tensile test device.](image)
The hardness testing of aluminum alloy samples is done using the Brinell hardness test found in the strength lab at the mechanical engineering department/Babylon University. The hardness test device used is HB-3000B, a 150 kg load, as shown in Figure 5. This test method compressing a ball made of steel or tungsten carbide on a clean and flat sample of the material. The results of the test for three samples of aluminum alloys are shown in Table 3.

### Table 3. Show hardness test.

| Material  | Specimens | Specimens |
|-----------|-----------|-----------|
|           | Brinell (BHN) |           |
|           | 1        | 2         | 3         |
| Aluminium | 111      | 116       | 119       | 115.3     |

![Figure 5. Hardness test device.](image)

There are two impact test methods, the first one is the Izod method, and another is the Charpy method. Izod impact test was done using the impact testing machine of type (Brooks AME 01-19) according to ISO A 370, as shown in Figure 6. This test was conducted in the strength lab at the Mechanical Engineering Department/Babylon University. Results of this test are shown in Table 4.

![Figure 6. Impact test device.](image)
Table 4. Show the Izod impact test.

| Material | Specimens | Impact strength (KJou/m²) | Toughness fracture (Mpa.m⁰.⁵) |
|----------|-----------|---------------------------|--------------------------------|
|          | 1         | 2                         | 3                             | Average | 440 | 174.11 |
| Al 7075  | 40        | 45                        | 48                            | 44      |

3. Fatigue specimens preparation

The fatigue test was done using a programmable CNC machine. Fatigue specimens are worked with dimensions that suitable for the requirement of the machine test for cylindrical specimens. Two types (notched and smooth) of fatigue specimens are prepared according to fatigue test device specifications. All the plain (smooth) and notched cylindrical fatigue specimens are designed from aluminum alloy 7075, adopting a standard manufacturing process. The fatigue test specimen is designed according to ASTM WP-140 (single cantilever rotating bending model) specifications shown in Figure 7. The notches are made of V shape with two angles (α= 45°) and (α= 90°). The notch depth was (h=1 mm) [12][13], as shown in Figure 8. In this investigation, the fatigue test machine is designed and manufactured for cylinder specimens. The constant amplitude load (fully reversed bending) acted on a single rotating cantilever beam. Figure 9 shows the fatigue test machine.

Figure 7. A Schematic diagram for fatigue test specimens according to ASTM WP-140 specifications.

Figure 8. V notch shape in the specimen.

Figure 9. Fatigue test machine.
4. Fatigue test

In this investigation, the specimen was subjected to reversed bending stress in the test machine. The load cycle that acted on the specimen was shown using a digital counter. A rotating shaft (sample) is fixed using a clamped from one side, and a concentrated force acted on the other side. In this experiment, the maximum force that can be applied is (500) N, and the repeated (sinusoidal) cyclic load with a stress ratio (R = -1) is applied. For constant amplitude, stress can determine mean stress (σm), stress range (Δσ), stress ratio (R), and alternating stress (σA) as shown in figure 10. The force is applied on the opposite side perpendicular to the axis of the sample in order to obtain the rotating fatigue moment, and therefore the bending stress is taking place in this sample.

\[
\sigma_m = \frac{\sigma + \sigma_{\text{min}}}{2} \quad (1)
\]

\[
\Delta\sigma = \sigma - \sigma_{\text{min}} \quad (2)
\]

\[
R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \quad (3)
\]

\[
\sigma_A = \frac{\Delta\sigma}{2} = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{2} \quad (4)
\]

![Figure 10. Stress fluctuation for fatigue specimen under constant amplitude stress.](image)

The specimen surface is acted by tension and compression due to applied load until the specimen is broken. The alternating bending stress is determined using bending moment values and can be determined directly using Equation (5).

\[
F = m \cdot a \quad (5)
\]

The alternating bending stress can be calculated from the following equation:

\[
\sigma = \frac{M}{W} \quad (6)
\]

\[
W = \frac{\pi d^3}{32} \quad (7)
\]

\[
\sigma = \frac{32 F \cdot a}{\pi d^3} \quad (8)
\]

\[
\sigma \approx 2 F \quad (9)
\]

Where; M: is the bending moment (N.m), F: is applied force (N), a: is bending moment arm (106mm), \(\sigma\): is bending stress (MPa), d: is the diameter of the specimen (8mm), W: is the section modulus of the specimen.

5. Experimental results and discussion

Table 5 shows the S–N curve of fatigue data for three groups of specimens. The first group is un-notched (plain) specimens, the second group is notched specimens with an angel of (α=45°), and the third group is notched specimens with an angle of (α=90°). All these specimens are tested with reversed bending load and stress ratio (R = -1) at room temperature. In particle, almost most of the
structures have stress (load), but most of the fatigue failure occurs in the notched place because of stress concentration. These discontinuities or stress concentration factors usually result in maximum local stresses ($\sigma_{max}$) that are many times greater than the nominal stress ($\sigma_{min}$) of the member. The ratio of stresses in ideal elastic members selects the theoretical stress concentration factor $K_t$ [14].

As increasing the applied bending stress, the life cycle of the specimen for the three groups is decreased. In general, the fatigue life is different due to the varying applied stress levels, as shown in Figure 11.

$$\sigma_f = 1094.1 \ (Nf)^{-0.144} \quad (10)$$

Figure 12 shows the S-N curve of fatigue life for notched specimens. From this figure, it can be observed that the notched specimen with a notch angle of ($\alpha=45^\circ$) is broken (fails) before the specimen that has a notch angle of ($\alpha=90^\circ$) when applying the same bending load (stress). Alternating bending stress can be determined from Equations (11 and 12) for the notched specimen. The stress concentration factor for V-notched specimens was found in the literature around 2.4 for the angle of ($\alpha=45^\circ$) and 1.8 for the notch angle of ($\alpha=90^\circ$) [15].

$$\text{When } (\alpha=45^\circ) \quad \sigma_f = 850.9 (Nf)^{-0.156} \quad (11)$$

$$\text{When } (\alpha=90^\circ) \quad \sigma_f = 1090.4 (Nf)^{-0.168} \quad (12)$$

Figure 13 shows the corporation between the un-notched (plain) specimens and notched specimens with two different angles ($\alpha=90^\circ$ and $\alpha=45^\circ$).

| Specimen No. | Bending stress MPa | Cycle No. of fatigue life |
|--------------|--------------------|-------------------------|
|              |                    | Notched 45° | Notched 90° | Un-notched |
| 1            | 160                | 2.74×10^4   | 5.06×10^4   | 3.05×10^7  |
| 2            | 200                | 2.04×10^4   | 3.27×10^4   | 1.97×10^5  |
| 3            | 240                | 3.31×10^4   | 1.06×10^4   | 5.86×10^3  |
| 4            | 280                | 0.87×10^3   | 4.15×10^3   | 1.415×10^4 |
| 5            | 340                | 0.48×10^3   | 0.76×10^3   | 2.554×10^3 |

Figure 11. S-N Curve for un-notched specimens.
There are more methods for fatigue analysis; in this present work, the stress life method is used for numerical analysis using ANSYS software 18.2, where the result shows from maximum to minimum with different colors. After definition the material properties and modeling the specimen, make mesh to give accurate results. The number of elements is (40566) and (18168) for the model represent the specimen with a total number of nodes of (84851) and (9953) nodes for un-notched and notched specimens, respectively. After the meshing process, the boundary condition has been applied. These boundary conditions are used according to the configuration of geometry for the fatigue model. Boundary conditions are supports, constraints, and externally applied load (force). In this investigation, the model was a cantilever beam and fixed it from one side and apply force on the other side. Figures 14 and 15 show the fatigue properties such as fatigue life, safety factor, and alternating bending stress. In these figures, it can be noticed that the failed locations are shown in red color.
Figure 14. Boundary conditions, fatigue life, safety factor, and alternating stress for the un-notched specimens.

Figure 15. Mesh, fatigue life, safety factor, and alternating stress for notched specimen.
7. Conclusions
The fatigue life behavior of aluminum alloy 7075 under rotating bend fatigue load was studied. The investigation involved plain specimen and notched specimen. The study involved two different types of specimens, which are plain and V-notched specimens. The V-notch specimen involved two different V-notch groups: the V-notch with an angle of \(\alpha=45^\circ\) and V-notch with an angle of \(\alpha=90^\circ\). The test was conducted under fully reversed bending load with \(R=-1\) and at room temperature. The following conclusion can be drawn from the study:

1. The fatigue life of aluminum is decreased when the V-notch is simulated in the specimen.
2. The fatigue life of specimens containing V-notch with an angle of \(\alpha=45^\circ\) is better than the fatigue life of specimens with an angle \(\alpha=90^\circ\).
3. The fatigue life was reduced by around 50% and 70% when simulating a V-notch with angles of \(\alpha=45^\circ\) and \(\alpha=90^\circ\), respectively, although the same depth is kept.

8. Recommendations
1. Study the notch effect on fatigue life of aluminum alloy 7075 under constant bending stress with different environmental temperatures.
2. Study the effect of heat treatment on fatigue life behavior of V-notched specimens made of aluminum alloy 7075.
3. Study the effect of different surface treatments on fatigue life of V-notched specimens such as coating and peening.
4. Study the effect of different shapes of the notch on the fatigue life behavior such as U-notch and compare the result with V-notch and plain specimen.

### Nomenclatures

| Symbol | Description                                      | Unit  |
|--------|--------------------------------------------------|-------|
| A      | Cross-section area                               | m²    |
| a      | Bending moment arm                               | mm    |
| a, b   | Curve fitting constant                           |       |
| D      | Diameter of the cross-section for specimen       | mm    |
| E      | Modules of elasticity of a material              | Gpa   |
| Ei     | Initial pendulum energy                          | Joule |
| Er     | Remaining pendulum energy                        | Joule |
| F      | Applied load                                     | newton|
| Gc     | Impact strength of the material                  | Joule/m²|
| K      | Stress intensity factor                          | Mpa   |
| Kc     | Fracture toughness of the material               | Joule.m⁰.⁵ |
| M      | Applied moment                                   | N.m   |
| N      | Number of cycles                                 | cycle |
| R      | Stress ratio                                     |       |
| Us     | Impact energy                                    | joule |
| W      | Section modulus of the specimen                  | mm³   |
| σ      | Alternating stress                               | Mpa   |
| Δσ     | Stress range                                     | Mpa   |
| σm     | Mean stress                                      | Mpa   |
| σa     | Amplitude stress                                 | Mpa   |
| σmax   | Maximum stress                                   | Mpa   |
| σmin   | Minimum stress                                   | Mpa   |
| σY     | Yield stress                                     | Mpa   |
| σult   | Ultimate stress                                  | Mpa   |
| ASTM   | American Society for Testing and Materials       |       |
| ANSYS  | Analysis software                                |       |
| BHN    | Brinell Hardness Number                          |       |
| FEM    | Finite element method                            |       |
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