Notch Fatigue Behavior of Aluminum 2024-T6 in Four Point Bending Rotation

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Abstract-In some engineering applications rotating machinery components experience bending stresses due to location supports or misalignments, which often leads to fatigue degradation of critical components. This effect is enhanced when there is a presence of notches or sharp bends.

In this research, effect of notches on fatigue strength of an aluminum alloy is evaluated numerically and experimentally. The effect of notch root radius and depth of notch is investigated against fatigue failure. The fatigue behavior of un-notched and notched specimens was examined in ambient conditions under rotating four point bending fatigue loadings. Tests were performed using three types of notched specimens with three different stress concentration factors (Kt); 2.06, 2.46, and 3.64.The stress concentration increases with the increase of depth and decrease as root radius of specimen increases. It was clear from the experiments that all the notched specimens showed lower fatigue strength than un-notched and smooth specimens. Cracks initiated at the outer surface of notch root having very sharp notch having small root radius, and then propagated towards the neutral axis. It was also observed that such behavior depended strongly on loading levels and stress concentration factors. The specimens having small root radii showed lesser fatigue strength than those with larger radii.

Keywords-Fatigue, Rotating Machinery, 4 Point Bending, Notches, Stress Intensity Factor

I. INTRODUCTION

Fatigue of engineering materials and structures cause progressive, localize, and permanent damage. Such phenomenon occurs when repeated strains act on a material at nominal stresses that is well below of its static yield stress [i-iv]. There are many factors affect the fatigue strength of an engineering components. In this regard, the following factors are important: (a)Design considerations, e.g. size and notch existence, (b) Micro-structural features of material, e.g. grain size, grain distribution and orientation, the existence of precipitates, pores and other phases, (c) Manufacturing processes, e.g. surface finish, and internal defects, (d) Loading types and patterns, e.g. axial, bending, twisting and multi-axial loading and constant amplitude, variable and random loading, (e) Operating environment, e.g. temperature and severe corrosive medium [v-vii]. Crack growth rate and its propagation direction from notch could be successfully predicted using finite element method[viii].

II. LITERATURE REVIEW

Notches have less tendency for generating localized stress distributions. The factor is known as the theoretical stress concentration factor (k_t), increases applied load at the concentrated location. When amount of this factor become higher than crack-opening-threshold stress, thus expediting early fatigue crack initiation [ix].

It is impossible for the designers to avoid the presence of notches in engineering components. Basically ,A notch is a geometrical discontinuity which is usually introduced accidentally. Presence of such notches result Stress concentration but other factors may also generate stress concentration [x, xi]. Reference [xii] performed staircase experiments to study fatigue strength of screws made of wrought aluminum alloy 6082 and 6056. Smooth and notched specimens with the stress intensity factor (K) of 1.8 do not show endurance limit. Also the reference [xiii] determined notch stress intensity factor for the welded aluminum alloy which were related to fatigue strength. The reference [xiv] performed fatigue experiments on steel alloy with different hardness and found that crack propagation is too much longer than crack initiation in notched specimens. The results attained after experiment demonstrate the reliability and confidence of the examined materials, wherein the lifespan to propagate a crack from initiation size to a critical size is important, which offers a supplementary design margin. The number [xv] investigated the effect of residual stresses on the notch fatigue life of aluminum alloys. This alloy was mechanically treated to increase fatigue performance. Specimens having different types of notches were subjected to reverse bending fatigue tests. It was identified that mechanical treatments such as shot-peening improved the fatigue strength of aluminum alloy even in the presence of geometrical discontinuities. More improvement of fatigue strength was observed for increasing stress concentration.

The main objective of this research is to investigate the effect of a notch on the fatigue strength of a material subjected to rotating four-point bending. Normal axial stresses are the result of this type of loading. Propagation of initiated cracks in this case is in the opening mode, which is the most dangerous mode for fatigue crack growth. The present work also involves Finite Element Stress Analysis of tested specimens for their stress concentration factors calculation. Aluminum 2024 alloy is used as test material for its broad applications in aerospace industry.

III. NUMERICAL SIMULATION

The specimens were modeled in Pro-E Wildfire with and without V-notch at its mid span with different values of 'h', which is equal to (D-d) and notch root radii "as show in Fig. 6. Total six different simulations were performed using ANSYS software. First three iterations were performed keeping the 'h' constant and varying the notch root radius from 0.16 to 1.0 mm. Second three iterations were performed using constant notch root radius and changing the depth of notch from 0.5 to 1.5 mm.

After modeling the test specimen with different notch root radii, the files were imported to IGES for analysis in ANSYS software. “Tet 10node 187” element was selected for the analysis. The element is defined by 10 nodes having 3 degrees of freedom at each node, translations in the nodal x, y, and z directions. The element has hyper-elasticity, plasticity, creep, stress stiffening, large strain capabilities and large deflections. It also has mixed formulation capability for simulating deformations of nearly incompressible elasto-plastic materials and fully incompressible hyper-elastic materials. After performing the meshing, stress was applied on the mapped meshing and the results obtained from the software (ANSYS) are shown in the table1and Table II. From the results of table 1, it is clear that as notch root radius increases the stress concentration decreases, indicating that fatigue life of the components working under fatigue loading increases. The results in table 2 indicate that if notch root radius is kept constant and increasing the depth of notch greatly influenced the fatigue life. The stress concentration factor increases as the notch depth increases indicating early failure of the components.

In ANSYS, the values of moment were manipulated and compared with the applied values of 100 N-mm (Supposed value). It was proved that there was little negligible difference between the simulation and theoretical values in bending moment. The stress distribution at the outer face of the specimen is shown in Fig. 1. The values of the stress are almost zero at the neutral axis but increases from neutral to the outer fibers of the specimen.

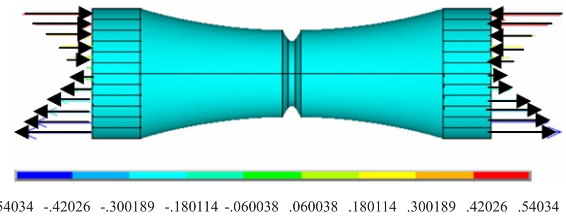

Fig. 1 Stress Distribution at outer face of the specimen After performing FEM analysis, it was came to know that stress is maximum at the outer periphery of the specimen containing a notch and stress distribution along the neutral axis is shown in Fig. 2.

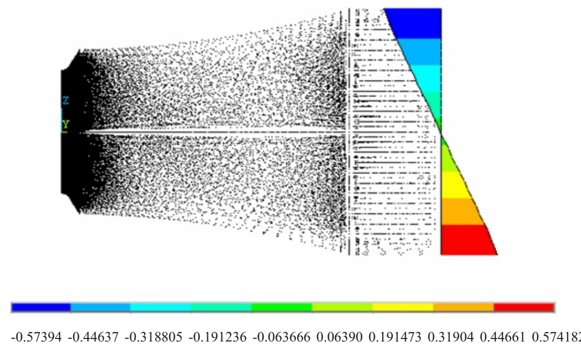

Fig. 2. Stress distributions along the neutral axis of the specimen

If notch root radius is kept equal to 0.356mm and depth of notch is 1 mm, the stress distribution is shown in Fig. 3.

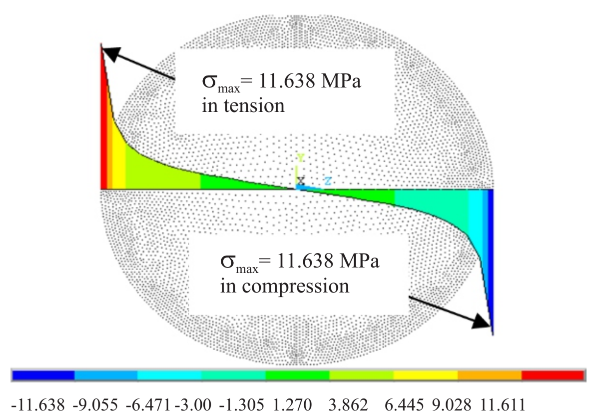

Fig. 3. Stress distribution in notched specimen having =0.356 mm, h =1 mm

If notch depth is decreases then stress also decreases at the outer most fibers of the components as shown in Fig. 4.

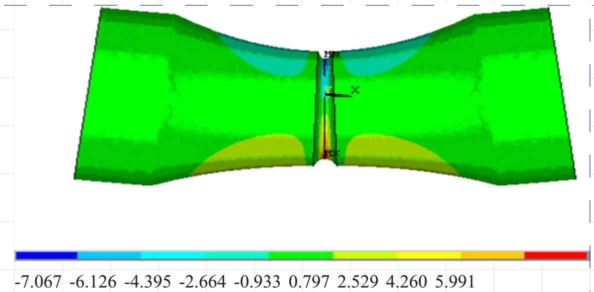

Fig. 4. Pictorial Stress distribution for a notch having =0.356 mm, h =0.5 mm.

The stress distribution calculated analytically is plotted and shown in Fig. 5, showing same values of stresses as shown in Fig. 4. The positive stress indicates tensile stress and negative stress indicates compressive stress as the specimen is under fully reverse bending.

IV. Experimental Analysis

The mathematical formulas were used to calculate stress concentration, bending moment, and maximum stress at notches by performing experiments on these specimens.

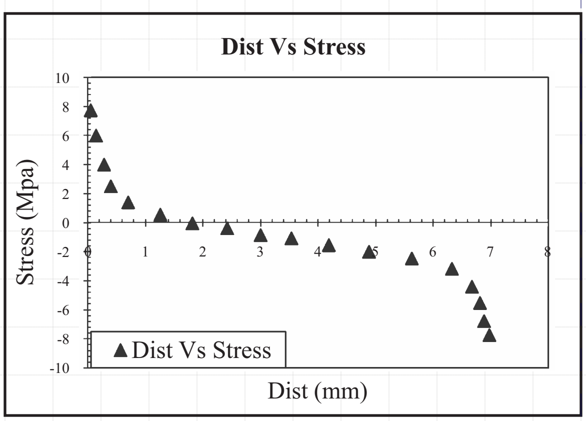

Fig. 5. Graphical Stress distribution for a notch having =0.356 mm, h =0.5 mm

Stresses acting parallel to the axis of notched and un-notched specimens having diameter d can be evaluated by using equation 1.

$$\sigma = \left(\frac{32M}{\pi d^3} \right) \tag{1}$$

where, M = Moment, 100 N-mm, d = Root diameter in mm

$$\sigma = \frac{1018.59}{d^3} \tag{2}$$

σ = Stress that is acting parallel to the axis of the notch root radius of the notched specimen. By using above formula, the calculated values of stresses (σ), the values of stress concentration factor is calculated by using equation 3 are shown in Table I and II.

$$K_t = \frac{\sigma_{max}}{\sigma} \tag{3}$$

TABLE I
Results of Stress Concentration Factor with Constant 'H'

Sr. No.	h (mm)	ρ (mm)	σ_{max} (Mpa)	Stress σ (Mpa)	K_t
1	1.0	0.16	17.169	4.718	3.64
2	1.0	0.356	11.611	4.718	2.46
3	1.0	1.0	8.627	4.718	2.06

TABLE II
Results of Stress Concentration Factor with Constant 'ρ'

Sr. No.	h (mm)	ρ (mm)	σ_{max} (Mpa)	Stress σ (Mpa)	K_t
1	0.5	0.356	7.857	2.971	2.39
2	1.0	0.356	11.611	4.718	2.46
3	1.5	0.356	19.516	8.153	2.64

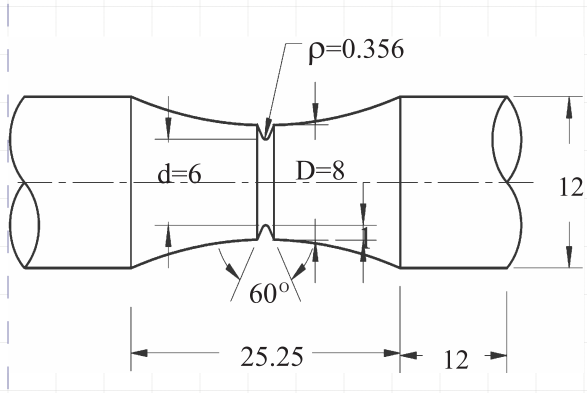

Fig. 6. Notched specimen

Experiments were conducted to investigate fatigue strength of notched specimens at room temperature. Tests were conducted on different configurations of specimens, One, external circumferential V-type notch as shown in Fig. 6 and the second configuration is un-notched specimen as shown in Fig. 7. It was found that the experimental stress concentration factor at room temperature increases with decreasing notch root radius keeping the depth of notch 'h' constant. Also the stress concentration factor increases with increasing the notch depth 'h' while keeping the notch root radius constant.

1. This experiment was conducted to investigate the stress concentration factor for a material 'Aluminum 2024-T6' having notches.
2. Four configurations of specimen were tested.
3. One configuration was un-notched.
4. The other three had circumferential notches with notch radii of 0.16 mm, 0.356 mm, and 1.0 mm respectively.

5. The minimum root diameter was 5 mm.
6. Testing was performed at room temperature.

V. RESULTS AND DISCUSSION

A. Mechanical properties

Following are the experimental results of the specimen tested on tensile testing machine.

TABLE III
MECHANICAL PROPERTIES OF THE TESTED MATERIAL

Dia mm	Area mm^2	Yield Load (kN)	Yield Str (Mpa)	Ul. Load (kN)	UTS (Mpa)	E (Gpa)
12.5	122.7184	42.4777	346.14	50.2232	409.26	68.7

B. Un-Notched Specimen

Un-notched specimens shown in Fig. 7, were tested on the fatigue & bend test machine. Total 10 specimens, until their breakage, were used for the analysis. The experimental results are plotted which are shown in Fig. 8, 9 and 10.

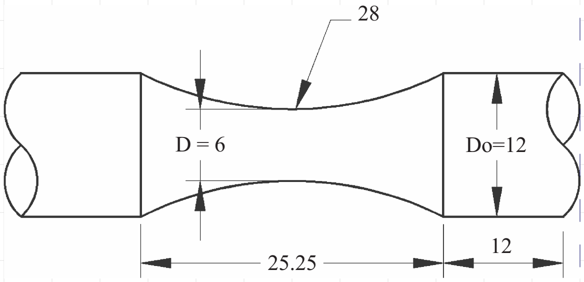

Fig. 7. Un-notched specimen

The S-N curve between Stress and cycles for un-notched specimens is shown in Fig. 8. From the S-N curve, it is clear that there is no Endurance Limit for an Aluminum material. Similar observations are also stated by number[xvi] for another non-ferrous alloy AA 6061-T6 even in giga-cycle regime.

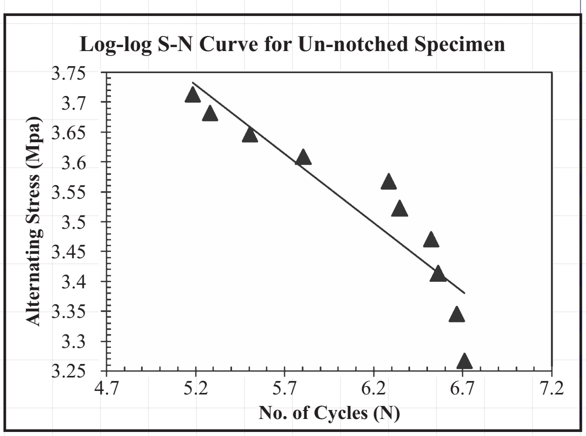

Fig. 8. S-N Curve for un-notched specimen

C. Notched Specimen

Fatigue and bend test machine was used to test specimens containing V type notches with different root radii. Analysis was performed on ten experimental tested specimens. The results obtained from the machine are plotted and are shown in Fig. 9.

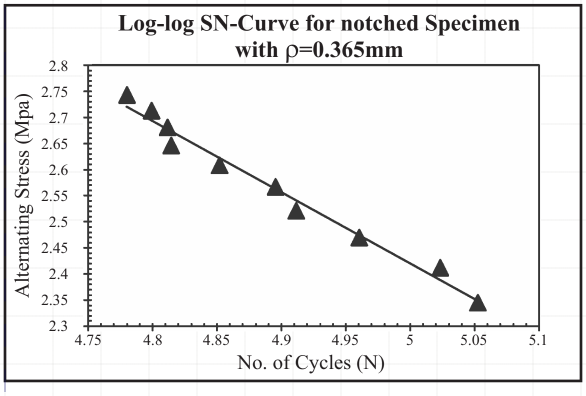

Fig. 9. S-N Curve of notched specimen, ρ=0.356 mm

S-N curve shows that there no main difference between Notched and Unnotched specimen, it is clear that there is no main difference. But due to notch, it fails at very low number of cycles at a small magnitude of load as all the dimensions of the tested specimens are same except a v type notch with a certain root radius.

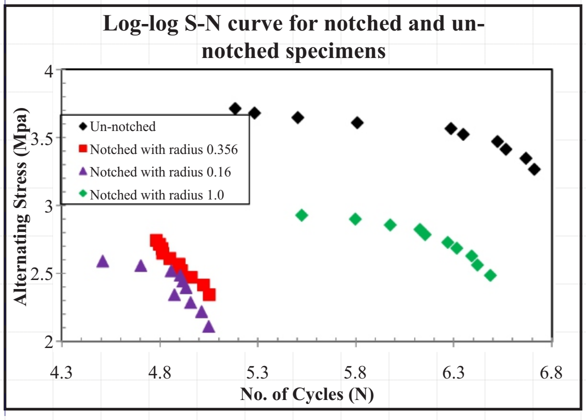

Fig. 10. Combined S-N Curves for notched and un-notched specimen at different notch root radius

From Fig. 10, it is obvious as notch root radius decreases the number of cycles to failure decrease.

VI. CONCLUSIONS

The experimental work is performed with different notch root radii and notch depth for Aluminum alloy to investigate its effects on fatigue life. Different types of analysis are performed i.e analytically, numerically and experimentally. After performing, it is identified that, by increasing the notch root radius with constant notch depth, the stress concentration factor decreases at room temperature because large notch root radius have low plastic region at the crack tip that causes lower stress concentration. By increasing the notch depth at constant notch root radii at room temperature, the stress concentration factor increases, because increasing the notch depth leads to higher stress concentrations.

Also by increasing root diameter the stress concentration decreases, having greater fatigue strength and fatigue life with greater root diameter. After drawing the different S-N curves, it is observed that the aluminum does not exhibit the endurance limit because the failure of aluminum occurs before the knee value of 10^6 cycles.

The results obtained by numerical simulation are very close to the experimental results.

The mechanical components must be avoid from sharp edges, V-type notches etc. to avoid early failures of the components working under fatigue loadings.

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