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Initiation and growth of fatigue cracks in sheets with U-shaped notches in the first and mixed modes of fracture

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A B S T R A C T

Abstarct This study presents the effects of the geometry of the notches on the fatigue life, crack initiation, and growth in mixed mode and first mode of the fracture. For this purpose, some samples were tested with U-shaped notches with different radii and depths and various orientations with respect to the loading directions under fatigue loads. Using the fatigue crack growth rates, the Paris law coefficients were obtained for the used material in different conditions. It was shown that these coefficients are independent of the geometry of the samples. Fatigue crack growth behaviors in the mixed mode tests were also in good agreement with the result of the numerical simulations. Predictions of the maximum tangential stress criterion and numerical simulation for the position of the crack initiation on the notch root were compared with the tested observations, which showed good agreement. The fatigue life of the test samples was compared with the analytical results provided by the Manson-Coffin law. It was shown that a 25% decrease in notch depth increases the fatigue life by 4 to 6 times, also, an increase of 0.5 mm in the notch radius increases the fatigue life by 40%. Finally, the fracture surface of the samples was checked using an optical microscope. This study showed that the fracture surfaces have one or two lateral shear lips and plane stress conditions were established.

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1. INTRODUCTION

Many engineering parts that are subjected to alternative loads during their lifetime have geometric discontinuities such as keyseats, oil holes, grooves, and threads which are generally known as notches. Commonly used notches in industrial parts are usually sharp (V-shaped) or curved (U-shaped). Notches, by creating the stress and strain concentrations, cause a significant reduction in the fatigue life of the parts. In the design process of structures, experimental and some numerical methods in calculating the fatigue life of notched parts have significant effects. Usually, the fatigue cracks occur in vulnerable areas of the parts, therefore, local stresses and strains in these areas and the fatigue properties of the materials must be considered. Some researchers have conducted various study in these fields.

Zheng [1] presented a proper relationship for the fatigue crack initiation life, related to the geometry of notched specimens, periodic loading conditions, metal behavior and properties, and the effect of tensile overload. The accuracy of this relationship was checked with the results of tests on the notched aluminum samples. De Freitas et al. [2] studied the crack initiation and microcrack growth in notched samples under different multi-axial loadings using the replica method. Zhang and Fatemi [3] investigated the growth behavior of a micro-crack from a notch, with considering the crack closure and stress ratio. They observed that at a lower stress ratio, the effect of the notch on the crack growth behavior is greater and more effective. Small cracks in a place affected by the notch have a higher growth rate than long cracks. Zhang et al. [4] in another study, based on the idea that fatigue failure is caused by periodic failure strains, introduced a concept of the critical failure value and developed a three-parameter model. This model includes three material efficiency parameters, namely fatigue ductility coefficient, fatigue ductility exponent, and theoretical strain endurance limit. The fatigue ductility coefficient indicates the presence of the critical damage quantity. Fatigue ductility shows the ability to resist material damage, and the theoretical strain endurance limit expresses the existence of the critical periodic strain. Using the presented

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model, it is possible to predict the life of the crack initiation life in the metallic materials.

Carpinteri and Paggi [5] investigated the effect of the crack and sample sizes on the relationship between the Paris and Wohler outputs. Branco et al. [6] investigated the fatigue behavior and life prediction of steel round bars with a side notch under bending-torsion loadings. They observed and analyzed crack initiation and crack growth using a high-resolution digital system. They investigated the notch effect using the concept of strain energy density and predicted the fatigue life with the Manson-Coffin model. They observed a very good agreement between the predicted and experimental fatigue lives, especially for lives greater than 10^4 cycles. These researchers proposed a criterion based on the principal stress amplitude to predict the most likely crack initiation location, surface crack growth path, and surface crack angle. The numerical predictions for different modes were very close to the experimental results. In their investigations, shear stress showed a significant effect on a-N and S-N diagrams. In this way, due to the increase in the range of the shear stress, a significant decrease in the fracture life and a lower slope due to the increase in shear stress were observed.

Gomez et al. [7] presented a simple but accurate criterion for predicting the failure load of brittle or quasi-brittle-notched specimens. They concluded that linear elastic fracture mechanics is not accurate for U-shaped notches, because these notches do not exhibit stress singularities. They observed a good agreement between the numerical predictions and the experimental results in studied cases. Benedetti et al. [8] investigated the effect of the notch geometry on the growth of the fatigue cracks caused by sharp notches. In their experiments, the effects of the notch geometries on the growth of the fatigue cracks caused by sharp V-shaped grooves by conducting experimental tests on Al-7075-T651 samples. Notches had grooves with opening angles of 45, 90, and 135 degrees. They investigated the path of the crack growth and determined the change in the growth angle due to the change in the loading angle. They concluded that the crack growth occurs from the root of a sharp notch in pure mode I. With the increase of crack length for loading in the direction of 45 degrees, the increase of mode II components was observed. Deviation of the crack was observed after 45 degrees of rotation in the direction of loading. Akhavan et al. [9] compared the numerical and analytical results with experimental data in calculating the fatigue life of the notched parts under uniaxial loading. They used the Smith-Watson and Fatemi-Socie methods to perform the analysis and compared the results of these two methods with the test results. They concluded that the Smith-Watson model is responsible for the range of stresses exceeding the yield limit, and in the range of low stresses, due to the dominance of elastic strain, this model provides more unrealistic predictions. Likewise, the Fatemi-Socie model shows more unrealistic results in this range due to the consideration of the shear stresses. Hu et al [10] theoretically investigated the Manson-Coffin relationship for life prediction of the microcracks. Using the theory of micro-fatigue crack growth, they derived the relationship between the growth rate of the fatigue cracks and the mechanical properties of the materials such as crack length, stress, and strain. They also compared the predicted crack growth rate with the experimental results of 16 types of carbon steels. Satisfactory consistency indicates that these relationships are widely applicable. Li et al. [11] expressed the interrelations between the parameters of the Paris law for fatigue crack growth. They developed the modified Walker equation and presented a relationship between the coefficients of the Paris relation in terms of the stress ratio. The original equations of Paris and Walker are the special and fundamental relations of the new equation. The life calculated by the new equation was in good agreement with the experimental results of 4 different materials.

Gomez et al [12] in another research used a new method for the study of the stress intensity factor (SIF) in notched samples under mixed mode loadings. They employed the averaged strain energy density criterion, cohesive zone model, or equivalent local mode approach for U-notched samples. They concluded that the critical stress intensity factor is only a function of the notch radius and independent of the loading mode.

In this study, the behavior of notched specimens in the first mode and mixed mode of failure under fatigue loading has been investigated. The effects of the notch geometry on the position of the crack formation, the crack Initiation life, and the final life of the samples have been determined. Also, it has been tried to provide a suitable and reliable method, composed of analytical method and numerical simulation, to calculate the fatigue life and crack propagation.

2. CRACK INITIATION AND GROWTH

Since the first studies on fatigue crack growth in the mixed mode I+II by Iida and Kobayashi [13], many advances have been made in this field. There are two important aspects in the mixed mode fatigue crack growth: growth direction and crack growth rate [14]. Various criteria have been proposed to predict the direction of crack growth in mixed-mode loading. The criterion of maximum tangential stress (MTS) is one of the most suitable theories used in this field which was presented by Erdogan and Sih [15]. This criterion is widely used despite its simplicity, and the prediction of crack growth is in good agreement with the experimental results [14]. The use of this criterion can be seen in the works of many researchers, such as Gdoutos [16], Yokobori et al. [17], Pook [18], Louah et al. [19], Nayeb-Hashemi et al. [20], Hyde and Chambers [21], Brown [22], Wang and Wang [23], Eftekhari and Xu [24] and other researchers.

Fatigue crack growth constitutes a significant part (more than a quarter) of the fatigue life of many engineering materials and components. Accurate prediction of the fatigue crack growth is the most important in determining the fatigue life. Crack length (a) variation versus loading cycles (N) is required to predict the fatigue crack growth for a given stress range ($\Delta\sigma = \sigma_{max} - \sigma_{min}$) at the critical point of any structure. In cases where the plastic deformation around the crack tip is small compared to the length of the crack, only one parameter, the SIF, can be used to determine the crack growth rate. In this method, the fatigue cycles are usually determined by the range of the SIF, $\Delta K = Q\Delta\sigma\sqrt{\pi a}$, where Q is the configuration factor.

The fatigue crack growth model expresses a differential equation that provides the best fit to describe the second region of the fatigue crack growth rate curve. One of the most widely used fatigue crack growth models is the model presented by Paris and Erdogan, known as the Paris Law.

$\frac{da}{dN} = C(\Delta K)^n$	(1)

where $\frac{da}{dN}$ is the crack growth rate, and *C* and *m* are the material constants.

For a wide range of crack growth in mode I, the information is conveniently represented by this equation. The constants C and m are experimental constants and are often considered parameters related to the material. If an effective value is defined for the SIF (ΔK_{eff}) versus the SIFs in various modes, the Paris law also can be used for loading in mixed mode. Tanaka [25] presented a relation for the first and second modes as follows:

$$\Delta K_{eff} = [\Delta K_I^4 + \Delta K_{II}^4]^{0.25} \quad (2)$$

Where ΔK_I and ΔK_{II} are the SIF ranges in mode I and mode II, respectively.

The efforts of other researchers such as Gerber, Goodman, and Soderberg led to a greater understanding of the fatigue phenomena and its relationship with the stresses created in structures. Coffin and Manson separately presented a proper equation for describing the relationship between induced elastic and plastic strain amplitudes and half cycles of the applied loads.

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \quad (3)$$

where $\frac{\Delta\varepsilon}{2}$ is the cyclic total strain amplitude, E is Young's modulus, σ_f' and b are the fatigue strength coefficient and exponent; ε_f' and c are the fatigue ductility coefficient and exponent; and $2N_f$ is the number of load reversals to failure.

Tateishi et al. in some studies [26, 27] proposed relations in the form of $\frac{\Delta\varepsilon}{2}N_i^k = C$ for estimating the crack initiation life, N_i where *k* and *C* are material constants. *C* parameter includes cyclic fatigue damage (Miner's rule) and ductile damage[28]. Based on the Manson and Coffin empirical equation and Tateishi relation, Zhang et al. [4] presented a proper relationship for the crack initiation cycles under cyclic damage strains as follows:

$$\frac{\Delta\varepsilon}{2} - \frac{\Delta\varepsilon_c}{2} = \varepsilon_f''(2N_f)^{c'} \quad (4)$$

where ε_f'' and c' are the fatigue ductility coefficient and exponent which differ from ε_f' and c in equation 3; $\Delta\varepsilon_c$ is the strain endurance limit and N_i is the number of load cycles to crack initiation. Based on the given data in [4], for AA 7075-T6 we have: $\varepsilon_f'' = 32.91\%$, $c' = -0.4765$, and $\frac{\Delta\varepsilon_c}{2} = 3.244 \times 10^{-3}$.

In engineering and using suitable tools for the inspection of structures, such as a microscope with normal accuracy, usually a crack with a length of 0.13mm to 0.25mm is considered an initiated crack [29]. However, in the principles of structural design, the length of the crack initiation is assumed to be in the range of 0.25mm to 2.5mm, and the number of loading cycles required until that stage is considered as the initiation life [30]. In the present research, these two relationships have been used to calculate the fatigue life of the samples as well as the initiation life.

3. EXPERIMENTS AND SAMPLES

To make notched samples, 7000 series aluminum sheets were prepared. To obtain the mechanical properties of the material and its constituent elements, required tests were performed. The XRF test results in Philips PW1730 machine confirmed that the alloy used in the production of the samples corresponds to the AA7075-T6 alloy. The results of the chemical composition test and comparison with the ranges given in the ASM handbook are depicted in Table 1.

Table 1. Chemical compositions in aluminum 7075-T6 alloy

Elements	Si	Fe	Cu	Mn	Mg
%wt in sample	0.07	0.13	1.5	0.03	2.5
	Zn	Ti	Cr	Al	
	5.7	0.04	0.18	89.1	
ASM Handbook	<0.4	<0.5	1.2-2	<0.3	2.1-2.9
	5.1-6.1	<0.2	0.18-0.28	87.1-91.4	

The tensile test was performed according to the ASTM E8/E8M standard by using the SANTAM tensile machine. By converting the engineering stresses and strains into true ones, the true stress-strain curve was calculated. The results are given in Figure 1. The calculated mechanical properties are as follows: Young's modulus 72GPa, yield stress 531MPa, ultimate strength 590MPa, and final failure strain 10%. According to the given data in reference [31], the final fracture stress is about 663 MPa, percentage of the cross-section reduction is 15%, and the Poisson's ratio will be 0.33.

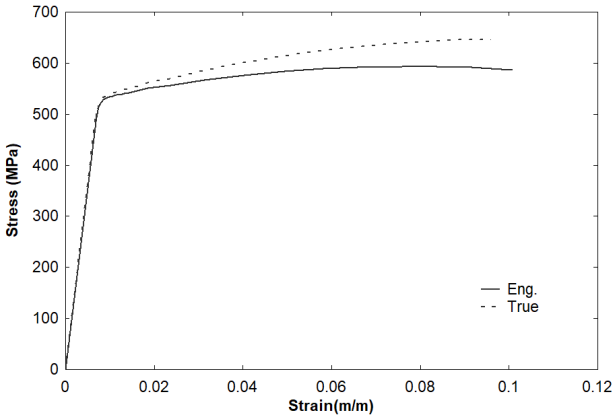
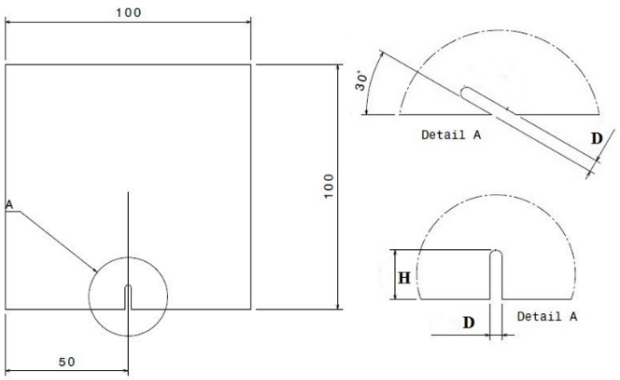


Figure 1. Engineering and true stress-strain curves for aluminum 7075-T6 alloy

Specimens with dimensions of 10 × 10 cm and 2 mm thickness were made. Then, notches with the required parameters were created on these samples. To create a notch, a mini milling machine with a milling blade with the required diameters was used. Through the simulations, milling cutters with diameters of 1.5, 2, 2.5, and 4 mm were found suitable and notches with these diameters were made on the samples. The depths of the notches on the samples were chosen to be 5, 20, and 15 mm. To investigate the behavior in mixed mode loading, notches were made with an angle of 90 degrees to the loading direction (for mode I) and 30 degrees (for mixed modes I and II). The construction details and a constructed sample are depicted in Figure 2.



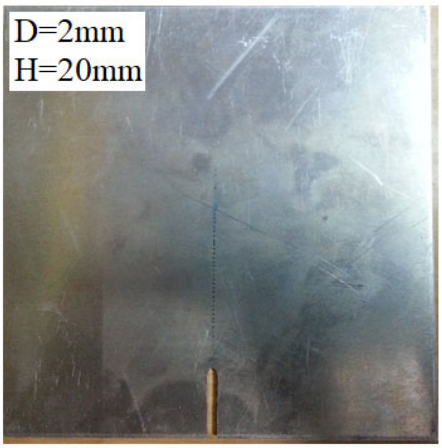


Figure 2. Dimensions of the specimens

12 samples were made with notch diameters of 1.5, 2.5, and 4 mm, depth of 5 and 15 mm in the vertical direction and 30-degree angle. Also, a sample with a notch diameter of 2 mm and a depth of 20 mm and another sample with a diameter of 4 mm and a depth of 15 mm were made to check the repeatability of the tests.

Fatigue tests were performed by a Zwick/Roell Amsler Hct 25 universal machine. This device is hydraulic and has a fixed lower jaw and a movable upper jaw. The view of this device and assembled mixed mode sample are shown in Figure 3. Due to the small size of the jaw clamps compared to the width of the test samples, suitable fixtures with rough surfaces were made to apply uniform loads. The maximum and minimum applied loads were 13kN and 1.3kN with a load ratio of 0.1. This means that the tests were subjected to a maximum stress of 65 MPa and a minimum stress of 6.5 MPa according to the cross-sectional area of the samples. Fatigue tests were performed with a frequency of 10 Hz. The frequency has not considerable effects on the fatigue in aluminum alloys [32]. To measure the length of the crack grown from the notch location, concentric circles with clear and short distances were created on the samples (Figure 3). This method is approximate but increases the speed of tests.



Figure 3. Fatigue testing machine with notched sample and concentric circles created on a sample.

In this research, the finite element method was used to determine the behavior of notched samples with and without cracks. An example of the built model, boundary conditions, and applied load, as well as fine elements around the notch and crack are given in Figure 4. As can be seen, the boundary conditions are displacement limitation at one edge and tensile surface traction at the opposite edge in the direction perpendicular to the notch.

For more appropriate analysis, singular elements around the crack tip have been used. For meshing of the cracked samples, an 8-node quadrilateral element in plane stress conditions, CPS8 was used. Also, the 4-node square elements were chosen for meshing the sample around the notch.

It should be noted that the accuracy of the finite element analysis can be increased to some extent by reducing the size of the elements at the crack tip, but this can lead to uneconomical analysis, especially in 3D models.

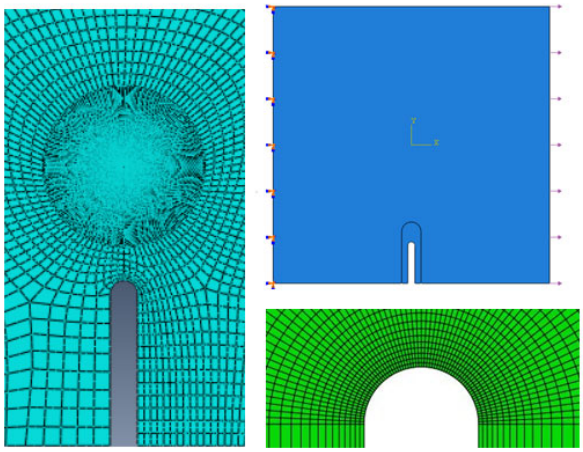


Figure 4. Notched sample and finite element models around the notch and crack

4. RESULTS AND DISCUSSION

To study the behavior of the samples with the presence of cracks, it was assumed that with the creation of a 0.2mm crack, the crack initiation phase has been completed and its growth phase started.

To investigate the effect of the notch diameter on the stress intensity factor for initiated cracks, a short crack with a length of 0.2 mm was modeled at the root of the notches with different radii. The obtained results for SIFs in terms of notch diameter changes are shown in Figure 5. As can be seen, for larger notches, changes in the SIFs are less, and in smaller notches, their changes are more noticeable.

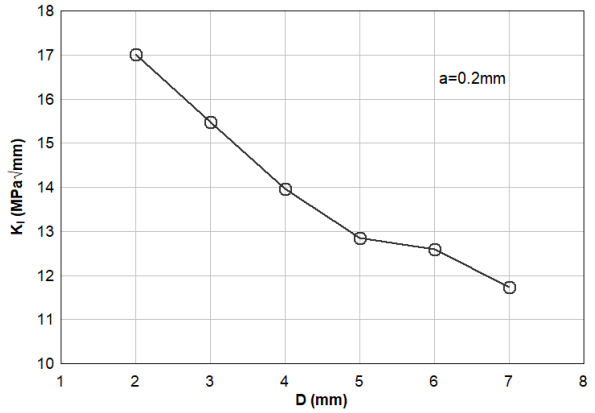


Figure 5. Variations of the SIF versus notch diameter for a short crack of 0.2 mm

After crack initiation and propagation, for a given number of cycles ΔN, the change in the crack length Δa, was recorded. The obtained changes in crack length versus number of loading cycles for fatigue cracks from vertical notches (T0) with diameters of 1.5, 2.5, and 4 mm are shown in Figure 6. It should be noted that for all three cases, the critical crack length is almost the same.

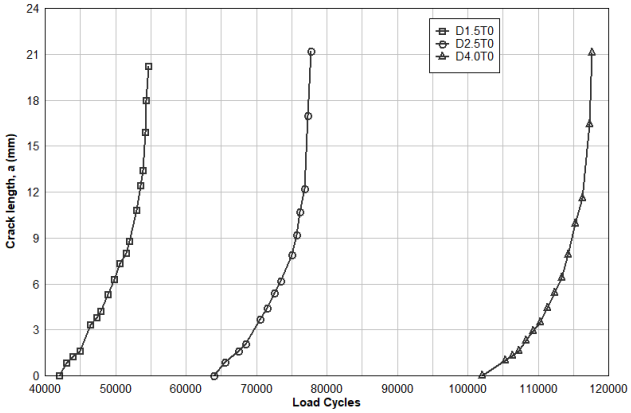


Figure 6. Crack length variations in samples with vertical notches (T0)

For the tested samples, ΔK values were extracted for different crack lengths in numerical modeling. Logarithmic graphs of fatigue crack growth were drawn for these samples. In each of the samples, a linear function was fitted to the data to obtain Paris correlation coefficients. It should be noted that in these charts, ΔK in $MPa\sqrt{m}$ and da/dN in $mm/cycle$ are placed. The results of these analyses are depicted in Figure 7 and the resulting coefficients are given in Table 2.

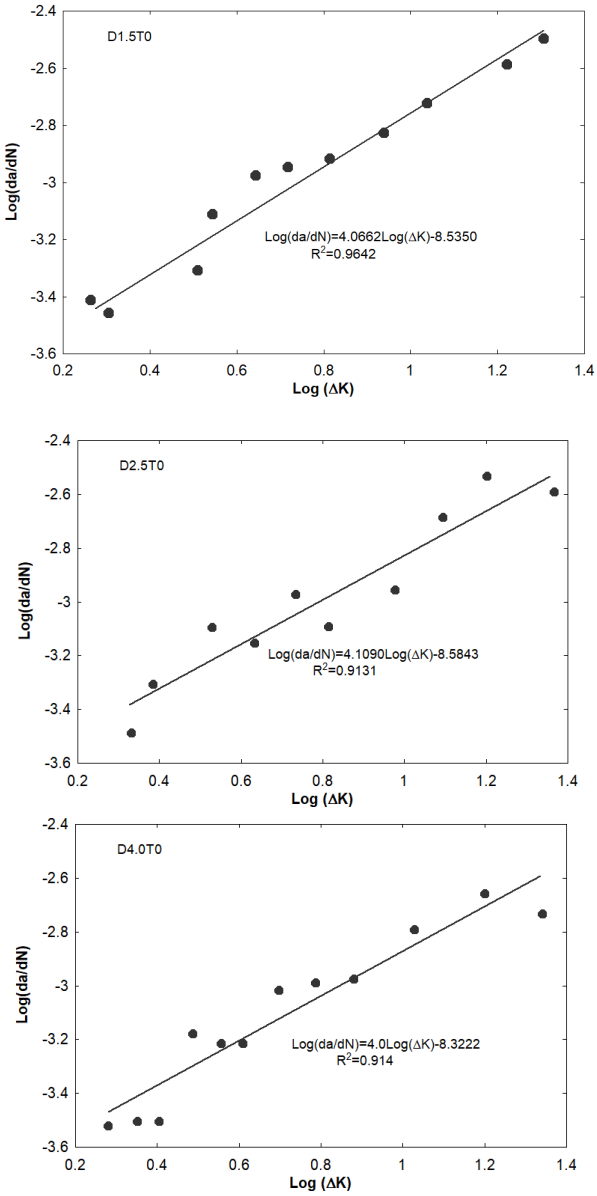


Figure 7. Variations of the fatigue crack growth rate versus SIF for notches with different diameters

Table 2. Paris correlation coefficients

D(mm)	C	m
1.5	$10^{-8.5350}$	4.0662
2.5	$10^{-8.5843}$	4.1090
4.0	$10^{-8.3222}$	4.0000
Average	3.43×10^{-9}	4.0584

According to the values obtained for the parameters of the Paris equation in Table 2, it can be said that the coefficients C and m are acceptably independent of the geometry of the samples. Of course, the effects of the geometry and dimensions of the samples in the ΔK calculation are included. By using the obtained Paris coefficients, the simulation has been done for samples with an angular notch with a diameter of 4 mm and 1.5 mm, and by advancing the crack growth step by step in the software, the crack length diagram is plotted in

terms of the loading cycles and compared with the test results. To make this comparison and use the Paris relation, the effective SIF in the mixed mode is used from equation (2). Changes in the effective SIFs in terms of the crack length for the D4.0T30 state (notch diameter 4.0mm and angle 30 degrees) are given in Figure 8. In the simulation, it was observed that after a short period of crack growth in the mixed mode, the crack grew in a direction perpendicular to the loading direction (mode I). These changes in Figure 9 can be observed. The comparison of the crack growth diagram in terms of loading cycles in the simulation with the experiment is shown in Figure 10.

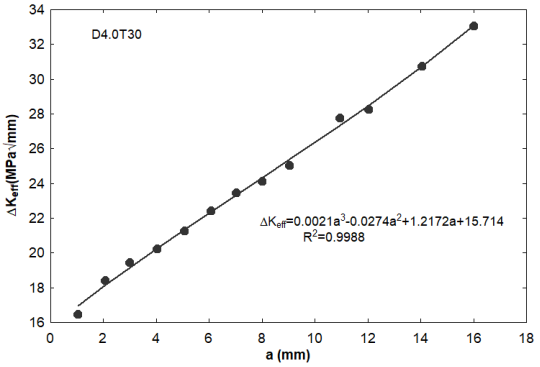


Figure 8. Variations of the ΔK_{eff} versus crack length for sample D4.0T30

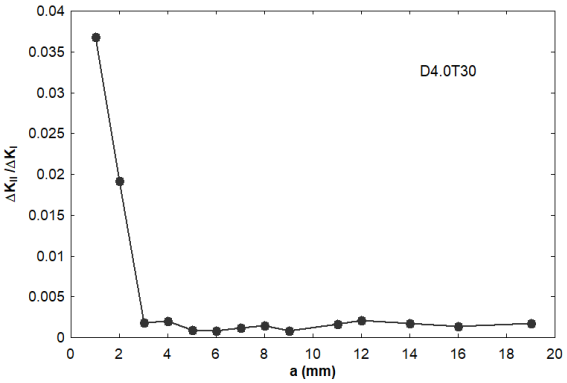


Figure 9. The ratio of SIFs in modes I and II, for sample D4.0T30

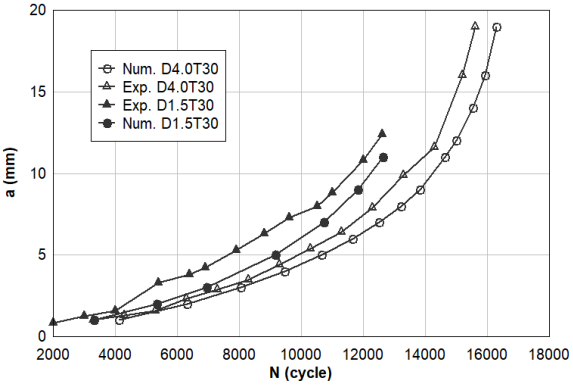


Figure 10. Numerical and experimental results of the crack length for T30 samples

It can be seen that the numerical prediction results have an acceptable agreement with the experimental data. The point is that the estimation with the help of numerical calculations gives a smaller crack length for a certain number of cycles than the experimental value.

4.1. PREDICTION OF CRACK INITIATION LOCATION

As mentioned, the simplest and most widely used criterion is the maximum tangential stress (MTS) for crack initiation location. In this research, an attempt was made to examine the place of the crack growth using this criterion and compare it with the test results. For this purpose and to determine the distribution of the tangential stress at the root of the notch in the results of the simulation, cylindrical coordinates were defined at the center of the notch and the stresses at these new coordinates were calculated. S_{22} shows the tangential stress in the simulation results. Figure 11 shows the location of the maximum tangential stress in samples with a notch diameter of 2.5 mm in vertical and inclined modes. The test performed on the sample with the same notch diameter confirms that the place where the crack starts is the place predicted by the MTS criterion. As it is seen, the MTS criterion has provided an appropriate prediction of the crack initiation location.

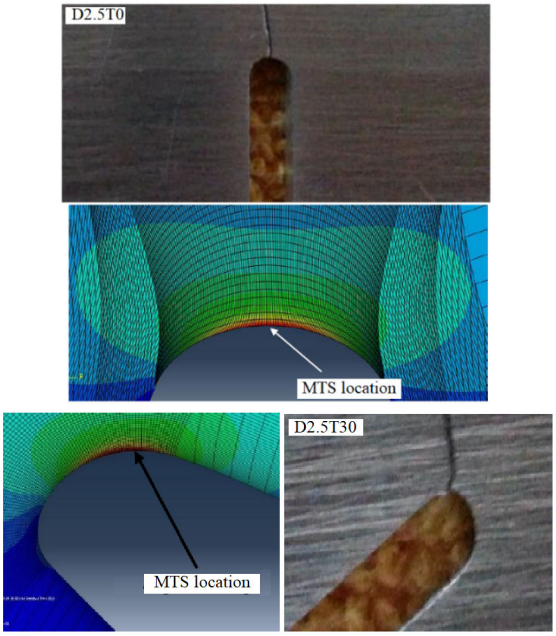


Figure 11. Comparison of MTS criterion with test results in predicting the crack initiation location

4.2 FATIGUE LIFE

The fatigue process of a structure until the final fracture can be considered as two separate stages. The load or strain cycles required to create a crack with a known little length are defined as the crack initiation life (N_i). Therefore, the crack propagation stage includes the number of remaining cycles N_p for the crack to grow to a critical size at fracture. Hence, $N_f = N_i + N_p$ where N_f is the total fatigue life. In this research, the crack initiation life is assumed the number of loading cycles until the observation of a crack with a short length (about 0.2mm) compared to the notch diameter. For the analytical

calculation of the overall fatigue life, the Manson-Coffin relationship has been used. The parameters of this relationship for the used aluminum alloy 7075-T6 are given different values in different references. As an example, a few are given in Equation 6. The results of these relationships as well as the result of the curve fitted to their average are presented in Figure 12. In the following, the average curve and its parameters are used.

$\frac{\Delta\varepsilon}{2}=\frac{1317}{72000}(2N_f)^{-0.126}+0.19(2N_f)^{-0.520}$	ASM [33]	(5)
$\frac{\Delta\varepsilon}{2}=\frac{970}{71300}(2N_f)^{-0.105}+0.044(2N_f)^{-0.461}$	Ref. [34]	
$\frac{\Delta\varepsilon}{2}=\frac{1067}{70500}(2N_f)^{-0.0893}+0.131(2N_f)^{-0.674}$	Ref. [31]	
$\frac{\Delta\varepsilon}{2}=\frac{1466}{71000}(2N_f)^{-0.143}+0.262(2N_f)^{-0.619}$	Ref. [35]	
$\frac{\Delta\varepsilon}{2}=\frac{1222}{72000}(2N_f)^{-0.1159}+0.1506(2N_f)^{-0.5724}$	Average	

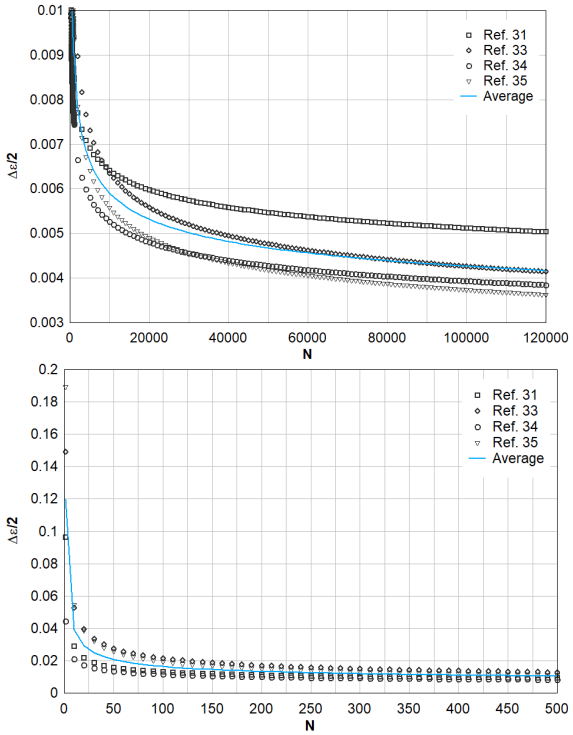


Figure 12. Manson-Coffin equation results for AA7075-T6 in different references and their average values

Stress concentration factors (SCFs) in parts with cracks, grooves, and notches are higher than the smooth and flawless parts under the same loading conditions. What is certain is that the existence of defects, notches, and cracks in the parts considerably reduces the fatigue life. Most engineering parts also have geometries with stress risers. The geometry of the notch has a great influence on the fatigue behavior of these parts. As shown in Table 3, smaller notch diameters create more stress concentration factors. In other words, it can be said that samples with a smaller notch diameter have a shorter fatigue life, which is in acceptable agreement with the experimental results. The test results for the life of crack initiation with about 0.2 mm and the final life of parts with different notches are given in Table 3. For all samples, the notch depth was 15 mm.

Table 3. Experimental lives of samples with different notch diameters

D(mm) T0	SCF	N_i (Cycle)	N_p (Cycle)	N_f (Cycle)
1.5	6.748	42000	13200	55200
2.5	5.348	64000	13700	77700
4.0	4.348	102000	15600	117600

As can be seen, the change of the notch diameter from 1.5 mm to 2.5mm and 4.0 mm respectively shows more than 40% and 110% increase in the final fatigue lives. On the other hand, it can be said that the diameter of the notch is quite effective on the lifetime of the crack initiation, but it does not have a significant effect on the life during the crack growth stage. For two small notch diameters, the crack growth life is about 13000 cycles and for larger diameter about 15000 cycles, which are at the fatigue life deviation level.

Therefore, it can be stated that the geometrical dimensions of the notch affect the short crack growing from the notching site, but for longer cracks growing, the fatigue behavior will not be different despite the presence of notches with different diameters. In other words, the geometry of the notch is more effective on the short cracks emanating from the notch root and raises the growth rate at the beginning near the root. Also, the critical crack length (a_c) and crack growth instability situations are almost the same for all samples. This point is also a confirmation that the effect of the notch geometry on cracks is noticeable in the early stages of growth and close to the root.

In the numerical analysis, the values of the effective strains at the critical point of the notches root under the maximum and minimum loads have been obtained using the stress-strain curve and specified geometry of the notches. Using these results, the range of the strains was calculated for each case. With these values, the predicted final life of the samples was calculated using the Manson-Coffin relationship with the average constants (the last relation in Equation 5). Also, the crack initiation life was determined from Equation 4 using the parameters given for AA7075-T6. The calculation results are given in Table 4.

Table 4. Calculated and experimental fatigue lives

D(mm)	$\frac{\Delta\varepsilon}{2}(\times 10^{-3})$	Cal. N_i	Exp. N_i	Diff. %
1.5	4.648	47060	42000	12
2.5	4.398	71019	64000	11
4.0	4.170	112718	102000	11
		Cal. N_f	Exp. N_f	Diff. %
1.5	4.648	52250	55200	-5
2.5	4.398	79100	77700	2
4.0	4.170	119000	117600	1

Comparison of fatigue life predicted by the Manson-Coffin relationship with test results shows that the error of this relationship is less than 5% for final failure and about 11% for initiation in all 3 samples. As a result, it can be said that the life predicted by this method is reliable. Of course, the life of the tested samples is less than the calculated life in most cases. Experimental fatigue lives for inclined and vertical specimens are given in Figure 13. It is interesting to note that in angular samples, the fatigue life has decreased considerably. The angular sample with a notch diameter of 1.5 compared with the vertical has a 57% reduction. For samples with a notch diameter of 2.5 and 4 mm, the lifetime of the angled samples was 53% and 35% less than their vertical samples, respectively.

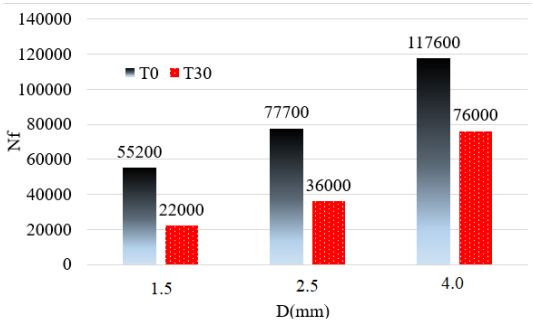


Figure 13. Comparison of fatigue lives for vertical (T0) and angled (T30) samples

Considering that the geometry and loading are the same in samples with inclined and vertical notches, it seems that the cause of this reduction in life is the larger stress area in angled samples. To investigate this issue, vertical and angular samples with a notch diameter of 4.0 mm were statically loaded and their Tresca stresses (twice of maximum shear stresses) were compared in Figure 14.

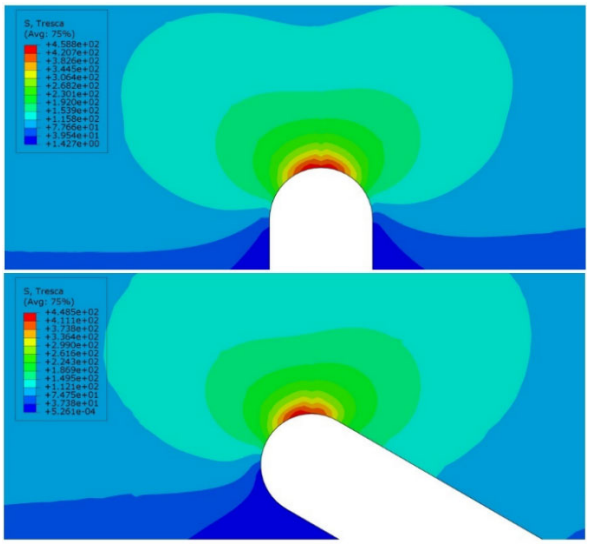


Figure 14. Tresca stress (in MPa) comparison around the notch root for D=4.0 mm.

As can be seen, the maximum value of Tresca stresses in the two cases is not significantly different, but the areas with high-stress levels are larger for the angled case, which can lead to micro cracks in more positions and reduce fatigue life.

The Manson-Coffin equation was used to investigate the effect of the notch depth on the fatigue life of the samples. The values of the strain amplitudes and predicted lives for different notch depths in D1.5T0 and D4.0T0 samples are calculated and listed in Table 5.

Table 5 Effect of notch depth H on the fatigue life in D1.5T0 and D4.0T0 samples

Sample	H(mm)	$\frac{\Delta\varepsilon}{2}(\times 10^{-3})$	Cal. N_f
D1.5T0	5	2.655	$> 10^6$
	15	4.648	58000
	20	6.1425	14000
D4.0T0	5	2.257	$> 10^6$
	15	4.170	113000
	20	5.354	20000

As Table 5 shows the depth of the notch has a significant effect on the fatigue life of the samples. In D1.5T0 samples, a 5 mm reduction in the depth of a 20 mm notch increases the fatigue life from 14000 to 58000 cycles (approximately 4 times) and for a more 5 mm reduction, the fatigue life will be unlimited. In the experimental test on a sample with a 5 mm depth notch, for up to 250000 load cycles, no cracks were observed. Mentioned behaviors also can be seen in D4.0T0 samples with smaller strain amplitudes and larger lives.

What emerges from the discussion is that increasing the notch diameter increases the fatigue life, while increasing the depth decreases the life of the sample. To investigate the simultaneous effect of these two parameters, a sample with a notch diameter of 2 mm and a depth of 20 mm and another sample with a notch diameter of 1.5 mm and a depth of 15 mm were tested. For the first sample, we reached 54000 cycles for fracture while for the second case, it was 21000 cycles. Considering that increasing the notch diameter increases the life but increasing the depth decreases it, one can see that the effect of the notch depth is greater due to the combination of these two modes. Of course, it should be kept in mind that with the increase of the depth of the notch, the nominal stress at the notch location increases, but with the increase of its diameter, the stress concentration coefficient decreases. It seems that in this confrontation, the effect of increasing far-field tension is dominant.

4.3 FRACTURE SURFACES

After the tests, the fracture surfaces were examined by an optical microscope. As shown in Figure 15, the fatigue crack growth zone can be divided into two distinct zones, in zone I, the crack grows in the flat surfaces in the initiations stages, and in zone II, the fracture surfaces take an angle of approximately 45 degrees and a one-sided or two-sided shear lips formed. This is due to the small thickness of the samples and plane stress conditions. In Figure 16, the fracture surface of samples with different notch diameters is shown.

It can be seen that the crack initiation surface is more uniform for the 4 mm sample. Zone I for this sample is also slightly larger than the other samples. Region II is the same and similar for all samples. In three samples, for the first stages the crack surface is almost flat and has grown in the form of plane strain conditions. The reason is that first, the crack starts growing from the sides and then from the middle segments. At the

beginning of the crack growth, fully three-dimensional stress and plane strain conditions exist. After the crack propagated through the entire thickness of the sample, plane stress conditions were established for all three samples, and the fracture surfaces were propagated with the shear lips.

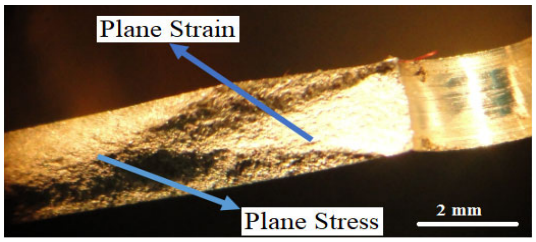


Figure 15 The fracture surface of the sample with a notch diameter of 2 mm

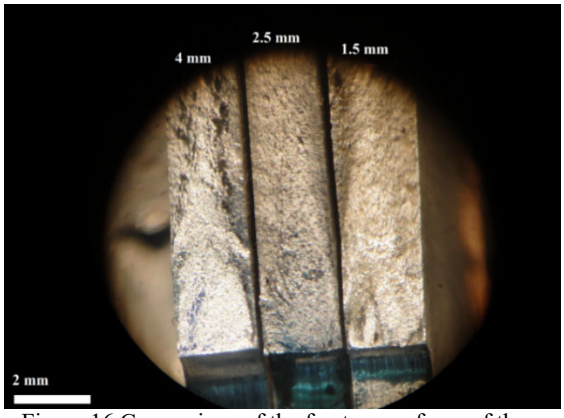


Figure 16 Comparison of the fracture surfaces of three samples with different notch diameters

5. CONCLUSIONS

In this study, the effects of notch geometry and profile in sheet samples on the fatigue behavior in the first and mixed modes of the fracture have been investigated. The situation of the crack initiation in the samples has been calculated with the maximum tangential stress criterion and compared with the experimental results. The crack initiation and fatigue lives of the samples were calculated with the Manson-Coffin's equation and compared with the results obtained in the experiments. Paris law coefficients for cracked samples were calculated according to strain rate diagrams and existing relationships. To investigate the effect of the notch geometry, samples with different dimensions were investigated. The samples were different from each other in terms of diameter, depth and notch angle.

Numerical simulations were performed to predict the crack growth rate and its characteristics. To investigate the crack growth in the first and mixed modes, Paris law was used with the average coefficients obtained in this research. The stress intensity factors in the first and second modes as well as their effective values in different stages of the crack growth were calculated and compared with the results obtained experimentally. Finally, fracture surfaces were observed using an optical microscope and compared in their different states in the samples. By carefully investigating the obtained results, the important conclusion are as follows:

- The fatigue life of the samples increases due to the increase in the notch diameter. Changing the notch diameter from 1.5mm to 2.5mm increases life by 40%, and a 4mm diameter notch increases life by over 110%.
- Increasing the depth of a notch has a significant effect on the fatigue life. Numerical simulations using the Manson-Coffin's equation showed that a 5 mm reduction in depth from 20 to 15 mm increases the calculated fatigue life approximately 4 to 6 times. With a depth of 5 mm, regardless of the diameter, the life of the sample will be unlimited.
- Fatigue life of samples with angled notch is significantly reduced compared to ones with vertical notches. The reason for this reduction in life is the increase of high stress areas in the critical points around the notch root.
- The maximum tangential stress criterion provides a good prediction of the crack initiation location.
- The growth direction in samples with vertical notch was perpendicular to the loading direction (Mode I) and for angled notches, after a little growth in the mixed mode, the direction of the crack inclined to first mode of the fracture.
- The maximum error of approximated life by using the Manson-Coffin's equation was about 10%. The predicted lives were higher than the obtained values in the experiments in all cases.
- Correlation coefficients of Paris law in the notched samples are independent of the geometry of the samples.
- The study of the fracture surfaces shows that in the samples with the desired thickness, the plane stress conditions are established and shear lips created for all samples. But in the initial stages of the crack propagation from the edges and sides of the notch root, one can see there is a state of the transformation from plane strain to plane stress conditions, which create a flat surface about twice the thickness.

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