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Ultrasonic and Conventional Fatigue Endurance of Aeronautical Aluminum Alloy 7075-T6, with Artificial and Induced Pre-Corrosion

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Abstract: Ultrasonic and conventional fatigue tests were carried out on the AISI-SAE AA7075-T6 aluminum alloy, in order to evaluate the effect of artificial and induced pre-corrosion. Artificial pre-corrosion was obtained by two hemispherical pitting holes of 500-µm diameter at the specimen neck section, machined following the longitudinal or transverse direction of the testing specimen. Induced pre-corrosion was achieved using the international standard ESA ECSS-Q-ST-70-37C of the European Space Agency. Specimens were tested under ultrasonic fatigue technique at frequency of 20 kHz and under conventional fatigue at frequency of 20 Hz. The two applied load ratios were: R = −1 in ultrasonic fatigue tests and R = 0.1 in conventional fatigue tests. The main results were the effects of artificial and induced pre-corrosion on the fatigue endurance, together with the surface roughness modification after the conventional fatigue tests. Crack initiation and propagation were analyzed and numeric models were constructed to investigate the stress concentration associated with pre-corrosion pits, together with the evaluation of the stress intensity factor in mode I from crack initiation to fracture. Finally, the stress intensity factor range threshold ∆KTH was obtained for the base material and specimens with two hemispherical pits in transverse direction.

Keywords: Al alloy 7075-T6; ultrasonic fatigue; artificial pits; pre-corrosion; crack initiation

1. Introduction

One of the most versatile metal used in industrial applications is aluminum and its alloys; it is the second widely produced metal after steel. Particularly, its alloys are often used in modern industries: more than 40% of aerospace and aeronautical parts are made of these alloys nowadays [1–4]. Frequently, such industrial applications imply a combination of mechanical loading and corrosion, which leads to stress concentration and failure of the material. Pitting corrosion is one of the most damaging effect on materials, difficult to predict in order to avoid damage and failure in industrial components [5–9]. In previous numeric investigations [10], it was found that orientation of the corrosion pits regarding the applied load plays a significant role on the stress concentration factors. An important number of studies has been focused to understanding how cracks initiate and propagate in materials influenced by external factors, such as corrosion pitting, surface conditions, temperature and others [10–13]. A main motivation to carry out this research work is that no studies have been developed concerning the effect of pre-corrosion on the fatigue endurance, under conventional and ultrasonic tests, on this aeronautical aluminum alloy. Concerning surface roughness, fatigue life has been studied in a carbon steel, showing that this superficial parameter influences fatigue life only during crack initiation.
stage [14]; others investigations [15,16], have referred that fatigue life is reduced with the increase of roughness. In this study, the roughness has been registered before and after the conventional fatigue tests, in order to record its variation.

On the other hand, several studies have pointed out the correlation between pitting corrosion and the reduction of fatigue life [17–20], taking the maximum or the average pit size as the initial crack size; nevertheless, no consideration of pits interactions has been considered inducing high values of stress concentrations factors. In this study, a numeric model reproducing two pits on the specimen surface is developed in order to investigate the increase of stress concentrations factors associated with its orientation. Fatigue endurance of pitting metals can be improved applying shoot peening, which induces compression residual stress [21,22].

2. Materials and Methods

The chemical composition (% in weight) and the main mechanical properties of AA7075-T6 aluminum alloy are listed in Tables 1 and 2, respectively. In order to obtain experimentally some mechanical properties as yield stress and ultimate tensile stress of this aluminum alloy (Table 2), tests were conducted on universal testing machine Instron 1255 (Instron, Norwood, NY, USA) on 4 specimens (cold-rolled Al7075-T6 sheet, tension applied parallel to the rolling direction of the sheet) of non-standard dimensions and at room temperature.

| Zn. | Mg | Cu | Cr | Fe | Al |
|-----|----|----|----|----|----|
| 6.9 Max. | 2.7 Max. | 1.87 Max. | 0.2 Max. | 0.4 Max. | Balance |

Table 2. Main mechanical properties of aluminum alloy 7075-T6.

| Density (kg/m³) | Hardness (HV0.1) | σ_y (MPa) | σ_u (MPa) | Poisson Ratio | Elastic Modulus (GPa) |
|----------------|------------------|----------|----------|--------------|----------------------|
| 2800           | 155.12           | 453      | 538      | 0.33         | 70                   |

The specimens used in ultrasonic fatigue test were machined from an AA7075-T6 plate, its dimensions were determined by modal numeric analysis in order to fit the resonance condition: the natural frequency of vibration in longitudinal direction close to frequency of excitation source (20 kHz ± 300 Hz). The dimensions (mm) are shown in Figure 1a for the ultrasonic specimen and, Figure 1b for the conventional specimen. In Figure 2 is depicted the result of modal analysis: 19,929 Hz of natural frequency for ultrasonic specimen with dimensions presented in Figure 1a, using the mechanical properties of Table 2: density, Young’s modulus and Poisson ratio. Ansys 19-R1 was used with 12,120 elements, 55,753 nodes and a fixed support at the specimen’s end as boundary condition.

Specimens used for conventional fatigue tests present similar dimensions of the previous ultrasonic specimens, slightly modifications were introduced, such as: a machined rope at the extremes of specimen in order to fix it to the testing machine, Figure 1b.

Experimental Set Up

All ultrasonic fatigue tests were performed with the self-designed and constructed machine Figure 3, which is totally controlled by a LabVIEW program (Version 2015, National Instruments, Austin, TX, USA), allowing the test initiation, the record of the number of cycles in real time and the automatic stop with the specimen’s failure. Calibration of displacements of specimens at the free end was carried out by an inductive proximity sensor (Keyence, Itasca, IL, USA), which has a resolution of ±2 μm, working at 1.5 MHz. All tests were obtained at room temperature (close to 23 °C), with environmental humidity between 35% to 55% and full reversed load ratio R = −1.
The experimental start up for each specimen under ultrasonic fatigue tests was as follows: stabilization of the system for 30 s with an applied load of 44 MPa (corresponding to the lower voltage of ultrasonic generator: 10 volts); afterwards, increasing 4.4 MPa each second to attain the desired applied load.

Conventional fatigue tests were conducted on a servo–hydraulic testing machine, in which frequency can be imposed from 0.5 to 20 Hz. The complete system of the machine was developed in the University of Maribor, Slovenia [23]; an overview is depicted in Figure 4. The manufacturing of
the parts and the whole controlling system for the machine was configurated to work between 0.5 to 20 Hz; all tests under conventional fatigue were obtained at the highest frequency and with load ratio $R = 0.1$, at room temperature without control of environmental humidity.

Roughness on surface of testing specimens was measured before and after the conventional fatigue tests, in order investigate the variation of this parameter. The measurements were obtained in longitudinal and transversal direction in regards the principal axis of specimens, using two roughness measuring devices: a TESA Rugosurf 10 G (Renens, Switzerland) and a Mitutoyo SURFTEST SJ-210 (Querétaro, Mexico). The use of these two devices allows to corroborate similarity of the average roughness obtained through the first and second MEASURING device.

Three initial types of specimens were tested: specimens with nomination A, which are the base material, nomination B with two artificial hemispherical pits (500-μm diameter) in transverse direction in regard the applied load, Figure 5 and nomination C with two artificial hemispherical pits (500-μm diameter), this time longitudinally oriented in regard the applied load, Figure 6. Specimens to be machined at the neck section are presented in Figure 7a (milling machine, model Dyna EM-3116, San José, CA, USA); whereas the two artificial pits were made with a tungsten drill bit of 500-μm diameter) in transverse direction, Figure 7b. Pre-corrosion was achieved by immersion of specimens during 30 h in a solution of distilled water with 3.5% in weight of NaCl (international standard ESA ECSS-Q-ST-70-37C). Figure 8a presents the process of immersion for pre-corrosion and Figure 8b, the microstructure of pre-corroded specimen on the flat surface, with a higher pit dimension of about 90 μm, approximately.

![Figure 4. Servo-hydraulic machine for conventional fatigue testing.](image_url)

![Figure 5. Specimen B—transverse pits.](image_url)
3. Results

3.1. Fatigue Endurance under Ultrasonic and Conventional Techniques

Ultrasonic and conventional fatigue tests on the base material, with two pits and pre-corroded specimens are plotted on Figure 9 (the maximum Von-Mises stresses of fractured specimens).
Figure 9. Results of ultrasonic and conventional fatigue tests.

Nomination for ultrasonic fatigue were as follows: VHCF-A the base material, VHCF-B for specimens with two artificial pitting holes in transverse direction, VHCF-C specimens with two artificial pitting holes in longitudinal direction and VHCF-P for specimens with pre-corrosion. Nomination in conventional fatigue was: LCF-A the base material specimens, LCF-B specimens with two artificial pitting holes in transverse direction and LCF-C specimens with two artificial pitting holes in longitudinal direction.

3.2. Roughness Measurements on the Conventional Fatigue Testing Specimens

Measurements of surface roughness were obtained before and after the conventional fatigue tests, as shown in Table 3.

The roughness parameter Ra was measured in four localizations: (a) longitudinal direction at the flat surface, (b) longitudinal direction at the side of specimen, (c) transverse direction at the flat surface and (d) transverse direction at the side of specimen, as illustrated in Figure 5. The obtained results show that roughness slightly decreases in all the specimens with nomination A (without holes) and in the specimens with nomination B and C (transverse and longitudinal pits, respectively), in the direction of the applying load and slightly increases in the transverse direction. The last behavior may be related to microplastic deformation in tension for the longitudinal direction and compression for the transverse direction.

In Table 3 are listed measured values of roughness before * and after ** the conventional fatigue tests; together with testing parameters: NT the target number of cycles, NF the real number of cycles, $F_{\text{max}}$ the value of maximum force, $\sigma_{\text{max}}$ the maximum stress in the specimen, R the load ratio and f the frequency of the cyclic loading.
Table 3. Roughness on specimens of aluminum alloy 7075-T6, before * and after ** the conventional fatigue tests.

| #  | NT  | Nf  | F_max (KN) | σ_max (MPa) | R  | f (Hz) | Ra Localization (a) (µm) | Ra Localization (b) (µm) | Ra Localization (c) (µm) | Ra Localization (d) (µm) |
|----|-----|-----|------------|-------------|----|-------|--------------------------|--------------------------|--------------------------|--------------------------|
| A1 | 10^7 | 382,956 | 4.86 | 110 | 0.1 | 20 | * 0.179 | 0.252 | 0.225 | 0.705 |
|    |     |       |       |     |     |     | ** 0.144 | 0.358 | 0.292 | 0.230 |
| A2 | 50,000 | 50,000 | 4.75 | 110 | 0.1 | 20 | * 0.141 | 0.409 | 0.322 | 0.643 |
| A3 | 10^7 | 460,002 | 4.39 | 110 | 0.1 | 20 | * 0.127 | 0.381 | 0.223 | 0.578 |
|    |     |       |       |     |     |     | ** 0.125 | 0.244 | 0.220 | 0.558 |
| A4 | 10^7 | 354,215 | 3.49 | 110 | 0.1 | 20 | * 0.17 | 0.323 | 0.193 | 0.871 |
|    |     |       |       |     |     |     | ** 0.176 | 0.298 | 0.224 | 0.548 |
| A5 | 10^7 | 10^7 | 2.31 | 110 | 0.1 | 20 | * 0.103 | 0.556 | 0.197 | 0.747 |
|    |     |       |       |     |     |     | ** 0.09 | 0.283 | 0.182 | 0.660 |
| A6 | 10^7 | 10^7 | 2.25 | 110 | 0.1 | 20 | * 0.105 | 0.48 | 0.145 | 0.253 |
|    |     |       |       |     |     |     | ** 0.113 | 0.441 | 0.158 | 0.606 |
| A7 | 200,000 | 200,000 | 2.34 | 110 | 0.1 | 20 | * 0.128 | 0.379 | 0.138 | 0.590 |
|    |     |       |       |     |     |     | ** 0.104 | 0.258 | 0.185 | 0.575 |
| A8 | 10^7 | 10^7 | 2.27 | 110 | 0.10 | 20 | * 0.11 | 0.628 | 0.164 | 0.619 |
|    |     |       |       |     |     |     | ** 0.103 | 0.331 | 0.158 | 0.590 |
| B1 | 10^6 | 692,023 | 4.24 | 110 | 0.1 | 20 | * 0.31 | 0.538 | 0.4 | 0.731 |
|    |     |       |       |     |     |     | ** 0.271 | 0.375 | 0.755 | 0.999 |
| B2 | 10^4 | 10^4 | 4.88 | 110 | 0.1 | 20 | * 0.794 | 0.663 | 0.547 | 0.487 |
| B3 | 10^7 | 10^7 | 2.29 | 110 | 0.10 | 20 | * 0.166 | 0.518 | 0.386 | 0.830 |
|    |     |       |       |     |     |     | ** 0.113 | 0.423 | 0.467 | 0.963 |
| B4 | 10^7 | 165,047 | 3.38 | 110 | 0.1 | 20 | * 0.228 | 0.467 | 0.403 | 0.866 |
|    |     |       |       |     |     |     | ** 0.145 | 0.393 | 0.342 | 0.885 |
| B5 | 50,000 | 50,000 | 2.31 | 110 | 0.1 | 20 | * 0.128 | 0.409 | 0.25 | 0.55 |
|    |     |       |       |     |     |     | ** 0.103 | 0.447 | 0.219 | 0.623 |
| B6 | 10^7 | 10^7 | 2.29 | 110 | 0.10 | 20 | * 0.119 | 0.599 | 0.18 | 0.633 |
|    |     |       |       |     |     |     | ** 0.125 | 0.450 | 0.189 | 0.654 |
| B7 | 200,000 | 200,000 | 2.33 | 110 | 0.1 | 20 | * 0.114 | 0.434 | 0.371 | 0.776 |
|    |     |       |       |     |     |     | ** 0.106 | 0.275 | 0.214 | 0.838 |
| C1 | 10^7 | 335,033 | 4.58 | 110 | 0.1 | 20 | * 0.244 | 0.586 | 0.382 | 0.98 |
|    |     |       |       |     |     |     | ** 0.159 | 0.596 | 0.395 | 1.091 |
| C3 | 10^7 | 10^7 | 2.28 | 110 | 0.10 | 20 | * 0.163 | 0.483 | 0.336 | 0.912 |
|    |     |       |       |     |     |     | ** 0.149 | 0.288 | 0.278 | 0.530 |
| C4 | 700,000 | 700,000 | 2.29 | 110 | 0.1 | 20 | * 0.166 | 0.643 | 0.265 | 0.812 |
|    |     |       |       |     |     |     | ** 0.17 | 0.486 | 0.273 | 0.909 |
| C5 | 50,000 | 50,000 | 2.22 | 110 | 0.1 | 20 | * 0.168 | 0.580 | 0.383 | 0.877 |
|    |     |       |       |     |     |     | ** 0.127 | 0.450 | 0.339 | 0.672 |
| C6 | 10^7 | 10^7 | 2.29 | 110 | 0.10 | 20 | * 0.155 | 0.538 | 0.279 | 0.709 |
|    |     |       |       |     |     |     | ** 0.19 | 0.461 | 0.265 | 0.657 |
| C7 | 200,000 | 200,000 | 2.32 | 110 | 0.10 | 20 | * 0.167 | 0.582 | 0.248 | 0.712 |
|    |     |       |       |     |     |     | ** 0.14 | 0.286 | 0.282 | 0.715 |
3.3. Microstructure of Crack Initiation and Propagation in Pre-Corroded Specimens and with Two Artificial Pits

Crack initiation for the pre-corroded specimens was frequently localized in one or some close pre-corrosion pits, as shown in Figure 10a; whereas crack propagation was systematically developed at the neck section of specimens, following an intergranular path, as illustrated in Figure 10b.

For the two artificial pitting holes, the crack initiates at the bottom of pits in the case of transverse pits, Figure 11a and it is localized at the bottom of one pit in the case of longitudinal pits, Figure 11b. A numeric analysis is developed in the next section in order to investigate the stress concentration factors induced by the two artificial pits in the transverse or longitudinal direction and its impact in fatigue endurance.

![Figure 10](image-url)  
**Figure 10.** (a) Crack initiation in a pre-corrosion pit; (b) crack propagation following intergranular path.

![Figure 11](image-url)  
**Figure 11.** (a) Crack initiation and propagation for two transverse pits; (b) crack initiation and propagation for two longitudinal pits.
3.4. Numeric Simulation of Stress Concentration

In order to assess the effect of artificial pits (two hemispherical pits oriented in transverse and longitudinal direction in regard the applied load), numeric simulations were carried out on the testing specimen. In Figure 12 is illustrated the stress distribution on the testing specimen without pits, undergoing a total displacement of 130 µm. The maximum Von Mises stress is located at the neck section with the value of 220 MPa (corresponding to the maximum applied stress in Figure 9 for VHCF-B and VHCF-C).

![Figure 12](image_url)

Figure 12. Stress distribution of testing specimen with 130 μm of displacement at the end.

The numeric results for the specimen with two hemispherical pits in transverse direction and separated 500 µm, are presented in Figure 13a. Physical fracture in this type of specimen is shown in Figure 13b; the maximum numeric Von-Mises stress was 358 MPa, approximately.

![Figure 13](image_url)

Figure 13. (a) Stress distribution for two pits in transverse direction and 130 µm of total displacement; (b) fracture on two pits in transverse direction.
The stress distribution for the specimen with two pits separated 500 μm, this time in longitudinal direction in regard the applied load, is illustrated in Figure 14a. The maximum numeric Von-Mises stress was 320 MPa. Comparing Figures 12–14, the stress concentration factor is: \( \frac{358}{220} = 1.63 \) for two pits in transverse direction and \( \frac{320}{220} = 1.45 \) for the two pits in longitudinal direction. Stress concentration factors was obtained by numeric simulation in different materials and conditions [24–26]. Numeric analysis in Figures 12–14 was obtained with the Ansys software (Version R19, Ansys Inc., Canonsburg, PA, USA), SOLID187 element type and 36,039 and 35,945 elements, respectively. One end side of specimen was fixed as boundary condition.

![Figure 14. (a) Stress distribution for two pits in longitudinal direction and 130 μm of total displacement; (b) fracture on two pits in longitudinal direction.](image)

### 3.5. Numeric Determination of Stress Intensity Factor in Mode I

The stress intensity factor (SIF) in mode I during the crack propagation of aluminum alloy 7075-T6 was evaluated assuming as crack initiation a hemispherical pit generated at the surface, Figure 15.

The 3D numeric simulation can be reduced to a 2D numeric simulation under the following considerations: the initial crack length is small (400 μm), compared with the specimen dimensions so that plane stress is assumed. The 2D model is illustrated in Figure 16a, with the initial crack length localized at the bottom of one pit, as shown in Figure 16b. Quadrilateral 2D elements was used: 25,636 elements and 26,190 nodes; fixed one vertical side of specimen for boundary conditions.
Assuming 2D loading and cylindrical coordinate system at the crack tip, the asymptotic stress distribution can be represented as:

\[ \sigma_{x} = \frac{K_{I}}{\sqrt{2\pi r}} \left(3 \cos \left(\frac{\phi}{2}\right) + \cos \left(\frac{3\phi}{2}\right)\right) + \frac{K_{II}}{\sqrt{2\pi r}} \left(-3 \sin \left(\frac{\phi}{2}\right) - 3 \sin \left(\frac{3\phi}{2}\right)\right) \]  

\[ \sigma_{y} = \frac{K_{I}}{\sqrt{2\pi r}} \left(3 \sin \left(\frac{\phi}{2}\right) + \sin \left(\frac{3\phi}{2}\right)\right) + \frac{K_{II}}{\sqrt{2\pi r}} \left(\cos \phi - 3 \cos \left(\frac{3\phi}{2}\right)\right) \]  

where \( \phi \) is the angle of crack propagation in the tip coordinate system.

Crack growth is determined as straight-line segments across the 2D body in the interval \( 0-S \), divided into steps \( \Delta s_{i}, i = 1 \ldots n \). For a determined state of stress and displacement \((\sigma, u)^{i}\), at the step \( i \) for the crack geometry \( E^{i} \), the crack growth evaluation consists to determine the geometry \( E^{i+1} \), corresponding to \( i+1 \) step.

The propagation angle \( \phi^{i+1} \) and the incremental length \( \Delta a^{i+1} \) for each step must be obtained; the selected criteria for the crack growth direction was the normal to the direction of maximum hoop stress \([27,28] \). Assuming 2D loading and cylindrical coordinate system at the crack tip, the asymptotic circumferential and shear stresses in this region are represented by:

\[ \sigma_{\varphi\varphi} = \frac{K_{I}}{\sqrt{2\pi r}} \left(3 \cos \left(\frac{\phi}{2}\right) + \cos \left(\frac{3\phi}{2}\right)\right) + \frac{K_{II}}{\sqrt{2\pi r}} \left(-3 \sin \left(\frac{\phi}{2}\right) - 3 \sin \left(\frac{3\phi}{2}\right)\right) \]  

\[ \sigma_{\rho\rho} = \frac{K_{I}}{\sqrt{2\pi r}} \left(3 \sin \left(\frac{\phi}{2}\right) + \sin \left(\frac{3\phi}{2}\right)\right) + \frac{K_{II}}{\sqrt{2\pi r}} \left(\cos \left(\frac{\phi}{2}\right) + 3 \cos \left(\frac{3\phi}{2}\right)\right) \]  

Figure 15. (a) Numeric 3D model for evaluate the stress intensity factor in mode I; (b) section view.

Figure 16. (a) 2D numerical model to evaluate SIF in mode I; (b) initial crack length of 400 μm.

Crack growth is determined as straight-line segments across the 2D body in the interval 0–S, divided into steps \( \Delta s_{i}, i = 1 \ldots n \). For a determined state of stress and displacement \((\sigma, u)^{i}\), at the step \( i \) for the crack geometry \( E^{i} \), the crack growth evaluation consists to determine the geometry \( E^{i+1} \), corresponding to \( i+1 \) step.
Equation (1) represents the principal stress in the direction of crack propagation. The shear stress $\sigma_{r\theta}$ is assumed vanishing in this direction; then, it is obtained:

$$\sigma_{r\theta} = \frac{1}{\sqrt{2\pi r}} \cos \left( \frac{r^2}{2} \right) \left( K_I \sin (\varphi) + \frac{K_{II}}{2} (3 \cos \varphi - 1) \right)$$

(3)

Here: $\varphi$ is the angle of crack propagation in the tip coordinate system.

The mixed mode can be approached to single mode loading, which leads to: $K_{II} \approx 0$ and equation 3 becomes: $K_I \sin (\varphi) = 0$. The last result implies that $\varphi = 0$ for each step along the crack propagation. Experimental observations seem confirm this result: crack initiation and propagation are developed at the neck section of specimens, perpendicular to the longitudinal axis of specimen, as observed in Figure 11a,b. The numeric domain was constructed with 25,636 quadrilateral elements and 26,190 nodes. $K_I$ was evaluated using the displacement correlation method [29,30], with the displacement vectors in the X direction $V_i$ and the equation:

$$K_I = \frac{G}{k+1} \sqrt{\frac{2\pi L}{4(V_1 - V_2) - (V_3 - V_4)}}$$

(4)

Figure 17 illustrates the parameters involved for the numeric evaluation of $K_I$. The mechanical properties were shear modulus $G = 26$ GPa, $k = (3-4\nu)$ for plane stress, $L$ is the length of the singular element and $\nu = 0.33$ the Poisson’s coefficient.

![Crack propagation parameters used in numeric simulation](image)

Figure 17. Crack propagation parameters used in numeric simulation.

The numeric stress intensity factor in mode I was obtained taking the following sequence:

- Determination of stress and strain distributions on cracked structure;
- Evaluation of displacements vectors at the crack zone on the X direction, to calculate the stress intensity factor in mode I;
- Compute the direction ($\varphi = 0$ for all steps), of crack extension and the incremental crack surface construction;
- Compute the number of load cycles of last increment for crack growth simulation;
- Re-meshing of boundary, if necessary;
- Return to first point.

$K_I$ was computed from $a_0 = 400 \mu$m to $a_{end} = 4000 \mu$m (the wide at the specimen neck section). Figure 18 shows the evolution of $K_I$ determined by FEA, using this method.
3.6. Evaluation of $\Delta K_{TH}$, for Base Material and Specimens with Two Hemispherical Pits in Transverse Direction

The stress intensity factor range threshold $\Delta K_{TH}$ was investigated for the base material and specimens with two hemispherical pits in transverse direction regarding its longitudinal axis.

The initial crack size is small compared with the specimen dimension; then, the stress intensity factor in mode I can be obtained with the approximation of edge crack in a semi-infinite body, with the expression:

$$\Delta K_I = Y \sqrt{\pi a} (\Delta \sigma)$$  \hspace{1cm} (5)

With: $Y$ the geometry correction factor, $Y = 1.12$. Ultrasonic fatigue tests were carried out with $R = -1$; the compressive stress does not make contribution toward the advancement of the fatigue crack. Under this condition, the stress intensity factor range was computed from $\Delta \sigma/2$. Ultrasonic fatigue testing in the base material specimens presented no crack propagation using the stress amplitude $\Delta \sigma = 95$ MPa, with an initial crack length $a_0 = 400 \, \mu m$; then, Equation (5) leads to: $\Delta K_{TH} \approx 3.77$ MPa (m)$^{0.5}$.

The crack growth behavior can be represented in the stable crack propagation zone by the Paris-Gomez-Anderson law:

$$\frac{da}{dN} = C (\Delta K)^n$$  \hspace{1cm} (6)

The constant $C$ and $n$ are properties of tested material, determined by experimental results. For the base material of 7075-T6 alloy at room temperature and $R = -1$, the corresponding values were: $C = 0.5 \times 10^{-12}$ and $n = 5$ and for specimens with two hemispherical pits in transverse direction, these values were: $C = 3.3 \times 10^{-12}$, $n = 5.8$. In Figure 19 are plotted the points $da/dN-\Delta K$ for the two specimens in the log scale.

Values obtained for $\Delta K_{TH}$ were: $\approx 4$ MPa (m)$^{0.5}$ and $\approx 1.8$ MPa (m)$^{0.5}$ for the base material and with two pits, respectively. Reported values for $\Delta K_{TH}$ with $R = -1$ and room temperature yielded close to $4$ MPa (m)$^{0.5}$ \cite{31}. This alloy coated with cladding layer under similar conditions as before and using the effective stress-intensity factor range ($\Delta K_{eff}$), leads to a threshold comprised between 1 and 4 MPa (m)$^{0.5}$ \cite{32}. The value of $\Delta K_{TH}$ for this aluminum alloy was reported decreasing when the load ratio $R$ increases, from $R = -1$, $R = 0$ and $R = 0.5$, regardless of taking $\Delta K$ or $\Delta K_{eff}$ \cite{33}.

On the other hand, the number of cycles in the stable zone of crack growth, may be estimate by the Paris–Gomez–Anderson equation:

$$ N_{II} = \int_{a_0}^{a_{end}} \frac{da}{C(\Delta K)^n} = \int_{a_0}^{a_{end}} \frac{da}{\frac{C}{Y(a)\Delta \sigma \sqrt{\pi a}} n} $$  \hspace{1cm} (7)
With: $N_{II}$ the number of cycles in this zone, $Y(a)$ the geometry factor, taken constant along the crack propagation $Y(a) = 1.12$, $a_0$ and $a_{end}$ the initial and the final crack length, respectively. Assuming that: $\Delta K = \Delta K_0 (a/a_0)^{1/2}$, together with: $\Delta K_0 = Y(a_0) \Delta \sigma (\pi a_0)^{1/2}$, $a_0 = 400 \mu m$, $a_{end} = 4000 \mu m$, Equation (7) becomes:

$$N_{II} = \frac{2a_0}{(n-2)C[\Delta K_0]^n} \left[ 1 - \left( \frac{a_0}{a_{end}} \right)^{\frac{n-2}{2}} \right]$$

With: $\Delta K_0 \approx \Delta K_{TH} \approx 3.77$ MPa (m)$^{0.5}$, $n = 5$ and $C = 0.5 \times 10^{-12}$, the number of cycles of base specimen in this zone is: 678,162 cycles, less than 7% of the total fatigue life ($\approx$10 million of cycles at 245 MPa, Figure 9), For the second case and using the values: $C = 3.3 \times 10^{-12}$ and $n = 5.8$, the number of cycles in the stable zone of crack growth is reduced to 28,609 cycles, less than 1% of total fatigue life of these specimens (2~3 million of cycles, Figure 9) at 220 MPa [34,35].

![Crack growth rate for aluminum alloy 7075-T6](image)

**Figure 19.** Crack growth rate for the base material and specimens with two pits, under ultrasonic fatigue tests.

### 4. Discussion

Conventional and ultrasonic fatigue tests were performed on the aluminum alloy 7075-T6 for the base material, specimens with two hemispherical pits disposed in transverse and longitudinal direction in regard the applied load and pre-corroded specimens. Two pits in transverse direction seem induce higher detrimental effect in fatigue endurance associate with the high stress concentration factors, which were determined by numeric simulation. Fatigue endurance for conventional tests revealed similar behavior: the lowest values was observed for specimens with two pits in transverse direction. Ultrasonic fatigue tests on aluminum alloy 7075-T6 were performed under similar condition compared to this study for the nomination VHCF-A [36]. The fatigue endurance was lower compared to the present study for the high load (260 MPa) and similar for the low load (200 MPa); this discrepancy is probably related to difference on the mechanical properties. Concerning measurement of roughness before and after testing under conventional fatigue tests, roughness decreases slightly after fatigue tests in parallel direction to applied load and increases slightly in perpendicular direction to applied load. These results may be associate with tension microplasticity in the first case and compression microplasticity in the second case.

Crack initiates in one or more close pits in the case of pre-corrosion; this localization is at the bottom of one or the two pits, in the case of two artificial pits. Crack initiation is frequently associated with the localization of high stress concentration; physical observations were supported by numeric results. The grain size mean value for this aluminum alloy was 80 μm and crack initiation may be triggered from a single pit occupying a grain or comprising different grains, depending on the crack initiation pit.
size and localization. The crack propagation in all fatigue tests follows an intergranular path across the specimen neck section; high temperature recorded for conventional fatigue was about 40 °C and close to 31 °C in the case of ultrasonic fatigue, as illustrated in Figure 20, using a thermographic camera.

![Temperature recorded by thermographic camera, during ultrasonic fatigue test.](image)

The stress intensity factor in mode I was evaluated numerically using the Displacement Correlation Method and the simplification of 2D domain; its values range from: \( \approx 11 \) MPa (m)\(^{0.5} \) at crack initiation \((a_0 = 400 \, \mu m)\) and \( \approx 22 \) MPa (m)\(^{0.5} \) at fracture \((a_{end} = 4000 \, \mu m)\). The stress intensity factor range threshold \( \Delta K_{TH} \) was obtained for the base material and specimens with two hemispherical pits in transverse direction: \( \approx 4 \) and \( \approx 1.8 \) MPa (m)\(^{0.5} \), respectively; these values are of the order found in literature. The reduction of \( \Delta K_{TH} \) in the second case is related to stress concentrations induced by the two pits. The number of cycles inside the stable zone of crack growth for the base material and specimens with two pits in transverse direction were evaluated, leading to less than 7% of the total ultrasonic fatigue life for the base material and less than 1% for specimens with two pits in transverse direction.

5. Conclusions

The following conclusions can be drawn from the present investigation:

- Ultrasonic fatigue tests were obtained on specimens of the aluminum alloy 7075-T6: base material, with two hemispherical pits and pre-corroded. In the case of conventional fatigue: base material and with two hemispherical pits;
- Pit orientation regarding the applied load plays an important role on the fatigue life of this aluminum alloy: fracture occurs first, for specimen with two transversal pits, following by specimens with longitudinal pits and pre-corroded specimens. The higher fatigue endurance corresponds to specimens of base material;
- Under conventional fatigue tests Ra roughness parameter slightly decreases in the direction of applied load after tests and slightly increases in perpendicular direction;
- Cracks initiate frequently associated with one or more pits for pre-corroded specimens and at the bottom of one or the two artificial pits. Crack propagation was always located across the specimen neck section, following an intergranular path;
- The stress concentration factor \( K_t \), plays a principal role affecting fatigue endurance in the pre-corroded and two pits specimens; values of \( K_t \) were obtained by numeric simulation;
- Stress intensity factor in mode I was obtained by numeric evaluation using the displacement correlation method, from crack initiation to fracture;
- The stress intensity factor range threshold was obtained for the base material and for specimens with two hemispherical pits in transverse direction;
• Specimens with pre-corrosion and artificial pits present decrease of the number of fatigue cycles, inside the stable zone of crack growth;

• Additional physical and numeric investigations should be undertaken to assess the quantitative effects of pits in the corroded surfaces—particularly the interaction effects of close pits associated with the crack initiation and propagation.

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