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The influence of residual stresses on the fatigue behaviour of 2024-T3 Al specimens

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The influence of residual stresses on the fatigue behaviour of 2024-T3 Al specimens

By
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Abstract

The main objective of the present work is the study of the effect of residual stresses due to the cold working process in the fatigue lives of structural engineering components, in this particular case specimens of simple geometry which are often used in the study of aircraft structures. This method introduces a compressive stress field around the hole reducing the tendency for fatigue cracks to initiate and grow under cyclic mechanical loading. As it is well known, for the accurate assessment of fatigue lifetimes a detailed knowledge of the residual stress profile is required. Powerful experimental and numerical tools are nowadays available for that purpose. In the present work both types of tools were used: X-rays measurements and 2D and 3D FEA analyses are used in order to evaluate the residual stress profile. The study of fracture surfaces was carried out in order to decode the information of the failure process. This fractography work was performed using SEM. Fatigue striations spacing were measured. CGR and fractographic reconstitution of fatigue crack history were performed based on these measurements. The statistical analysis of the fatigue tests is presented and discussed.
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Nomenclature

A, B  Constants in fatigue life increase equation proposed in the present thesis
a  Crack length
\( \hat{a} \)  Fitted value of crack length
\( a_c \)  Critical crack length
\( a_{eq} \)  Equivalent crack length
\( a_{left} \)  Fatigue crack on the left side
\( a_{right} \)  Fatigue crack on the right side
\( b_0, b_1 \) and \( b_2 \)  Regression parameters
\( C_1, C_3 \)  Data scale factors
CCC  Critical correlation coefficient
CDF, F  cumulative distribution function
\( C_{m} \)  Paris law constants
\( \frac{da}{dN} \)  Crack growth rate
\( \bar{D} \)  Mandrel diameter
D  Hole diameter
d  Spacing lattice
dist.  Distance from hole
\( d_m \)  Mandrel displacement
n  Directions vector
E  Young’s modulus
f  Frequency
h(x,a)  Weight function
\( i \)  
Radial interference

\( K \)  
Stress intensity factor

\( K_0 \)  
Material constants

\( K_c \)  
Critical material toughness

\( K_{cl} \)  
Crack closure stress intensity factor

\( K_I \)  
Stress intensity factor in mode I

\( K_c \)  
Plane strain fracture toughness

\( K_{II} \)  
Stress intensity factor in mode II

\( K_{Ir} \)  
Reference stress intensity factor, mode I

\( K_{res} \)  
Residual stress intensity factor

\( K_{th,max} \)  
Maximum threshold stress intensity factor

\( \ell \)  
Total length of the crack front under SEM observation

ligament  
Ligament area

\( N \)  
Number of cycles

\( n \)  
Integer number

NFC  
No fatigue crack

NVR  
No video recorded

PDF, \( f \)  
Probability density function

\( R_0 \)  
Material constants

\( r^2 \)  
Coefficient of determination

\( r \)  
radial polar coordinate

\( r_e \)  
External radius

\( r_i \)  
Internal radius

\( r \)  
Correlation coefficient

\( R \)  
Stress ratio \((=\sigma_{min}/\sigma_{max})\)

\( r, \theta \)  
Polar coordinates

\( r_y \)  
Radius of the yield zone in a crack tip

\( s \)  
Striation spacing
t  Thickness

$u_{lr}$  Reference case displacement field for a cracked body under symmetrical loading

$u_y$  Displacement around the crack tip

$u_{i,j}$  Local crack growth rate

W  Width

Y  Geometry parameter

$\alpha$  Summit angles of diffraction cones

Significance level associated with rejection hypothesis

$\beta$  Weibull shape parameter

$\Delta K$  Stress intensity factor range

$\Delta K_{app}$  Applied stress intensity factor range

$\Delta K_{th}$  Threshold stress intensity factor range

$\Delta K_{th,eff}$  Effective threshold stress intensity factor range

$\Delta \sigma_{rr}$, $\Delta \sigma_{\theta \theta}$  Radial and circumferential normal stresses ranges in polar coordinates

$\Delta \ell$  Width of the total crack length front under SEM observation

$\varepsilon$  Conventional strain

$\varepsilon_{i,i}$  $(i,j = 1,2,3)$ Strain tensor components

$\varepsilon_n$  Strain in direction $\mathbf{n}$

$\varepsilon_{\phi \psi}$  Spherical strain component

$\sigma_{i,i}$  $(i,j = 1,2,3)$ Stress tensor components

$\eta$  Weibull scale parameter

G  Energy release rate

$\Gamma$  Weibull gama function

$\lambda$  X-ray length

$\mu$  Expected value

Material shear modulus

$\mu(K_c)$  Plane strain fracture toughness mean value

$\Omega_{left}$  Fatigue crack area on the left side
\( \Omega_{\text{right}} \) Fatigue crack area on the right side

\( \phi, \Psi \) Cylindrical coordinates angles

\( \sigma \) Stress
   Standard deviation

\( \sigma^2 \) Variance

\( \sigma_a \) Stress amplitude

\( \sigma_c \) Critical tensile stress

\( \sigma_{\text{max}} \) Maximum stress

\( \sigma_m \) Mean stress

\( \sigma_{\text{min}} \) Minimum stress

\( \sigma_{rr}, \sigma_{\theta\theta} \) Radial and circumferential normal stresses in polar coordinates

\( \sigma_u \) Ultimate tensile stress

\( \sigma_{xx}, \sigma_{yy} \) Stresses in direction x and y direction respectively

\( \sigma_{\text{yield}} \) Yield stress

\( \sigma(K_c) \) Plane strain fracture toughness standard deviation

\( \tau_{\tau\theta}, \tau_{\tau z}, \tau_{\theta z} \) Shearing-stress components cylindrical coordinates

\( \theta \) Diffraction angle
Acronyms

ADMIRe Advanced Design Concepts and Maintenance by Integrated Risk Evaluation (European Union research project)

AGARD Advisory Group for Aerospace Research and Development

ASTM American Society for Testing and Materials, USA

BEM Boundary Element Method

CGR Crack Growth Rate

CEMDRX Centro de Estudos de Materiais por Difracção de Raios X, Universidade de Coimbra, Portugal

CEMUP Centro de Materiais da Universidade do Porto, Portugal

CTU Czech Technical University in Prague, Czech Republic

CW Cold Worked

DASA DaimlerChrysler Aerospace Airbus, previously Daimler-Benz Aerospace Airbus

DBEM Dual Boundary Element Method

DEMEGI Departamento de Engenharia Mecânica e Gestão Industrial, FEUP

FCG Fatigue Crack Growth

FCH Fatigue Crack History

FEA Finite Element Analysis

FEG Field Emission Gun

FEM Finite Element Method

FEUP Faculdade de Engenharia da Universidade do Porto, Portugal

FLI Fatigue life increase

FTI Fatigue Technology Inc., Seattle, USA

fps frames per second
IDMEC Instituto de Engenharia Mecânica
LEFM Linear Elastic Fracture Mechanics
MEPP Material Elastic Perfectly Plastic
SCF Stress Concentration Factor
SEM Scanning Electron Microscopy
SIFs Stress Intensity Factors
SMAAC Structural Maintenance of Ageing Aircraft (European Union research project)
UC Universidade de Coimbra, Portugal
WFT Weight Function Technique
Date: December 2003

Author: Paulo Fernando Pinto de Matos

Title: The influence of residual stresses on the fatigue behaviour of 2024-T3 Al specimens

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Chapter 1

Introduction

1.1 Motivation and objectives

This work is a part of the Instituto de Engenharia Mecânica (IDMEC) contribution to the European research project Advanced Design Concepts and Maintenance by Integrated Risk Evaluation (ADMIRE).

The main objective of the present work is to contribute to the understanding of the effect of residual stress effect due to cold working on the fatigue lives of structural engineering components, in this particular case specimens of simple geometry which are often used in the study of aircraft structures.

For this purpose, the following studies were carried out:

- Residual stress field profile measurement, and the cold working process simulation;
- The study of the influence of residual stress on the fatigue striation spacing;
- Crack Growth Rate (CGR) estimation using different techniques;
- Residual strength calculation;
- Estimation of the fatigue tests statistical distributions.

The practical relevance of this subject has been motivating several researchers to contribute to the development of tools that can predict the cold working effect using analytical and numerical tools. The increase in fatigue life gained from cold working fastener holes has been documented by several experimental observations. The present work quantifies the influence of this mechanical treatment on the fatigue life. Different residual stress predictions using finite elements models with different degrees of complexity were carried out. The cost in accuracy, when simplified models are used is quantified with the analyses carried out. Fatigue striation spacing was also studied, and an original contribution on this subject is presented.
1.2 Work structure

This thesis is divided in 7 chapters as follows:
Chapter 1 presents the work motivation, objectives, work structures and summary of accomplishments.
Chapter 2 concerns fatigue testing.
Chapter 3 presents the work related with residual stress, residual stress effect, residual stress measurements and Finite Element Analysis (FEA) simulation. Residual stress intensity factors are also calculated using the Weight Function Technique (WFT).
Chapter 4 concerns fatigue crack growth measurements based on video recording. CGR based on these surface measurements are also presented.
Chapter 5 presents the fractography work. Fatigue striations spacing measurements are presented as well as CGR and fatigue crack history reconstitution based on this measurements. The measurements of fatigue crack areas and crack lengths are presented, and the residual strength is calculated.
Chapter 6 presents the statistical analysis performed with fatigue tests results and crack length measurements.
Chapter 7 presents conclusions and some proposals for future works.

The global structure of this work is presented in Figure(1.1).
The open hole specimens’ test program has 45 specimens, 24 normal hole and 21 cold worked specimens. Before fatigue testing the residual stress field profile was measured using X-ray and FEA was used for the validation these measurements. After this validation WFT was used for the calculation of the residual stress intensity factors, which were used in $K$ calibration for CGR measurements.
During fatigue testing of both types of specimens, Fatigue Crack Growth (FCG) was measured using a video Webcam and CGR was calculated. After fatigue testing S-N curves were plotted and the specimens’ fracture surface was observed by Scanning Electron Microscopy (SEM). SEM work is divided in two parts: fatigue striation measurements and fatigue crack areas and lengths measurement. Fatigue striation spacing was used for CGR measurements and Fatigue Crack History (FCH) reconstitution. Fatigue crack measurements were used for the residual strength calculation.
FCH reconstitution is compared with FCG measurements.
CGR measurements based on micro measurements (striation spacing) are compared with macro surface (video) measurements.
Figure 1.1: Work organization chart.
1.3 Accomplishments

Specific accomplishments of this study are as follows:

- The residual stress effect consists on the increase of the fatigue life. This effect decreases with increasing external applied stress level. In the present tests, a factor of approximately 1.5 to 6.5 was found when comparing cold worked specimens with specimens of the same geometry without residual stresses.

- An estimation of the "price" in accuracy to be paid when simplified finite element models are used. A 2D axisymmetrical finite element model gave interesting results as an "infinite" domain approximation.

- The residual stress effect decreases the fatigue striation spacing along the crack depth and length.

- Good estimations of CGR can be obtained with fatigue striation spacing measurements.

- The use of $D = D(s)$ concept showed to be of high importance in fractographic reconstitution specially in the initiation stage. This importance was not noticed in the CGR because the striation spacing measurements in the initiation stage were not taken into account.

- Typical statistical distributions (Lognormal and Weibull with two parameters) were used to describe the fatigue life and critical crack size data.
Chapter 2

Fatigue testing

2.1 Introduction

The present chapter is concerned with fatigue testing. The main objective is the determination of stress amplitude-life (S-N) curves for open hole specimens with and without residual stress. This chapter starts with a short overview on fatigue, and proceeds with the presentation of the fatigue tests performed. Finally, according to the results obtained some conclusions are stated.

2.2 Fatigue, short introduction

The progressive damage of materials subjected to cyclic stress or strain is known as fatigue. This phenomenon is of great importance in the design of structures and machines, because the larger part of the in-service ruptures are related with fatigue. Fatigue life data is usually presented as conventional S-N diagrams representing the number of cycles to failure as a function of the applied nominal stress or stress range. A good example of the S-N curves application are aircraft structures that usually contain many basically similar structural details and components with known fatigue characteristics. The main source of fatigue damage are fastener holes. A study of in-service fatigue failures in aircraft structures revealed that 70 per cent of fatigue cracks originated from the holes of riveted or bolted joints [1]. Several researchers have measured the improvement in fatigue life gained from cold working fastener holes and a summary of such work was given by McNeil and Heston [2]. Most of the experimental observations suggest that cold expansion can increase fatigue life to failure by a factor from 3 to 10, depending upon the fatigue stress level [3, 4].

2.3 Specimens test

The specimens tested have simple geometry (see Figure (2.1)) and are designed as open hole specimens. They were manufactured by DaimlerChrysler Aerospace Airbus (DASA). The material is the aluminium alloy 2024-T3, and its mechanical properties are presented in Appendix A. The hole diameter D in Figure (2.1) can be found in section 2.3.3 for each one of the specimens tested.
2.3.1 Load conditions and test parameters

Forty five specimens were tested, 24 normal open hole, and 21 cold worked open hole at 5 stress levels. Table (2.1) presents the stress levels and the corresponding forces.

<table>
<thead>
<tr>
<th>Stress levels [MPa]</th>
<th>Nr. specimens per stress level</th>
<th>( F_{\text{min.}} )</th>
<th>( F_{\text{m}} )</th>
<th>( F_{\text{max.}} )</th>
<th>( F_{\text{a}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>5</td>
<td>600</td>
<td>3300</td>
<td>6000</td>
<td>2700</td>
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<td>140</td>
<td>5</td>
<td>700</td>
<td>3850</td>
<td>7000</td>
<td>3150</td>
</tr>
<tr>
<td>160</td>
<td>5</td>
<td>800</td>
<td>4400</td>
<td>8000</td>
<td>3600</td>
</tr>
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<td>900</td>
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<td>200</td>
<td>5</td>
<td>1000</td>
<td>5500</td>
<td>10000</td>
<td>4500</td>
</tr>
</tbody>
</table>

Tests were performed according to the stress levels in Table (2.1) with constant \( R=0.1 \) \( (R=\sigma_{\text{min}}/\sigma_{\text{max}}) \) and frequency \( f = 10Hz \). The force values in Table (2.1) were calculated considering the remote cross section of the specimens \( 25 \times 2 \text{ mm}^2 \) and were applied according to Figure (2.2).
The test machine used was a MTS 312.31 with a load cell of 100kN working in the lower force range of 10kN, shown in Figure (2.4).

2.3.2 Testing set up

The testing set up is shown in Figure (2.4). Its components are:
A - bottom fork connected to the actuator; B - grip; C - top fork connected to the load cell; D - fork shaft; E - grip shaft.
Figure 2.4: Complete test assembly.
The setup in Figure (2.4) is aligned as follows: the center of the actuator is aligned with the center of the bottom and top shaft forks, the center of the grip shafts, the center of the hole and the center of the load cell. Figure (2.5) enlarged details of the shaft forks of Figure (2.4).

The holes in sections 1 and 3 in Figure (2.6) were made to allow greater precision in the alignment (using grip shafts) of the specimen with the load cell and actuator, since the system used is mechanical. The force is not imposed by the grip shafts but by means of friction. To improve friction between the specimen and grips sandpaper glued on the grips was used.

2.3.3 Geometric characterization of the specimens

Specimens were measured in three sections as shown in Figure (2.6). Measurements on sections 1 and 3 give information about the specimen alignment with the load cell and the actuator. Measurements on section 2 give information about the hole dimension and alignment.
All the measurements performed according to Figure (2.6) are presented in Appendix (B).

2.4 Fatigue tests results

The fatigue tests results are presented in Tables (2.2) to (2.6). Data presented report the number of cycles to failure for the stress levels of $\sigma_{\text{max}} = 120, 140, 160, 180$ and $200$ MPa for both types of specimens, normal open hole (with plain hole) and Cold Worked (CW) open hole. The number of cycles since the first crack was noticed is also presented, for some of the tested specimens. This information was obtained using a video Webcam recording camera with a resolution of $640 \times 480$ at $30$ fps. For some specimens it was not possible to record the tests and in those cases NVR (No video recorded) is shown in the table. When the fatigue crack growth process was only present on one of hole sides (left or right), NFC (No fatigue crack) is recorded in the table, on the side without fatigue crack.
Table (2.2) present the fatigue tests results for the specimens tested at $\sigma_{\text{max}} = 120 \text{ MPa}$.

<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>Hole condition</th>
<th>Life to crack on</th>
<th>Fatigue life cycles</th>
<th>Failure position</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5</td>
<td>Plain</td>
<td>NVR</td>
<td>NVR</td>
<td>162494</td>
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<tr>
<td>8.2</td>
<td>Plain</td>
<td>NVR</td>
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<tr>
<td>8.3</td>
<td>Plain</td>
<td>NVR</td>
<td>NVR</td>
<td>129000</td>
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<td>4.4</td>
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<td>8.1</td>
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<tr>
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<td>83642</td>
<td>93392</td>
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</table>

<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>Hole condition</th>
<th>Life to crack on</th>
<th>Fatigue life cycles</th>
<th>Failure position</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
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<td>CW</td>
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<td>CW</td>
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<td>879783</td>
<td>884283</td>
</tr>
<tr>
<td>7.3</td>
<td>CW</td>
<td>NFC</td>
<td>1180744</td>
<td>1184994</td>
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<tr>
<td>Mean values</td>
<td></td>
<td></td>
<td>1030264</td>
<td>754801</td>
</tr>
</tbody>
</table>

Comparing the mean values of fatigue life obtained for both types of specimens it is shown that the cold worked specimens tested at $\sigma_{\text{max}} = 120 \text{ MPa}$ have a fatigue life approximately 6.5 times larger than that of non-cold worked specimens.

Table (2.3) present the fatigue tests results for the specimens tested at $\sigma_{\text{max}} = 140 \text{ MPa}$.

<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>Hole condition</th>
<th>Life to crack on</th>
<th>Fatigue life cycles</th>
<th>Failure position</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3</td>
<td>Plain</td>
<td>NVR</td>
<td>NVR</td>
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<td>7.2</td>
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<td>69506</td>
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<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>Hole condition</th>
<th>Life to crack on</th>
<th>Fatigue life cycles</th>
<th>Failure position</th>
</tr>
</thead>
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</table>

Comparing the mean values of fatigue life obtained for both types of specimens it is shown that the cold worked specimens tested at $\sigma_{\text{max}} = 140 \text{ MPa}$ have a fatigue life approximately 3 times larger than that of non-cold worked specimens.
Table (2.4) present the fatigue tests results for the specimens tested at $\sigma_{max} = 160$ MPa.

<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>Hole condition</th>
<th>Life to crack on</th>
<th>Fatigue life cycles</th>
<th>Failure position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Left</td>
<td>Right</td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td>Plain</td>
<td>28029</td>
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<td>5.4</td>
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<tr>
<td>Mean values</td>
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<td>36882</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>Hole condition</th>
<th>Life to crack on</th>
<th>Fatigue life cycles</th>
<th>Failure position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>10.2</td>
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<tr>
<td>Mean values</td>
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<td>122032</td>
</tr>
</tbody>
</table>

Comparing the mean values of fatigue life obtained for both types of specimens it is shown that the cold worked specimens tested at $\sigma_{max} = 160$ MPa have a fatigue life approximately 3.3 times larger than that of non-cold worked specimens.

Table (2.5) present the fatigue tests results for the specimens tested at $\sigma_{max} = 180$ MPa.

<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>Hole condition</th>
<th>Life to crack on</th>
<th>Fatigue life cycles</th>
<th>Failure position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Left</td>
<td>Right</td>
<td></td>
</tr>
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<th>Fatigue life cycles</th>
<th>Failure position</th>
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Comparing the mean values of fatigue life obtained for both types of specimens it is shown that the cold worked specimens tested at $\sigma_{max} = 180$ MPa have a fatigue life approximately twice larger as large as that of non-cold worked specimens.
Table (2.6) present the fatigue tests results for the specimens tested at $\sigma_{\text{max}} = 200$ MPa.

<table>
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<th>Life to crack on</th>
<th>Fatigue life cycles</th>
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Comparing the mean values of fatigue life obtained for both types of specimens it is shown that the cold worked specimens tested at $\sigma_{\text{max}} = 200$ MPa have a fatigue life approximately 1.4 times larger than that of non-cold worked specimens.

Figure (2.7) presents the fatigue test results for the different stress levels tested.

![S-N curves for the specimens with and without cold work.](image)

Figure 2.7: S-N curves for the specimens with and without cold work.
2.5 Summary and conclusions

1. Basic fatigue S-N test results were presented for normal and cold worked open hole specimens.

2. Larger scatter was found on the cold worked open hole specimens fatigue life.

3. For each stress level, fatigue lives of cold worked specimens are higher than those of non-cold worked specimens. Larger differences were found for lower stress levels, the results for both types of specimens being closer for higher stress levels. The trend is the diminution of the beneficial effect of the residual stress beneficial effect as the stress level increase.

4. The residual stress effect was noticed by the differences found in the fatigue life. Cold worked specimen 10.6 CW tested at $\sigma_{\text{max}} = 120$ MPa and specimen 8.5 CW tested at $\sigma_{\text{max}} = 140$ MPa broke in a remote cross section and not at the hole diameter plane, also suggesting the beneficial effect of cold work.

5. Based on the data of Figure (2.7), Figure (2.8-a)) shows the increase in fatigue life (FLI-fatigue life increase) for several stress levels ($\sigma_{\text{max}}$). Figure (2.8-b)) is a plot of these data using logarithmic axes. Based on this information, it is suggested that an empirical correlation between FLI and maximum stress level would be:

$$FLI \simeq A \cdot \sigma_{\text{max}}^B.$$  

(2.1)

For the present tests ($R=\sigma_{\text{min}}/\sigma_{\text{max}}=0.1$, open hole Al 2024 T3-Alclad specimens), the relevant constants were found to be: $A=2.577E6$, $B=-2.711$ and the correlation factor $R^2=0.908$.

Subject to further verification using a larger number of specimens and eventually other geometries, it is suggested an empirical "law" such as equation 2.1 may be of industrial interest.

Figure 2.8: Fatigue life increase due to residual stress.
Chapter 3

Residual stress

3.1 Introduction

The present chapter concerns the work related with the residual stresses. It starts with some considerations about residual stress, being focused on experimental and numerical techniques used for the assessment of the residual stress field in the specimens with cold expansion. The X-ray technique was used to measure experimentally the residual stress field, and some theoretical considerations are presented concerning this method. The numerical work was performed using ABAQUS. Two and three dimensional finite element analyses are presented, using elastic perfectly plastic and hardening material behaviour. Three dimensional finite element analyses are used to model the cold working process and compared with the simpler uniform hole expansion. Experimental and numerical results are compared. After the validation of the experimental measurements, the weight function technique is used to estimate the residual stress intensity factors associated with the present residual stress field. Finally some conclusions are stated.

3.2 Effect of residual stresses

Residual stresses are self-equilibrating stresses existing in materials or structures under uniform temperature conditions. This type of stresses is present in most of engineering components as a product of assembling or manufacturing procedures such as flame cutting, welding and cold working. These processes cause residual stress by inducing plastic deformation of the metal through severe temperature gradients, mechanical forces or microstructure changes [5].

Problems related with ageing aircraft may be reduced by enhancing the fatigue performance of aeronautical structures, especially in critical zones, acting as stress raisers, such as access and riveted holes. Fastener hole fatigue strength may be enhanced by creating compressive residual circumferential stresses around the hole. This technique (cold-work) has been used in the aeronautical industry for the past thirty years to delay fatigue damage and retard crack propagation. Research has been concentrated mainly on modelling the residual stress field using analytical or numerical two-dimensional (2D) or three-dimensional (3D) methods [6, 7, 8, 9, 10], on the experimental measurement of the residual stress field [11, 12], on the experimental characterization of the cold-worked hole behaviour in fatigue [13, 14],
and on the stress intensity factor calibration for cracks that may develop after cold work [7, 15, 16]. Subtopics considered include the consideration of thickness effects [10, 17], the consideration of eventual pre-existence of cracks of various sizes before hole expansion is carried out [13], the possible re-cold-working of already cold-worked holes [18], and the stress analysis of neighbouring cold-worked holes [19].

The compressive circumferential residual stress field around the rivet holes is created by applying pressure on the hole surface by means of a mandrel. Once the pressure is removed, the desired residual compressive stress field is achieved. According to Leon [20], the main benefits associated with the improvement of the fatigue life are the reduction of unscheduled maintenance, increasing the time between inspection intervals, reduction of maintenance costs and improvement of aircraft readiness.

Two cold-working processes are normally used in the aeronautical industry [20, 21]: the split sleeve process, using a solid tapered mandrel and a lubricated split sleeve, and the split mandrel process, using a lubricated, hollow and longitudinally slotted tapered mandrel, see Figure(3.1), ref. [22]. In service conditions, cracks may initiate and grow from the surface of the hole. However, due to the compressive residual stress, there will be a minimum value of remote tensile stress required to open the crack. Furthermore, once the cracks are open, the respective stress intensity factor, $K$, will be smaller than that obtained in the absence of cold-working. Therefore, the cold-working process retards crack growth, increasing the fatigue life of the structure. Since the reduction of the stress intensity factor is a function of the residual stresses, it is important to relate the magnitude of the residual stress field with the expansion of the mandrel (or with the pressure applied to the rivet hole) when designing a riveted connection.

![Diagram](image)

Figure 3.1: Schematic diagram of the FTI cold working process, ref. [22].
3.3 Experimental work

Experimental measurements using X-ray technique were performed. This work was carried out in the Universidade de Coimbra, Portugal (UC) by the Centro de Estudos de Materiais por Difracção de Raios X, Universidade de Coimbra, Portugal (CEMDRX) led by Professor A. Morão Dias and the measurements were performed by Dr. José P. Pina.

3.3.1 Principle of X-ray stress measurement

A concise introduction to X-ray stress measurement is given by Noyan et al. in reference [23] as described in the following paragraphs. When a monochromatic beam irradiates a solid material, it is scattered by the atoms composing the material. For a perfect crystalline material, atoms are packed regularly into a three-dimensional periodic lattice. The distance between crystallographic planes is perfectly defined and is a material characteristic in a given environment. Because of the atoms regular distribution, the scattered waves lead to interferences similar to visible light diffraction by an optical diffraction pattern. The intensities of scattered waves sum up into a constructive interference when the condition $2d \sin \theta = n \cdot \lambda$ is fulfilled (see Figure (3.2)), where $d$ is the distance between diffracting planes, $\theta$ is the angle between the incident beam and the diffracting planes, $\lambda$ is the X-ray length and $n$ is an integer. If this condition, called Bragg's Law, is fulfilled, the diffracted beam and the incident beam are symmetrical in relation to the lattice planes normal.

When a X-ray beam irradiates the surface of a crystalline material, it is constructively scattered only if it meets lattice planes oriented to fulfill Bragg's Law.

![Figure 3.2: Bragg's Law - X-ray diffraction.](image)

If the material is composed of many grains randomly oriented, there are always a group of them suitably oriented to produce diffracted beam. Figure (3.3) shows the diffraction pattern obtained on a fine powder sample. Because the random distribution of crystallites has rotational symmetry, several cones of diffracted beams with the incident beam as the axis can be observed, each of them corresponding to a specific lattice plane. Figure (3.3) shows what happen for a mechanical part composed of many grains. Diffraction cones can also be observed but only on one side because the specimen is massive and the penetration depth of X-rays usually used do not exceed 30-40 μm. The summit angles of these cones are:

$$\alpha_i = \pi - 2\theta_i$$  (3.1)
where \( \theta_i \) are the diffraction angles related to the spacing lattice "d" from the Bragg’s law. If these angles can be measured by an appropriate device, it is then possible to know the lattice spacing "d" of the analyzed crystallographic planes.

![Diffraction pattern obtained with fine grains structure.](image)

Figure 3.3: Diffraction pattern obtained with fine grains structure.

In a polycrystalline (metal or ceramic) part, with a fine grain and stress-free, the lattice spacing \( d_0 \) (see Figure (3.4)) for a given planes family does not vary with the orientation of these planes. If the specimen is stressed, due to elastic deformation, the lattice spacing varies according to the orientation of these planes relatively to the stress direction (see Figure (3.5)).

![Interplanar distance \( d_0 \) for all family planes, in material without stress.](image)

Figure 3.4: Interplanar distance \( d_0 \) for all family planes, in material without stress.

The crystal lattice (crystallographic planes) is used as a strain gauge which can be read by diffraction experiments. As in any extensometric method, the stress can be calculated from strains measured in several directions.

A diffraction peak is the result of X-rays scattering by many atoms in many grains, so a change in the lattice spacing will result in a peak shift only if it is homogeneous over all these atoms and grains, i.e., over all the irradiated volume. Thus the strain determined from peak measurements is representative of a macroscopic elastic strain (applied or residual). On the other hand, all the crystal defects (dislocations, vacancies, staking faults...) lead to a local fluctuation of the lattice spacing which results in a peak broadening. This broadening can be analyzed by a Warren-Averbach method to estimate the microstrains and microstresses.
3.3.2 X-ray diffraction determination of strains and stresses

The measured strain can be expressed in relation to a reference state of the material called stress-free state. In this state, the lattice spacing \{hkl\} equal to \(d_0\) which is a function of the lattice parameters of the stress-free crystal. Then, because an elastic deformation, the lattice spacing will be equal to \(d\). The conventional strain can be expressed as:

\[
\varepsilon = \frac{d - d_0}{d_0} \tag{3.2}
\]

Using the Bragg’s Law:

\[
\varepsilon = \frac{\sin \theta_0}{\sin \theta} - 1 \tag{3.3}
\]

The elastic strain of the crystal can therefore be obtained from the position of diffraction peaks recorded before and after deformation.

Biaxial state of stress

In the biaxial stress state, the tensor stress components are \(\sigma_{11}, \sigma_{12}\) and \(\sigma_{22}\). The problem is three dimensional and is necessary to measure strains along a direction \(\mathbf{n}\) described by two angles \(\phi\) and \(\Psi\) (Figure 3.6), ref. [23].

The components of vector \(\mathbf{n}\) are (\(\sin \Psi \cos \phi, \sin \Psi \sin \phi\) and \(\cos \Psi\)). The stress-strain relations can be written:

\[
\begin{align*}
\varepsilon_{11} &= \frac{1}{E} \sigma_{11} - \frac{\mu}{E} \sigma_{22} \\
\varepsilon_{12} &= \frac{2(1 + \mu)}{E} \sigma_{12} \\
\varepsilon_{22} &= -\frac{1}{E} \sigma_{11} + \frac{\mu}{E} \sigma_{22} \\
\varepsilon_{33} &= -\frac{1}{E} \sigma_{11} - \frac{\mu}{E} \sigma_{22} \tag{3.4}
\end{align*}
\]

The measured strain \(\varepsilon_n = \varepsilon_{\phi\Psi}\) is the projection of tensor \(\varepsilon\) on the measured direction \(\mathbf{n}\):

\[
\begin{align*}
\varepsilon_{11} = \mathbf{n} \cdot \varepsilon \mathbf{n}^t &= n_i n_j \varepsilon_{ij} = & sin^2 \Psi cos^2 \phi \varepsilon_{11} + sin^2 \Psi sin^2 \phi \varepsilon_{22} + cos^2 \Psi \varepsilon_{33} + \\
& sin^2 \Psi sin^2 \phi \varepsilon_{12} + sin^2 \Psi sin \phi \varepsilon_{23} + sin^2 \Psi cos \phi \varepsilon_{13} \tag{3.5}
\end{align*}
\]
Using stress-strain relations, it becomes:

\[
\varepsilon_{\phi\psi} = \frac{1 + \mu}{E} \left( \sigma_{11} \cos^2 \phi + \sigma_{12} \sin 2\phi + \sigma_{22} \sin^2 \phi \right) + \sin^2 \Psi - \frac{\mu}{E} \left( \sigma_{11} + \sigma_{22} \right)
\]  

(3.6)

It can be seen that the term between the first parentheses is the projection of stress the stress tensor on direction \( L'1 \) with components \((\cos \phi, \sin \phi, 0)\), i.e., the stress value along \( L'1 \). The term between the second parentheses is the trace \((\text{Tr})\) of tensor \( \sigma \):

\[
\varepsilon_{\phi\psi} = \frac{1 + \mu}{E} \sigma_{\phi} \sin^2 \Psi - \frac{\mu}{E} \text{Tr}(\sigma) = \frac{1}{2} S_2 \sigma_{\phi} \sin^2 \Psi + S_1 \text{Tr}(\sigma)
\]  

(3.7)

To determine the stress along a given direction \( \phi \), the measured strain \( \varepsilon_{\phi\psi} \) can be plotted versus \( \sin^2 \Psi \), the slope is then proportional to \( \sigma_{\phi} \) and the interception is proportional to the trace of the stress tensor. This equation is called the \( \sin^2 \Psi \) law.

For \( \phi = 0 \), the stress \( \sigma_{\phi} \) is equal to \( \sigma_{11} \) and for \( \phi = \pi/2 \), the stress \( \sigma_{\phi} \) is equal to \( \sigma_{22} \). It is thus sufficient to make a measurement in a third direction \( \phi \) to obtain the full stress tensor.

### 3.3.3 Experimental procedure

As previously mentioned the common X-ray technique has about 30-40 \( \mu m \) of penetration. For this reason it was necessary to measure the clad thickness assuring that the measurements were performed in the aluminium alloy, see Figure (3.7). The procedure adopted for measuring the clad thickness is presented in Appendix (C), where it was concluded that the clad thickness is approximately 41 \( \mu m \). Figure (3.7) presents one of the figures used to measure the clad thickness. Two different regions can be identified: a light grey region corresponding to the layer of Al clad (pure Al) and a darker region corresponding to the attacked aluminium alloy. The boundary grain between the two parts is also visible.

The first step was to take off the clad from the measurements of the specimen. This work was done using a clad dissolution by electrolytic polishing. The specimens’ hole was previously fulfilled with epoxy resin to avoid the hole wall attack. The thickness of the removed material was between 35-40 \( \mu m \), this process was controlled by a micrometer with 1\( \mu m \)
of precision. The polishing effects were observed using a microscope. Some traces of clad where still found in the aluminium alloy, but these traces were not relevant for the measurements performed. The diffraction penetration depth used was approximately 30 μm. The first measurements showed that the plate had a crystallographic texture that should be considered in the method used. The crystallographic texture characterization was done in both parts of the plate in two different positions, one near the hole and other at 5 mm distance from the hole wall. In all cases the crystallographic texture showed two same components with variable relative intensity. The components \{110\}<110> and \{100\}<001> were identified, and according to the literature are due to rolling operation and its posterior recrystallization treatment, ref. [24].

Due to the texture characteristics, the ideal directions method was used to measure the residual stress. It was possible to study XX (θ=0° - see Figure(3.8)) direction, although the YY (θ=90°) direction was not accessible and the number of specimen inclinations available in each direction reduced. Because of these reasons and to guarantee good results precision, the stress tensor was determined in each point. Six directions and eleven inclinations in each direction were used. The aluminium crystallographic planes were studied with Kα-Cu radiation.

According to the X-ray diffraction specificity, each measured point corresponds to the center of one irradiated rectangle area with 2 mm of height and 1 mm width.

3.3.4 X-ray experimental results

The stress tensor calculation allowed the determination of the stress principal directions and the shear stress, which presents values considered null.
Figure 3.8: Radial and circumferential stresses. a) Radial ($\sigma_{rr}$) and circumferential ($\sigma_{\theta\theta}$) stress for $\theta=0^\circ$.

Residual stress measurements for $\theta=0^\circ$ and $\theta=90^\circ$ are presented, in each point the FWHM (Full-Width Half-Maximum) mean values of the diffraction peaks width at mean height for all peaks were calculated. The interest is the relationship between this parameter and the level of material hardening.

The X-ray measurements along $\theta = 0^\circ$ for the entrance and exit faces are presented in Table (3.1) and (3.2) respectively.

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<th>$\tau_{rz}$ [MPa]</th>
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Dist. - Distance from hole.
Table 3.2: X-ray measurements, $\theta=0^\circ$. Exit face

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The X-ray measurements along $\theta = 90^\circ$ for the entrance and exit faces are presented in Table (3.3) to (3.5) respectively.

Table 3.3: X-ray measurements, $\theta=90^\circ$ (cont.). Entrance face

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Table 3.4: X-ray measurements, $\theta=90^\circ$. Exit face

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23
Table 3.5: X-ray measurements, $\theta=90^\circ$. Exit face (cont.)

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Figure (3.9) shows the graphical results of the X-ray stress measurements from Tables (3.1 to 3.4). For each one of the pictures a) to d) a polynomial fit for the residual stress measurements is suggested.

Figure 3.9: Radial and circumferential residual stresses: a) entrance face, $\theta = 0^\circ$; b) exit face, $\theta = 0^\circ$; c) entrance face, $\theta = 90^\circ$; d) exit face, $\theta = 90^\circ$.  

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The results shown in Figure (3.9) are in broad agreement with other literature results [25, 26, 22]. Figure (3.10) presents the FWHM correspondent to the residual stress measurements shown in Figure (3.9).

Figure 3.10: Diffraction peaks width: a) entrance face, $\theta = 0^\circ$; b) exit face, $\theta = 0^\circ$; c) entrance face, $\theta = 90^\circ$; d) exit face, $\theta = 90^\circ$.

3.4 FEM work

Two and three dimensional FEA were performed using ABAQUS [27]. The finite elements used are shown in Figure (3.11). As it is known, the non linear characteristics considered in structural analysis can be the result of the individual or combined action of two different types of non linearities: geometric and material. In the present work both cases were considered. The non linear geometric effects are related with the stability of the structure equilibrium configuration and occur when the deformation and/or rotations suffered by the structure are considerable. On the other side the non linear material effects occur when the material leave the linear behaviour. Figure (3.12) present the two material behaviours used in 2D and 3D.
Figure 3.11: Finite elements used in 2D and 3D analysis. CAX4 - axisymmetric linear element of 4 nodes, CPS8 - bi-quadratic plane stress element of 8 nodes and C3D8 is a solid linear element of 8 nodes.

FEA, Material Elastic Perfectly Plastic (MEPP) and hardening material behaviour were considered. The hardening behaviour was modelled using experimental data points from a tensile test (see Appendix A).

Figure 3.12: Material models used in FEM analysis.
3.4.1 Finite Element Analysis: two dimensional work

Two dimensional FEM work was performed using three models, 2D cylindrical and real geometry, 2D axisymmetrical. As a first attempt a model with cylindrical geometry was used (see Figure (3.13)), \( r_i = 2.415 \text{ mm} \) (internal radius) and \( r_e = 50 \text{ mm} \) (external radius) in order to simulate an "infinite" domain. The real geometry was modelled in order to obtain more realistic results.

The residual stress field was determined for different values of radial interference, defined as:

\[
i = \frac{\bar{D} - D}{D} \cdot 100\%
\]  

where \( \bar{D} \) is the diameter of the mandrel, \( D \) the diameter of the hole. Eight different values of interferences were considered, \( i = 1\%, 2\%, 3\%, 4\%, 5\%, 6\%, 7\% \) and \( 8\% \). Elastic perfectly plastic and hardening material behaviour were considered.

For determining the residual stress field, a non-linear geometric procedure was used. On a first step, the radial interference was applied and on a second step the radial interference was removed by setting free the nodal displacements at the hole boundary. In this second step, the reverse plasticity might be modelled. At the end of the second step, the residual stress field has already been created. A similar procedure was used by Pavier et al. [26] for obtaining the residual stress field in a finite plate with hole.

The cold working process was simulated using 2D axisymmetric elements for the model with circular geometry in order to evaluate the residual stress field through the thickness. A similar procedure was also used by Pavier et al. [28].

3.4.1.1 Two dimensional FEA, cylindrical geometry

Figure (3.13) shows details of a quarter of a cylinder mesh used for modelling the infinite domain.

![Figure 3.13: 2D FEM model with cylindrical geometry. a) Mesh, 10000 plane stress elements - CPS8; b) Mesh detail, \( R = 2.415 \text{ mm} \).](image)

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Figure (3.14) presents the residual stress fields obtained for the "infinite" behaviour considering an elastic perfectly plastic material model for different interference levels.

Figure 3.14: Residual stress field considering an elastic perfectly plastic material model: a) radial residual stress field; b) radial residual stress field, detail; c) circumferential residual stress field; d) circumferential residual stress field, detail.

Figure (3.14) shows that the residual stress field has the bigger stress gradients in a band of 5 mm from the hole surface. These stress gradients become smaller with increasing distance from hole. It is noticed that the residual stress effect is disappears after a distance of approximately 20 mm from the hole surface.
Comparable results are presented in Figure (3.15) for the hardening material behaviour.
Figure 3.15: Residual stress field considering the hardening material model: a) radial residual stress field; b) radial residual stress field, detail; c) circumferential residual stress field; d) circumferential residual stress field, detail.

The trend of the stress distributions in Figure (3.15) is the same as that found in Figure (3.14), although higher tensile and compressive stress values were found using the hardening material behaviour.
3.4.1.2 Two dimensional FEA, real geometry model

As previously stated the real geometry was also modelled in order to have more accurate and realistic results. Figure (3.16) shows details of a quarter of the real model plate.

Figure 3.16: Quarter of the real model 2D FEM mesh. a) Mesh, 5000 plane stress elements - CPS8; b) Mesh detail, R= 2.415 mm.

The finite element procedure used was described in the beginning of section (3.4.1).
Figure (3.17) shows some results obtained for the present analysis, using ABAQUS. It concerns 4% interference considering an elastic perfectly plastic material model.

Figure 3.17: 2D FEM results for 4% of interference, MEPP: a) Von Mises stress field; b) Total displacement field; c) $\sigma_{xx}$ residual stress; d) $\sigma_{yy}$ residual stress.

The results presented in Figure (3.17) are almost axisymmetric, although it is noticed that the boundary has a small influence in the results.

The results obtained using both types of material behaviour, for the interference levels considered, are presented in Figure (3.18).
Figure 3.18: 2D FEM results for different interference levels and $\theta = 0^\circ$ (see Fig. (3.8)): a) $\sigma_{rr}$, MEPP; b) $\sigma_{\theta\theta}$, MEPP; c) $\sigma_{rr}$, hardening behaviour; d) $\sigma_{\theta\theta}$, hardening behaviour.

Figure (3.18) allows the comparison of results between for both types of of material models. Higher residual tensile and compressive stresses were found for the hardening material model, for both stress components $\sigma_{rr}$ and $\sigma_{\theta\theta}$. 

The data presented here is based on the methodology outlined in Section 3.4.1.
3.4.1.3 2D FEA Axisymmetric model

As previously stated a 2D axisymmetric model was used to evaluate the residual stress field through the thickness. The finite element analysis of 4.5% cold working (CW) process is presented, where the technique of drawing a mandrel through a hole in a 2024-T3 aluminium plate is accurately simulated using contact elements. The results of the analysis are compared with a simpler axisymmetric finite element model where the cold working process is simulated by applying a uniform expansion (UE) of the hole edge. The model geometry is presented in Figure (3.19).

![Figure 3.19: Axisymmetric model, dimensions.](image)

Since the present model has a thin thickness, some bending problems can appear during the cold working process depending on boundary conditions. In order to study the boundary conditions effect, the constraint BC in Figure (3.20) took the following values:

- BC-A $\rightarrow$ BC = 42.48mm;
- BC-B $\rightarrow$ BC = 37.90mm;
- BC-C $\rightarrow$ BC = 27.80mm;
- BC-D $\rightarrow$ BC = 17.85mm.

It must be mentioned that other authors (ref. [28]) simulated a similar model with 6 mm of thickness and they did not use the constraint BC, although in the present model this was not possible because of the plate bending.
Figure 3.20: Axisymmetric model, boundary conditions.

Figure (3.21) presents the complete axisymmetric model and consists of a rigid mandrel a steel sleeve and an aluminium alloy plate. Contact elements were used between the mandrel and sleeve and between the sleeve and plate hole. More details on the mandrel, sleeve and the cold working process can be found in section (3.4.2).

Figure 3.21: Axisymmetric model mesh: a) entire model assembly, 15800 axisymmetric elements. The plate and sleeve have respectively 15000 and 800 elemets; b) detail near the mandrel; c) sleeve and plate near the hole.

Figure (3.22) describes the evolution of the Von Mises stress field during the cold working process. The mandrel displacement \((d_m)\) is presented in each one of the pictures.
Figure 3.22 shows the asymmetric residual stress field through the thickness after the cold working process using a mandrel. The simple uniform hole expansion (see Figure 3.35) considering the same material behaviour was also simulated. Figure 3.23 shows differences in symmetries, in the case of the Von Mises residual stress profile.

Figure 3.24 shows the bending effect on the radial and circumferential residual stresses through the plate thickness considering an elastic perfectly plastic material behaviour. Differences were found at the entrance and exit faces, although the bigger differences were found at the entrance face. In the mid-thickness plane the results are almost coincident because, as it is known, the bending component does not exist in the mid plane. Figure 3.25 shows the effective radial enlargement of the hole through the thickness for both uniform expansion analysis and the cold working simulation with the different boundary conditions. Using the cold working process higher radial enlargement was found through all the thickness. For the cold working process it is shown that at the entrance face the radial enlargement of the hole increases with the bending diminution, being independent of the boundary condition at the exit face. Figure 3.26 compares the axial deformation at the hole edge for the uniform expansion analysis and the cold working simulation with the different boundary conditions. For the cold working process the axial deformation increases as the constraint level decreases as would be expected. It is also noticed that for the boundary conditions BC-A and B the axial deformation is very close than for the uniform expansion at the entrance face improving elsewhere through the thickness.

The same kind of results are presented considering the hardening material behaviour. Fig-
a) Cold working process using a uniform hole expansion;

b) Cold working process using a rigid mandrel;

Figure 3.23: Von Mises residual stress field after the hole deformation process, MEPP. Axisymmetric model revolution (180°).

Figure (3.27) compares the radial and circumferential residual stress results for the uniform hole expansion and the cold working process with different boundary conditions. Qualitatively the results are similar to those for MEPP, although higher (tensile and compressive) stress values were found.

Figure (3.28) shows the same trend as MEPP, although the difference between the cold working process and uniform hole expansion decreases slightly. Figure (3.29) compares the axial deformation for the uniform and cold working processes with different boundary conditions.
Figure 3.24: Influence of the boundary conditions in the residual stress field, MEPP: a1) residual radial stress, entrance face; b1) residual circumferential stress, entrance face; a2) radial stress, mid-thickness; b2) residual circumferential stress, mid-thickness; a3) residual radial stress, exit face; b3) residual circumferential stress, exit face.
Figure 3.25: Variation of the effective radial permanent enlargement of the hole as a percentage of the nominal enlargement through the plate thickness for the finite element analysis of uniform cold expansion compared to the results of the simulation of the cold working process with different boundary conditions, MEPP.

Figure 3.26: Variation of the permanent deformation of the hole through the plate thickness for the finite element analysis of uniform expansion compared to the results of the simulation of the cold working process with different boundary conditions, MEPP.
Figure 3.27: Influence of the boundary conditions in the residual stress field, hardening material behaviour: $a_1$) residual radial stress, entrance face; $b_1$) residual circumferential stress, entrance face; $a_2$) residual radial stress, mid-thickness; $b_2$) residual circumferential stress, mid-thickness; $a_3$) residual radial stress, exit face; $b_3$) residual circumferential stress, exit face.
Figure 3.28: Variation of the effective radial permanent enlargement of the hole as a percentage of the nominal enlargement through the plate thickness for the finite element analysis of uniform cold expansion compared to the results of the simulation of the cold working process for different boundary conditions, hardening material behaviour.

Figure 3.29: Variation of the permanent deformation of the hole through the plate thickness for the finite element analysis of uniform expansion compared to the results of the simulation of the cold working process for different boundary conditions, hardening material behaviour.
3.4.1.4 Two dimensional FEA: comparison of results

The comparison of results was done in the following way:

- comparison of results between the cylindrical ("infinite") and the real model, in order to study the geometry effect and boundaries influence;
- comparison of results between 2D and 2D axisymmetrical models, in order to compare residual stress results through the thickness.

Figure (3.30) compares the results for the cylindrical and the real model geometry for different interference levels and material behaviours. The geometry effect is noticed in both stress components as follows:

- The radial stress results are almost coincident close to the hole surface, and until a small distance after \( \sigma_{rr} \) reaches the minimum value. After this point the difference starts to increase because \( \sigma_{rr} \) is zero at the limit of the width 10.085 mm for the real model geometry, while for the "infinite" model this occurs at a larger distance, approximately 47.585 mm;
For the residual circumferential stress the results are almost coincident close to the hole surface until approximately the second inflexion stress point. After this point the difference increases because in the real model the equilibrium (force correspondent to the area between the stress curve and the zero axis) must be attained in a very short distance, while for the "infinite" model the equilibrium is reached at a larger distance. After the second stress inflexion point, as the interference level increases, higher positive stress values are obtained until the boundary for the real model. For the "infinite" model the trend is the diminution of the stress after the second inflexion stress point.

Figure (3.31) presents the comparison of results between 2D and 2D mid-thickness axisymmetrical results, for the radial and circumferential residual stresses considering MEPP and hardening behaviour.

Figure 3.31: Residual stress comparison of results between 2D and 2D axisymmetric mid-thickness results: a) residual radial stress, MEPP; b) residual circumferential stress, MEPP; c) residual radial stress, hardening behaviour; d) residual circumferential stress, hardening behaviour.
The present work shows that the results obtained using 2D and 2D axisymmetrical models are similar just on the mid-thickness plane. A previous work reported the same kind of results, see [26]. Because of this reason the 2D results are compared with 2D axisymmetrical mid-thickness results. It was also concluded that the boundary conditions do not have a significant effect in the mid-thickness residual stresses, therefore 2D axisymmetrical results are presented only for one of the boundary conditions studied, BC-A. The results for the 2D model are presented for 4 and 5% of interference. The results in Figure (3.31) agree closely, although 2D model does not describe the stress gradients showed by 2D axisymmetric uniform hole expansion and cold working process for 4.5%.

3.4.2 Finite Element Analysis: three dimensional work

The results so far presented concern the two dimensional residual stress simulation of cold working. The literature reports that the actual method of cold working where a tapered mandrel is drawn through the hole, gives a variation of the residual stress through the thickness, [28, 22, 26, 29].

Two 3D finite element analyses were, therefore, carried out: (i) the cold working process has been simulated accurately by drawing a rigid mandrel through the plate and (ii) a simpler model of hole expansion (see Figure (3.35)). Figure (3.32) shows the the finite element model used. The boundary conditions are presented in Figure (3.33). Mandrel and sleeve diameter dimensions were taken from Fatigue Technology Inc., Seattle, USA (FTI) [30] catalogue for a hole diameter of 4.83 mm corresponding to ≈ 4.5% of cold expansion. It must be mentioned that according to FTI [30] for typical fastener hole diameters in aluminium and mild steel, the applied expansion ranges from 3 to 6%. The applied expansion is given by the following formula:

\[ i = \frac{(D + 2t - SHD)}{SHD} \times 100\% \]  

(3.9)

where D is the major mandrel diameter, t is the sleeve thickness and SHD is the starting hole diameter. Mandrel and sleeve dimensions are presented in Figure (3.34). Frictionless conditions were assumed between the mandrel and sleeve, and the sleeve and the aluminium alloy plate. The assumption of frictionless contact is justified since the the sleeve is well defined and slip occurs between the mandrel and sleeve rather than the sleeve and plate. A linear elastic model was used for the sleeve with a Young’s modulus of 210 GPa and Poisson’s ratio of 0.3. The mandrel was modelled as a rigid surface, using the revolution feature of ABAQUS. The plate in Figure (3.32 a) has 41600 three-dimensional eight-node linear elements for the aluminium plate with eight integration points, the sleeve in Figure (3.32 g) has 600 elements more. The contact between the hole surface and sleeve and also between the sleeve and the mandrel was modelled. Zero friction was assumed between the contacting surfaces. It must be mentioned that sixteen elements along the plate thickness were used.

Initial work and other references [28] showed that considerable refinement of the mesh on the surface of the plate and in the vicinity of the hole edge Figure (3.32 d and e) is required as also reported in reference [22].
a) Model assembly, aluminium alloy plate, steel sleeve and rigid mandrel;

b) Model assembly detail;

c) Plate and sleeve assembly;

d) Plate and sleeve mesh, detail;

e) Hole mesh detail;

f) Rigid mandrel;

g) Steel sleeve;

Figure 3.32: Details of the three dimensional finite element model used for the cold working process simulation.
a) Boundary conditions applied in the plane xy;

b) Boundary conditions applied in the plane xz;

Figure 3.33: Boundary conditions used in the 3D finite element cold working simulation.
Figure 3.34: Sleeve and mandrel dimension details.

Figure 3.35: Hole detail showing the uniform displacement applied to simulate the uniform hole expansion.
Figure (3.36) illustrates the von Mises stresses along the cold working process. The mandrel displacement $d_m$ is presented in each one of the pictures.

a) Mandrel initial position;  
b) $d_m = 1.247$ mm;

c) $d_m = 2.5$ mm;  
d) $d_m = 3.54$ mm;  
e) Final hole deformation;

Figure 3.36: Von Mises Stresses along the cold working process, MEPP.

As previously stated the same model was used for the uniform hole expansion. Figure (3.37) shows the Von Mises stress field for both deformation processes, cold-working and uniform hole expansion modelling.
a) Von Mises stress field at the end of the cold-working process;

b) Von Mises stress field at the end of the cold working process by uniform hole expansion;

Figure 3.37: Comparison of results using different hole expansion techniques, MEPP.

Figure (3.37) shows that the residual stress field is very different in both situations. The residual stress field due to the cold-working process is asymmetrical while for the uniform hole cold expansion it is symmetrical.

Figure (3.38) shows the circumferential and the radial residual stress fields through the plate thickness for the cold-working process and uniform hole cold expansion, considering an elastic perfectly plastic material model. The results are plotted for the mid-thickness, entrance and exit faces. Figure (3.38) shows the substantial differences between the two sets of results. Concerning the radial residual stress Figure (3.38 - e) shows that the uniform expansion analysis has higher compressive stresses, although the mid-thickness and exit face results are close. Figure (3.38 - f) shows that the circumferential residual stress results match reasonably closely in the entrance and mid-thickness for both processes.

Figure (3.39) shows the effective radial enlargement of the hole through the thickness for both processes, uniform hole expansion analysis and the cold working simulation. First of all it is noticed that more element layers would be necessary in the model to describe more accurately the permanent radial hole enlargement. Although with the available information it is shown that the radial hole enlargement is a portion of the 4.5% nominal expansion. Using the cold working process higher radial enlargement was found, 2% at
the entrance and 10% at the exit face were found. Through the thickness some instability was noticed and the minimum relative enlargement verified at approximately $z/t=0.2$ ($t$ is the plate thickness). Figure (3.40) compares the permanent axial deformation at the hole edge from the two sets of finite element results. A small difference was found at the entrance but elsewhere more axial deformation was found in the simulation of cold working.

The same type of results is presented considering the hardening material behaviour. Figure (3.41) compares radial and circumferential residual stresses results for the uniform hole expansion and cold working process. Figure (3.41 - e) shows that the uniform hole expansion has higher compressive radial stresses at the exit face, although the shape of the curve is similar. Larger differences were found for the mid-thickness and entrance planes. Figure (3.41 - f) shows that only the circumferential residual stresses on the mid-thickness match reasonably closely. Larger differences between both techniques were found in the entrance and exit faces.

Figure (3.42) shows the radial enlargement. At the entrance face the results agree closely, while at the exit face the enlargement calculated with the cold working model is much higher. Despite the lack of resolution through the plate thickness a polynomial fit of the radial enlargement is suggested. Figure (3.43) compares the permanent axial deformation at the hole edge for the two sets of finite element results. Some difference was found at the entrance but elsewhere more axial deformation was found in the simulation of cold working.
Figure 3.38: Residual stress distribution through the plate thickness for the finite element analysis of uniform expansion and the simulation of cold working process, MEPP: a) residual radial stress CW; b) residual circumferential stress CW; c) residual radial stress UE; d) residual circumferential stress UE; e) residual radial stress comparison of results; f) residual circumferential stress comparison of results.
Figure 3.39: Variation of the effective radial permanent enlargement of the hole as a percentage of the nominal enlargement through the plate thickness for the finite element analysis of uniform cold expansion compared to the results of the simulation of the cold working process, MEPP.

Figure 3.40: Variation of the permanent deformation of the hole through the plate thickness for the finite element analysis of uniform expansion compared to the results of the simulation of the cold working process, MEPP.
Figure 3.41: Residual stress distribution through the plate thickness for the finite element analysis of uniform expansion and the simulation of cold working process, hardening material behaviour: a) residual radial stress CW; b) residual circumferential stress CW; c) residual radial stress UE; d) residual circumferential stress UE; e) residual radial stress comparison of results; f) residual circumferential stress comparison of results.
Figure 3.42: Variation of the effective radial permanent enlargement of the hole as a percentage of the nominal enlargement through the plate thickness for the finite element analysis of uniform cold expansion compared to the results of the simulation of the cold working process, hardening material behaviour.

Figure 3.43: Variation of the permanent deformation of the hole through the plate thickness for the finite element analysis of uniform expansion compared to the results of the simulation of the cold working process, hardening material model.
Figure (3.44) presents the residual stresses predicted using elastic perfectly plastic and hardening material behaviour.

![Graph a) Residual Radial Stress](image1)

![Graph b) Residual Circumferential Stress](image2)

Figure 3.44: Comparison of residual stress distribution for elastic perfectly plastic and hardening material models obtained from the finite element simulation of cold working: a) residual radial stress; b) residual circumferential stress.

Figure (3.45) shows that the radial hole enlargement is bigger using the elastic perfectly plastic material behaviour, being this difference larger at the entrance face.
Figure 3.45: Comparison of the variation of the effective radial permanent enlargement of the hole as a percentage of the nominal enlargement through the plate thickness for the finite element analysis of the simulation of the cold working process for the elastic perfectly plastic and hardening material behaviour.

The axial permanent hole deformation (Figure 3.46) using MEPP is bigger at the entrance face, the trend inverts at $z/t=-0.12$ being slightly inferior at the exit face.

Figure 3.46: Comparison of the variation of the permanent deformation of the hole through the plate thickness for the finite element analysis of the simulation of the cold working process for the elastic perfectly plastic and hardening material behaviour.
3.4.3 Comparison of two and three dimensional FEA results

The present section compares the results obtained with the following FEA:

- between two and three dimensional FEA, real model;
- between 2D axisymmetrical (cylindrical "infinite") model and the 3D real model.

This work shows that 3D results are in agreement with 2D FEA in the mid-thickness of the plate only. The 3D stress near the entrance and exit faces generally higher (less compressive) than the 2D results. The same trend of results was reported by Pavier et al. [26]. In Figure (3.47) 3D four and five percent of hole expansion are compared, because the cold working process was 4.5%.

![Graph a) showing residual radial stress](image1)

![Graph b) showing residual circumferential stress](image2)

Figure 3.47: comparison of results between 2D and 3D finite element analysis at the mid-thickness plane, MEPP: a) residual radial stress; b) residual circumferential stress.
Figure (3.47) shows that the mid-thickness results for the cold working process and uniform hole expansion match closely with 2D FEA analysis. It is noticed that for uniform hole expansion the circumferential results are almost coincident with 2D FEA. Figure (3.48) shows the same type of results considering the hardening material behaviour.

![Radial residual stress](image)

![Circumferential residual stress](image)

Figure 3.48: Comparison of results between 2D and 3D finite element analysis at the mid-thickness plane, hardening material behaviour: a) radial residual stress; b) circumferential residual stress.

Figure (3.49) compares the residual stress results through the thickness using 2D axisymmetric model with different boundary conditions and the 3D real model, considering MEPP. Figure (3.49) shows that the larger differences appear at the entrance face. The 2D axisymmetric model overestimate maximum tensile and compressive residual stress for radial and circumferential stress components. The 2D circumferential stress for the entrance face present, for boundary condition A and B, tensile stresses close the hole surface, see
Figure (3.49 - $b_1$). At the mid-thickness plane and exit face the results are very close. Figure (3.50) compares the permanent hole enlargement for both models. It was noticed that 2D axisymmetric model overestimate the hole enlargement for the uniform hole expansion and cold working process. Figure (3.51) presents the hole axial deformation for both models. Using uniform hole expansion the results are very close, although for the cold working process this depends on the boundary conditions.

The same type of results, with the same trend but higher tensile and compressive stresses are presented in Figure (3.52) for the hardening material behaviour. Figure (3.53) and (3.54) present results for the permanent hole enlargement and axial deformation respectively. In the present comparison of results we must remember that 2D axisymmetrical model can be compared to a "infinite" domain while the 3D real model is a finite domain. Because of this reason all the comparisons presented above have an approximate value.
Figure 3.49: Comparison of results 2D axisymmetric model and 3D real model, MEPP: a1) residual radial stress, entrance face; b1) residual circumferential stress, entrance face; a2) residual radial stress, mid-thickness; b2) residual circumferential stress, mid-thickness; a3) residual radial stress, exit face; b3) residual circumferential stress, exit face.
Figure 3.50: Variation of the effective radial permanent enlargement of the hole as a percentage of the nominal enlargement through the plate thickness for the finite element analysis of uniform cold expansion compared to the results of the simulation of the cold working process for different boundary conditions and finite elements models, MEPP.

Figure 3.51: Variation of the permanent deformation of the hole through the plate thickness for the finite element analysis of uniform expansion compared to the results of the simulation of the cold working process for different boundary conditions and finite element models, MEPP.
Figure 3.52: Influence of the boundary conditions in the residual stress field, hardening material behaviour: $a_1$) residual radial stress, entrance face; $b_1$) residual circumferential stress, entrance face; $a_2$) residual radial stress, mid-thickness; $b_2$) residual circumferential stress, mid-thickness; $a_3$) residual radial stress, exit face; $b_3$) residual circumferential stress, exit face.
Figure 3.53: Variation of the effective radial permanent enlargement of the hole as a percentage of the nominal enlargement through the plate thickness for the finite element analysis of uniform cold expansion compared to the results of the simulation of the cold working process for different boundary conditions and finite element models, hardening material behaviour.

Figure 3.54: Variation of the permanent deformation of the hole through the plate thickness for the finite element analysis of uniform expansion compared to the results of the simulation of the cold working process for different boundary conditions and finite element models, hardening material behaviour.
3.5 Finite element analysis \textit{versus} experimental measurements, comparison of results

The present section presents the comparison of results between the finite element analysis and the experimental X-ray measurements. The following comparisons were performed:

- 2D FEA real model \textit{versus} experimental results;
- 2D FEA axisymmetrical (cylindrical "infinite") model \textit{versus} experimental results;
- 3D FEA real model \textit{versus} experimental measurements.

3.5.1 Two dimensional FEA \textit{vs} X-ray measurements

Figure (3.55) and (3.56) show the framing of the experimental data in the 2D FEM simulation for different interpenetration levels. It must be mentioned that the experimental results presented in Figures (3.55) to (3.58) concern the maximum experimental values measured, exit face and $\theta=0^\circ$ (see Figure (3.8)).

![Graph showing residual stress vs distance from hole](image)

Figure 3.55: Real model radial residual stress for $\theta=0^\circ$ (see Figure (3.8)) and experimental measurements, MEPP.

Figure (3.55) shows that the larger part of the experimental measurements fit between 3 and 5\% of hole expansion.
Figure 3.56: Real model circumferential residual stress for $\theta=0^\circ$ (see Figure (3.8)) and experimental measurements, MEPP.

Figure (3.56) shows that the larger part of the experimental measurements fit between 3 and 5%, although this trend is less clear than for the radial stress.

Figure (3.57) and (3.58) show the same trend found in the two previous figures. Although as the maximum compressive stresses are higher, the level of interference seems to decrease.

Figure 3.57: Real model radial residual stress for $\theta=0^\circ$ (see Figure (3.8)) and experimental measurements. Hardening material behaviour.
Figure 3.58: Real model circumferential residual stress for $\theta=0^\circ$ (see Figure (3.8)) and experimental measurements. Hardening material behaviour.
3.5.2 Two dimensional axisymmetrical FEA vs X-ray measurements

Figure (3.59) shows the residual stress comparison between the 2D axisymmetrical model and experimental measurements performed at $\theta=0^\circ$ and $\theta=90^\circ$ (see Figure (3.8) for the entrance and exit faces, considering MEPP.

Figure 3.59: Influence of the boundary conditions in the residual stress field, MEPP: $a_1$) residual radial stress, entrance face; $b_1$) residual circumferential stress, entrance face; $a_2$) residual radial stress, exit face; $b_2$) residual circumferential stress, exit face.

Agreement between FEA and experimental measurements is noticed after approximately 2mm from the hole surface. Close to the hole the agreement is poor because experimental measurements are averaged over an irradiated volume, and it is not possible to resolve the steep stress gradients in the vicinity of the hole, [31].
Figure (3.60) shows the residual stress comparison between the 2D axisymmetrical model and experimental measurements performed at $\theta=0^\circ$ and $\theta=90^\circ$ (see Figure (3.8) for the entrance and exit faces, considering hardening material behaviour.

![Graph a1)](image1)

![Graph b1)](image2)

![Graph a2)](image3)

![Graph b2)](image4)

Figure 3.60: Influence of the boundary conditions in the residual stress field, hardening material behaviour: a1) residual radial stress, entrance face; b1) residual circumferential stress, entrance face; a2) residual radial stress, exit face; b2) residual circumferential stress, exit face.

Figure (3.60) shows the same trend as that found for the previous figure. For the hardening material the stress gradients in the near hole region present higher tensile and compressive values increasing the differences in the hole region.
3.5.3 Three dimensional FEA vs X-ray measurements

Figure (3.61) presents the comparison of results on the entrance and exit faces of the specimen for a 3D FEA and experimental X-ray techniques for $\theta=0^\circ$ (see Figure (3.8)).

![Graphs showing comparison of residual stress](image)

Figure 3.61: Comparison of results between 3D FEM and experimental X-ray measurements for $\theta=0^\circ$ (see Figure (3.8)) : a) radial residual stress, MEPP; b) circumferential residual stress, MEPP; c) radial residual stress, hardening material behaviour; d) circumferential residual stress, hardening material behaviour.

FEA results are somewhat different from the experimental measurements. It was noticed that on the entrance face FEA results have the same trend as the corresponding experimental measurements. The same thing happens for the exit face. Larger differences were found for the hardening material behaviour because higher residual stress values were found elsewhere.
Figure (3.62) presents the comparison of results on the entrance and exit faces of the specimen for a 3D FEA and experimental X-ray techniques for $\theta=90^\circ$ (see Figure(3.8)).

![Graphs showing comparison of results](image)

Figure 3.62: Comparison of results between 3D FEM and experimental X-ray measurements for $\theta=90^\circ$ (see Figure(3.8)): a) radial residual stress, MEPP; b) circumferential residual stress, MEPP; c) radial residual stress, hardening material behaviour; d) circumferential residual stress, hardening material behaviour.

The same trend as for the previous figure was found, although the agreement between both types of results is better. This better agreement can be due to the larger number of experimental measurements, taken along a larger specimen length.
3.6 Residual stress intensity factors determination using the weight function method

A very efficient method for determining the stress intensity factor is the weight function method, introduced by Bueckner [32]. In order to use it, it is necessary to know a complete solution (the stress intensity factor and the displacements of the crack faces) for a crack problem for one loading system. Using these results, one may obtain the solution for the stress intensity factor for the same crack configuration with any other loading.

Rice [33] showed that, if the stress intensity factor $K_{Ir}(a)$, and the displacement field $u_{Ir}(x, a)$ for a cracked body under a symmetrical loading (called the reference case) are known, the Mode I weight function can be determined, in the co-ordinate system shown in Figure(3.63), from:

$$h(x, a) = \frac{E'}{K_{Ir}} \frac{\partial u_{Ir}(x, a)}{\partial a} \quad (3.10)$$

where $E' = E$ for the case of plane stress, and $E' = E(1 + \nu^2)$ for plane strain.

![Figure 3.63: Co-ordinate system for the weight function equations.](image)

Once the weight functions are determined for a given geometry, then the stress intensity factor for any other loading system applied to the same cracked body can be calculated by:

$$K = \int_0^a \sigma(x) \cdot h(x, a) \, dx = \frac{E'}{K_{Ir}} \int_0^a \sigma(x) \cdot \frac{\partial u_{Ir}(x, a)}{\partial a} \, dx \quad (3.11)$$

In equation (3.11), $\sigma(x)$ are the stresses on the crack line that appear in the uncracked body due to the loading for which the stress intensity factor is calculated.

Values for the stress intensity factor for different structures and loadings can be found in several stress intensity factor handbooks [34, 35, 36], but very seldom accompanied by
expressions of the crack face displacements. In order to be able to apply the weight function technique in this case, several approaches were proposed. The approach used here is the one of Petrovski and Achenbach [37]. They use the well-known expression of the displacement around the crack tip in an infinite cracked plate:

\[ u_y(x, a) = \frac{4K}{E'} \left( \frac{a-x}{2\pi} \right)^{1/2} \]  

(3.12)

in which \( K = \sigma(\pi a)^{1/2} \). Starting from this expression, they propose for the crack face displacements a series expansion having the first term in the form given by (3.12), and the other terms tend to zero while approaching the crack tip:

\[ u(x, a) = \sum_n c_i (a - x)^{i-n} \]  

(3.13)

From this series expansion, they used only the first two terms, written in the form:

\[ u_{lr}(x, a) = \frac{\sigma_0}{E' \sqrt{2}} \left[ 4F \left( \frac{a}{L} \right) a^{1/2} (a-x)^{1/2} + G \left( \frac{a}{L} \right) a^{-1/2} (a-x)^{3/2} \right], \]

(3.14)

where \( F(a/L) \) and \( G(a/L) \) are functions of the crack length and characteristic dimension.

The function \( F(a/L) = K/[(\pi a)^{1/2}] \) can be calculated from the solutions for the stress intensity factor taken from handbooks and \( G(a/L) \) is obtained from equation (3.11) written for the reference case \( K = K_{lr} \) (self-consistency). In this case, one obtains:

\[ K_{lr}^2 = E' \int_0^a \sigma_r(x) \cdot \frac{\partial u_{lr}(x, a)}{\partial a} dx \]  

(3.15)

\( \sigma_r(x) \) being the crack line stress in the reference case. Introducing (3.14) in (3.15), integrating with respect to \( a \) and using the known values of the reference stress intensity factor, one obtains an equation in which \( G(a/L) \) is the only unknown. Solving this equation it yields that:

\[ G \left( \frac{a}{L} \right) = \frac{[I_1(a) - 4F(a/L) \sqrt{a} \cdot I_2(a)] \sqrt{a}}{I_3(a)} \]  

(3.16)

with:

\[ I_1(a) = \pi \sqrt{2\sigma_0} \int_0^a \left( \frac{a}{L} \right) \cdot a \, da \]  

(3.17)

\[ I_2(a) = \int_0^a \sigma_r(x) \cdot (a-x)^{1/2} \, dx \]  

(3.18)

\[ I_3(a) = \int_0^a \sigma_r(x) (a-x)^{3/2} \, dx \]  

(3.19)
Once the weight function is known, then the stress intensity factor can be determined from equation (3.15) for any other loading case $\sigma(x)$, as:

$$K = \frac{E}{K_{H}} \frac{a}{x} \int_{0}^{a} \sigma(x) \frac{\partial u_{H}(x,a)}{\partial x} \, dx = \frac{\partial}{\partial a} \left[ \sigma(x) \frac{\partial}{\partial a} \left( 4F \left( \frac{a}{L} \right) a^{1/2} (a-x)^{1/2} + G \left( \frac{a}{L} \right) a^{-1/2} (a-x)^{3/2} \right) \right] \, dx$$

(3.20)

### 3.6.1 Weight function procedure

In order to apply the weight function method, a reference case must be chosen. Since the weight function is independent of the loading, any loading case is suitable for obtaining it. That is why one should choose a very simple loading case, with known results from the literature. For this work, the loading case of remote tensile stress was considered suitable. The reference stress intensity factor for a finite plate with one central circular hole and two symmetrical cracks Figure (3.64), was taken from three different sources according to the application range of each one:

- for $c/R \leq 0.1$ was used the equation (3.21), reference [38];
- for $0.1 < c/R < 0.17$ was used the numerical technique based on DBEM, reference [39];
- for $c/R \geq 0.17$ was used the equation (3.22), reference [34].

![Figure 3.64: Finite plate with a circular hole under uniform tension $\sigma_{app}$](image)

$$K = \sigma_r(x) \cdot \sqrt{\pi c}$$

(3.21)
\[ K = F \cdot \sigma_{appr} \sqrt{\pi a} \]
\[ F = \varphi \cdot \psi \]
\[ \alpha = \frac{a}{W} \]
\[ \overline{\alpha} = \frac{\pi}{2} \alpha \]
\[ \delta = \frac{b}{R} \]
\[ \gamma = \frac{R}{W} \]
\[ \beta = \frac{\alpha - \gamma}{1 - \gamma} \]
\[ g = 0.13 \left( \frac{2}{\pi} \arctan \delta \right)^{2} \]
\[ \varepsilon = \frac{2}{\pi} \arctan \left( 0.6 \sqrt{\delta} \right) \]
\[ \psi = \xi \left( 3 \cdot \beta^{2/3} \cdot 3 - 2 \sqrt{\xi} \beta^{3} \right) \]
\[ P = \frac{\log \left( \xi^{-3/2} \right)}{\log \left( \beta^{*} \right)} \]
\[ \beta^{*} = \frac{\gamma \cdot \delta}{\gamma (2\delta - 1) + 1} \]
\[ \xi = 1 + \frac{2}{\pi} \arctan \left( \frac{3}{2} \sqrt{\delta} \right) \]

The application range of equations (3.22) is:

- \[ 0 \leq \delta \leq 10 \quad \text{Accuracy: } \pm 5\% \]
- \[ 0.1 \leq \gamma \leq 0.8 \quad \text{if } F \geq 1.0 \]
- \[ \gamma \leq \alpha \leq 0.95 \]
The graphical representation of the reference stress intensity factor calibration is shown in Figure (3.65).

![Graph of K/(σπe) vs c/R](image)

**Figure 3.65: Stress intensity factor calibration.**

In order to use these values in the weight function, a tenth order polynomial fit was used. For applying equation 3.10 to determine the weight function, the expression of the crack face displacements should be derived following relation (3.14). The coefficient $G(a/R)$ was calculated according to equations (3.16-3.19) in which the expression $σ_r(x)$ of the stress distribution on the crack line was calibrated using the software CRACKER based on the Dual Boundary Element Method (DBEM), which was developed by Professor Artur Portela, ref. [39]. The stress concentration effect on the crack line is presented in Figure (3.66).

![Graph of σ/σ_app vs Distance from hole [mm]](image)

**Figure 3.66: Stress concentration effect.**

A polynomial fit was used to describe $σ_r(x) = T \cdot σ_{app}$, where $T = σ_r/σ_{app}$. 

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After determining the displacement variation in the reference case, the stress intensity factor can be calculated for the loading consisting of residual stress, using equation (3.20). A MAPLE worksheet capable of automating the calculation of K values was created and thus, a parametric study of the residual stress intensity factor for different values of the crack length was easily performed.

It should be mentioned that similar calculations were made by Grandt and Kullgren [40] that presented values of the stress intensity factor for a complex loading consisting of residual stress and remote uniform stress.

3.6.2 Results and discussion

The values of the residual stress intensity factor obtained base on the residual stress measurements (see Figure(3.9)) with the weight function technique are shown in Figure (3.67).

![Figure 3.67: Residual stress intensity factors obtained with WFT.](image)

It was shown in a previous work [41] that the precision of this technique is similar to that obtained by finite element method, using the J integral.
3.7 Summary and conclusions

1. Two and three dimensional finite element analysis of the hole cold expansion were presented with two different types of material behaviour, elastic perfectly plastic and hardening material.

2. Experimental measurements of the residual stress field profile were performed using the X-ray technique.

3. An axisymmetric finite element simulation of cold working with different boundary conditions was presented. The influence of the boundary conditions in the residual stress field was discussed. The bending effect has larger influence at the entrance face, being almost inexistent in the mid-thickness plane, as expected. The radial and axial deformation of the hole surface were presented and quantified for the uniform hole expansion and the cold working process.

4. Two dimensional analyses showed that the residual stresses in the region near the hole predicted using the real geometry model or a cylindrical 2D model simulating an "infinite" domain are very close.

5. The results of the cold working simulation were compared with the simplified uniform hole cold expansion applied to the hole surface, and it was concluded that the residual stresses due to the hole cold expansion can only be estimated accurately by using a realistic simulation of the cold working process.

6. Agreement between 3D and 2D analysis was found for the mid-thickness plane of the plate only.

7. 2D axisymmetric FEA overestimates maximum tensile and compressive stress values in the near hole region. Larger differences between 2D axisymmetric model and 3D real model were found at the entrance face.

8. 2D axisymmetric FEA overestimates the permanent hole enlargement and axial deformation by comparison with the 3D real model.

9. Using the experimental X-ray technique inevitably the stresses are averaged over the irradiated volume. Therefore it is not possible to resolve the steep stress gradients in the vicinity of the hole, and the peak values predicted by finite element simulation result underestimated.

10. The results from the cold working finite element simulations presented seem to be in general agreement with experimental results.

11. The weight function technique was used for the calculation of the residual stress intensity factors, which are used for the $\Delta K$ calculation in the crack growth process.
Chapter 4

Fatigue crack growth

4.1 Introduction

The aim of this chapter is the study of fatigue crack growth using macroscopic techniques of measurement. It starts with a brief reference to basic concepts of linear elastic Fracture Mechanics, crack propagation under constant amplitude loading and finally about mode I crack growth laws. Measurements of the fatigue crack length as a function of the number of cycles are presented for ten specimens, five normal hole and five with cold worked open hole. The da/dN vs ΔK curves were calculated for each one of these specimens. This chapter ends with the summary and some conclusions.

4.2 Basic linear elastic fracture mechanics

One of the aims of Fracture Mechanics is to establish the local stress and strain fields around a crack tip in terms of global parameters such as the loading and the geometry of a structure. Usually, fracture mechanical approaches are divided into 1) linear elastic solutions and 2) non-linear methods. Only the first approach is discussed here. The present formulation is also restricted to long cracks subjected to constant amplitude cyclic loading (a distinction between long and short cracks for normal engineering structures is sometimes assumed to be about 1 mm in length according to Tanaka [42], but a more detailed classification can be done according to reference [43] and other authors).

4.2.1 Modes of crack tip deformation

For linear elastic materials, Irwin [44] suggested describing the stresses in the vicinity of the crack tip by Stress Intensity Factors (SIFs). There are basically three different types of SIFs, each describing one of the deformation modes illustrated in Figure (4.1). The superimposition of these three modes can be characterized as follows:

- Mode I is in-plane tensile mode where the crack surface is symmetrically opened;
- Mode II is the sliding or shear mode which is present when the crack is exposed to skew-symmetric in-plane loading;

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Mode III is an anti-plane mode where the crack surface is twisted by forces perpendicular to the crack plane.

The crack propagation in a plate structure, it is usually the combination of mode I and mode II. Irwin analyzed this in-plane mixed mode problem, by the use of Westergaard stress functions [46], he found an analytical solution for the stress solutions in the crack tip vicinity:

\[
\sigma_{xx} = \frac{K_I}{\sqrt{2\pi r}} \cos \theta \left(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2}\right) + \frac{K_{II}}{\sqrt{2\pi r}} \sin \frac{\theta}{2} \left(2 + \cos \frac{\theta}{2} \cos \frac{3\theta}{2}\right) + O(r^{1/2})
\]

\[
\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \cos \theta \left(1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2}\right) - \frac{K_{II}}{\sqrt{2\pi r}} \sin \frac{\theta}{2} \left(2 + \cos \frac{\theta}{2} \cos \frac{3\theta}{2}\right) + O(r^{1/2})
\]

\[
\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \cos \theta \left(2 \sin \frac{\theta}{2} \cos \frac{3\theta}{2}\right) + \frac{K_{II}}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2}\right) + O(\tau^{1/2})
\]
where the stresses are given in the polar coordinate system illustrated in Figure (4.2) and higher order terms are neglected. Equations (4.1) are therefore valid in the region close to the crack tip \((r \ll a)\) only. It is seen that the magnitude of stresses is controlled by the stress intensity factors \(K_I, K_{II}\), while the distribution of stresses is governed by the position relative to the crack tip given by \(r\) and \(\theta\). It is also observed that the distribution of stresses is singular for \(r = 0\), which is only true for fully elastic behaviour. That is the main limitation for a linear elastic approach, since most materials exhibit some state of plasticity at the crack tip.

The displacements are also controlled by the stress intensity factors:

\[
\begin{align*}
u & = \frac{K_I}{4\mu}\sqrt{\frac{r}{2\pi}} \left( (2\kappa - 1) \cos \frac{\theta}{2} - \cos \frac{3\theta}{2} \right) + \frac{K_{II}}{4\mu}\sqrt{\frac{r}{2\pi}} \left( (2\kappa + 3) \sin \frac{\theta}{2} + \sin \frac{3\theta}{2} \right) \\
v & = \frac{K_I}{4\mu}\sqrt{\frac{r}{2\pi}} \left( (2\kappa + 1) \sin \frac{\theta}{2} - \sin \frac{3\theta}{2} \right) + \frac{K_{II}}{4\mu}\sqrt{\frac{r}{2\pi}} \left( (2\kappa - 3) \cos \frac{\theta}{2} + \cos \frac{3\theta}{2} \right). \tag{4.2}
\end{align*}
\]

where \(\mu\) is the shear modulus of the material, and \(k\) is 3-4\(\mu\) for plain strain and \((3-\mu)/(1+\mu)\) for plain stress.

### 4.2.2 Stress intensity factor

Equation (4.1) shows that the stress intensity factors are the fundamental quantities describing the singular elastic stresses. The stress intensity factors are functions of the length and the orientation of the crack, the geometry of the body, and the applied load distribution. For uniaxially loaded case, the mode I stress intensity factors can be calculated from

\[
K = Y \cdot \sigma \cdot \sqrt{\pi a} \tag{4.3}
\]

where \(Y\) takes into account the geometry effects, the crack length and the applied load. \(Y\) is equal to 1.0 for a crack located in a uniformly loaded infinite plate perpendicular to the load direction. Analytical and empirical expressions for stress intensity factors are collected in compendiums such as Tada et al. [38], Murakami [34], Sih [36] and Rooke et al. [35] for specimens of simple geometries with various crack configurations and load conditions. Unfortunately, structural members used in practical engineering are not generally of simple geometry and they are exposed to complex load conditions, so specific analysis must be resorted to. In such cases, different methods are available, but for complex mixed mode conditions, the finite element methods and boundary element methods seem to offer the best solutions due to their flexibility and easy computerization.

### 4.2.3 Energy release rate, \(G\)

The basic concept of the energy released method was established in 1921 by Griffith. For an ideally brittle material, he stated that the crack propagation will occur if the energy supplied at the crack tip is equal or grater than the energy required for the crack growth. This criterium was reformulated by Irwin [44] by the introduction of the energy release rate, which is a measure of the energy available for an increment of crack extension:
\[ G = -\frac{d\Pi}{dA} \]  

(4.4)

where \( \Pi \) is the potential energy and \( A \) is the released crack area. Crack initiation occurs when the energy released rate reaches a critical value called the fracture toughness of the material, \( G_c \). The fracture toughness is considered a material parameter, and theoretically this parameter should be determined by calculating the energy needed for the nucleation of the atomic bounds in the material. However, materials contain imperfections and crack propagation starts before the theoretical value of the fracture toughness is reached. Thus, instead of using the theoretical approach the fracture toughness is usually determined using standardized experiments, such as 3 point bend (3PB) and compact tension (CT) specimen test described in [47, 48].

A very simple relation is often used for linear elastic materials to describe the relation between the fracture toughness and the stress intensity factors in the mixed mode condition:

\[ G = \frac{K_{I}^2}{E'} + \frac{K_{II}^2}{E'} \]  

(4.5)

where \( E' \) is the Young’s modulus \( E \) for plane stress and \( E/(1 - \mu^2) \) for plane strain condition. The critical mode I stress intensity factor \( K_{Ic} \) is sometimes used as a measure of the material fracture toughness, and it can also be determined by experiments. The relation between \( G_c \) and \( K_{Ic} \) is obtained through equation (4.5) with \( K_{II} \) equal to zero. From above it can be seen that fracture toughness of the material is a function of the stress intensity factors and a function of the stress state (\( E' \)). This means that \( G \) has to be related to the present stress state, and experiments therefore have to be carried out for both plane stress and plane strain conditions. A way of avoiding that for through cracks is to make sure that plane strain is present in the major part of the crack surface. By analyzing the size of the yield zone at the crack tip (\( r_y \approx (K_{Ic}/\sigma_{yield})^2/(6\pi) \)), for plane strain), the following expression has been established:

\[ t > q \frac{K_{Ic}^2}{\sigma_{yield}^2} \]  

(4.6)

where \( t \) is the thickness of the specimen and \( \sigma_{yield} \) the yield stress of the material. The parameter \( q \) differs from material to material, but an ASTM standard (ref.[48]) suggest that \( q \) equal to 2.5 is to be used, which results in a plastic zone with a radius \( \approx t/50 \). The minimum crack length has to be sufficiently large relative to the plastic zone at the crack tip to ensure ”brittle material behaviour”.

### 4.3 Crack propagation models for constant amplitude loading

Fatigue may be defined as a process of cycle-by-cycle accumulation of damage in a material undergoing fluctuating stresses and strains. The main goal of crack propagation models is therefore to relate the material damage to the cyclic loads applied. A fatigue process
undergoes several stages and from an engineering point of view it is a convenient to divide the fatigue life of a structure into three stages [5]:

I - Fatigue crack initiation;

II - Stable crack propagation;

III - Unstable crack propagation.

The first of the three stages cover the crack initiation and the early crack growth state, which includes cyclic plastic deformation prior to crack initiation, initiation of one or more microscopic cracks and coalescence of these micro-cracks to form an initial macro-crack (see Figure 4.3-a) [49]. Notch stress-strain analysis and low-cycle fatigue concepts can be used for the estimation of this initiation period. Fatigue cracks always begin at concentrations of plastic strain. Consequently if no other manufacturing imperfections are present, fatigue cracks have their origins at the surface. The so-called slip band formation, extrusions and intrusions Figure 4.3-b) on the surface of an otherwise uncracked material form fatigue crack initiation sites. The second period is characterized by stable crack growth, while at the last stage crack growth accelerates due to the interaction between fatigue and fracture mechanisms. The duration of the third period is usually quite short and it can without great loss of accuracy be neglected in the fatigue life estimations.

Figure 4.3: a) Stages I and II of a fatigue crack. b) Schematic representation of intrusions and extrusions.

Since a crack initiates, it can propagate with greater or smaller rate according to the load conditions until the crack length reaches critical dimensions responsible for the catastrophic rupture. A crack propagation curve is the registry of the crack length as function of the number of cycles. Figure (4.4) shows two typical crack growth curves for a constant amplitude loading and a geometry whose stress intensity factor increase with the crack length. The two curves presented in Figure (4.4) concern to the crack growth in two possible scenarios. In both scenarios the crack has the same initial length, being submitted to two
different maximum stress levels $\sigma_1$ and $\sigma_2$ (and $R=0$). Despite the crack growth in both curves, in the curve of higher stress level the rupture occur for a lower number of cycles. The rupture happens when a defect reaches a critical dimension $a_c$. The critical defect dimension can be a critical piece dimension, as the thickness, or the crack length for which the stress intensity factor hit the critical material toughness, $K_c$. In the last case the crack propagation is unstable and the critical crack size is calculated as follow:

$$a_c = \frac{K_c^2}{Y^2\sigma^2\pi}$$  \hspace{1cm} (4.7)

For stress intensity factor values lower than critical material toughness the crack propagation is stable (subcritical crack growth).

![Diagram of crack propagation curves](image)

Figure 4.4: Crack propagation curves, for a crack with two remote tensile maximum stresses $\sigma_1$ and $\sigma_2$ with $\sigma_1 > \sigma_2$, and $R=0$.

### 4.3.1 Mode I crack growth

The lifetime of structures with initial cracks is very closely related to the crack propagation period, since the initiation time is frequently short. Current experimental and theoretical linear elastic approaches try to describe the stable and unstable crack growth by a crack propagation rate. This rate is defined as the incremental crack growth $da$, divided by the incremental number of the number of cycles $dN$, as a function of the stress intensity factor range $\Delta K$ during a load cycle. The SIF range is determined as $K_{I,max} - K_{I,min}$. A schematic illustration of crack growth rate is given in Figure (4.5), reference [50].

The shape of the curve suggests that the crack propagation period is divided into three regions:

- Region I bounded by the threshold value where the crack growth rates goes asymptotically to zero. As $\Delta K$ approaches $\Delta K_{th}$ the crack remains dormant or propagates at crack growth rates which can not be determined experimentally;

- Region II, where stable crack propagation takes place which can be described by linear relationship between $\log da/dN$ and $\log \Delta K$;
Region III crack growth is described by a rapid increase in the crack growth rate going towards "infinity" as the maximum value of the cyclic stress intensity factor $K_{max}$ reaches the fracture toughness of the material $K_{IC}$.

### 4.3.2 Threshold stress intensity range $\Delta K_{th}$

By integrating the crack growth curve over the critical crack length $a_c$ ($a_c$ is defined as the crack length causing failure of structures/components), it is possible to obtain the total number of loading cycles resulting in failure for a given structure/component [45]. The crack growth in region I can therefore play an important role, since the amount of time spent in this region may be predominant for high-cycle fatigue.

The threshold stress intensity factor range $\Delta K_{th}$ was initially assumed to be a material constant, but numerous studies have shown that it depends on several parameters. A recent review on fatigue thresholds for long-crack fatigue in metallic materials is given by Hadrboletz et al. [51]. They divided the factors affecting the threshold stress intensity factor range into extrinsic and intrinsic parameters. The extrinsic parameters cover:

- Mean stress/stress ratio effect, which again was believed to be influenced by the material grain size and the closure of the crack surfaces;

- The effect of overloads where an overload peak results in a retardation of crack growth due to several mechanisms, e.g., plasticity induced closure and residual stress;

- Temperature related to changes in material parameters such as young modulus $E$, and the strength $\sigma_{yield}$. $E$, $\sigma_{yield}$ and $\Delta K_{th}$ usually decrease with the increasing of temperature, but in special cases an increase in $\Delta K_{th}$ was observed, which was explained by closure of crack faces due to corrosion;
• The environment where formation and dissolution of surface layers, closure of crack surfaces due to corrosion and incompressible fluids in the crack are known to be important effects.

The intrinsic parameters include:

• Microstructural features, such as grain size, single and multi-phase microstructures, porosity, solid solution effects, and dislocation arrangements;

The conclusion drawn from the review was that the many intrinsic and extrinsic variables do not permit a quantification of the threshold value derived from basis principles. For a more detailed discussion of the parameters listed above, see Hardrboletz et al. [51]. The number of affecting parameters may, however, be reduced by the introduction of an effective fatigue thresholds stress intensity factor defined by

$$\Delta K_{th, eff} = K_{th, max} - K_{cl}$$  \hspace{1cm} (4.8)

where $K_{th, max}$ is the maximum stress intensity factor and $K_{cl}$ is the stress intensity factor at which crack faces close. $\Delta K_{th, eff}$ may be obtained from experiments, $\Delta K_{th, eff}$ is reported to be in the range 2.4-2.6 MPam$^{1/2}$ for steel and in the range 0.9-1.9 MPam$^{1/2}$ for aluminium alloys [51].

Tanaka and Soya [52] analyzed the rack growth behaviour of six grades of steel ($\sigma_{yield}$ in the range 163-888 MPa) under various stress ratios. They found that all the metals could be characterized by the same $\Delta_{th, eff}$, which was outside the range given in [51], namely 3.45 MPam$^{1/2}$. An expression for $\Delta_{th}$ was also suggested which was found to be a function of $R$ and $\Delta K_{th, eff}$:

$$\Delta K_{th} = Max[(\Delta K_{th, eff} + K_0)(R_0 - R), \Delta K_{th, eff}]$$  \hspace{1cm} (4.9)

where $K_0$ and $R_0$ are material constants. Their experimental results indicate that $K_{th}$ is well described for both $R > 0$ and $R < 0$.

4.4 Mode I crack propagation laws

The Paris law [53], equation (4.10) is a simple, but very often used model for description of the crack growth rate in the linear region II. It reads:

$$\frac{da}{dN} = C\Delta K^m$$  \hspace{1cm} (4.10)

where $da/dN = \text{fatigue crack growth rate}$

$\Delta K = \text{stress intensity (} \Delta K = \Delta K_{max} - \Delta K_{min})$

$C, m = f(\text{material variables, environment, frequency, temperature, stress ratio})$

Attempts have been made to complete the description of the crack growth curve. The popular formula which incorporates the threshold range is:

$$\frac{da}{dN} = C[\Delta K^m - \Delta K_{th}^m]$$  \hspace{1cm} (4.11)
where the factors affecting the threshold range (discussed in 4.3.2) are taken into account when $\Delta K_{th}$ is inserted. This equation is valid for region I and II but does not cover unstable crack propagation. Forman equation is often employed to model the crack growth rate in the regions of stable and unstable crack propagation:

$$\frac{da}{dN} = \frac{C\Delta K^m}{(1 - R)K_{lc} - \Delta K}$$ (4.12)

where the influence of the peak stress is accounted by the stress ratio coefficient $R (\sigma_{min}/\sigma_{max})$. Other modifications have been proposed. A list of nine proposed models is given in [42].

4.5 Crack growth measurements

Crack growth rate (CGR) measurements were performed for the specimens presented in chapter 2 during the fatigue tests. The load conditions were also presented in chapter 2, and the material properties are presented in Appendix A. Crack growth measurements were performed using a WebCam record. The use of this equipment has the following advantages:

- remote monitoring of the fatigue tests;
- allow the record of crack growth process.

The videos were recorded with a resolution of $640 \times 480$ at 30 frames per second (fps).

The crack growth measurements were performed in ten specimens, five normal open hole and five cold worked open hole. For each one of these specimens the crack length on the left and right sides Figure (4.6), was recorded as function of the number of cycles until the cracks became imperceptible in the image. This work was done with an Excel worksheet and the image software Corel Photopaint.

Section (4.5) presents the crack growth curves on the left and right side cracks and the total crack length $2a$ (Figure (4.6)), for the normal and cold worked open hole specimens respectively.

![Figure 4.6: Finite plate with a central hole and two symmetrical cracks.](image-url)
Figures 4.7 and 4.8 present the crack growth (left, right and total crack length 2a) in specimens 8.1 and 7.3 CW fatigue tested at $\sigma_{\text{max}}=120$ MPa, respectively.

Figure 4.7: Crack growth measured in specimen 8.1, fatigue tested at $\sigma_{\text{max}}=120$ MPa.

Figure 4.8: Crack growth measured in specimen 7.3 CW, fatigue tested at $\sigma_{\text{max}}=120$ MPa.
Figures (4.9) and (4.10) present the crack growth (left, right and total crack length 2a) in specimens 7.5 and 7.1 CW fatigue tested at $\sigma_{\text{max}}=140$ MPa, respectively.

Figure 4.9: Crack growth measured in specimen 7.5, fatigue tested at $\sigma_{\text{max}}=140$ MPa.

Figure 4.10: Crack growth measured in specimen 7.1 CW, fatigue tested at $\sigma_{\text{max}}=140$ MPa.
Figures (4.11) and (4.12) present the crack growth (left, right and total crack length 2a) in specimens 7.3 and 10.3 CW fatigue tested at $\sigma_{max}=160$ MPa, respectively.

Figure 4.11: Crack growth measured in specimen 7.3, fatigue tested at $\sigma_{max}=160$ MPa.

Figure 4.12: Crack growth measured in specimen 10.3 CW, fatigue tested at $\sigma_{max}=160$ MPa.
Figures (4.13) and (4.14) present the crack growth (left, right and total crack length 2a) in specimens 4.2 and 7.5 CW fatigue tested at $\sigma_{\text{max}}=180$ MPa, respectively.

Figure 4.13: Crack growth measured in specimen 4.2, fatigue tested at $\sigma_{\text{max}}=180$ MPa.

Figure 4.14: Crack growth measured in specimen 7.5 CW, fatigue tested at $\sigma_{\text{max}}=180$ MPa.
Figures (4.15) and (4.16) present the crack growth (left, right and total crack length 2a) in specimens 7.1 and 8.6 CW fatigue tested at $\sigma_{max}=200$ MPa, respectively.

Figure 4.15: Crack growth measured in specimen 7.1, fatigue tested at $\sigma_{max}=200$ MPa.

Figure 4.16: Crack growth measured in specimen 8.6 CW, fatigue tested at $\sigma_{max}=200$ MPa.
Figure (4.17) shows the crack growth process in the specimen 7.3 fatigue tested at $\sigma_{\text{max}} = 160$ MPa.

Figure 4.17: Crack growth process in specimen 7.3 tested at $\sigma_{\text{max}}$ 160 MPa: a) 0 cycles; b) 38988 cycles; c) 40138 cycles; d) 40838 cycles; e) 41188 cycles; f) 41328 cycles; g) 40368 cycles; h) 41378 cycles (rupture moment).

Figure (4.18) and (4.19) shows the evolution of the total crack length $2a$ as function of the number of cycles for the maximum stress levels of 120, 140, 160 180 and 200 MPa for specimens with normal hole and cold worked hole respectively.
Figure 4.18: Crack length 2a versus nr. kcycles. Normal open hole specimens 8.1, 7.5, 7.3, 8.4, 6.4.
Figure 4.19: Total crack length 2a versus nr. kcycles. Cold worked open hole specimens 10.1, 7.1, 6.1, 6.2, 8.4.
4.6 Determination of $da/dN$ vs $\Delta K$

The standard ASTM E 647-95a [54] (Standard Test Method for Measurement of Fatigue Crack Grow Rates) was followed in the present test procedure.

4.6.1 Data analysis

The data was analyzed according the standard [54], which recommends the incremental polynomial method. This method for computing $da/dN$ involves fitting a second-order polynomial (parabola) to sets of $(2n + 1)$ successive data points where $n$ is 3. The form of the equation for the local fitting is as follows:

$$\hat{a}_i = b_0 + b_1 \left( \frac{N_i - C_1}{C_2} \right) + b_2 \left( \frac{N_i - C_1}{C_2} \right)^2$$

(4.13)

where,

$$-1 \leq \left( \frac{N_i - C_1}{C_2} \right) \leq +1$$

(4.14)

and $b_0$, $b_1$ and $b_2$ are the regression parameters that are determined by the least-squares method (minimization of the square of the deviations between observed and fitted values of crack length) over the range $a_{i-n} \leq a \leq a_{i+n}$. The value $\hat{a}_i$ is the fitted value of crack length at $N_i$. The parameters $C_1 = \frac{1}{2}(N_{i-n} + N_{i+n})$ and $C_2 = \frac{1}{2}(N_{i+n} - N_{i-n})$ are used to scale the input data, thus avoiding numerical difficulties in determining the regression parameters. The rate of the crack growth at $N_i$ is obtained from the derivative of the above parabola, which is given by the expression,

$$\left( \frac{da}{dN} \right)_{\hat{a}_i} = \frac{b_1}{C_2} + \frac{2b_2(N_i - C_1)}{C_2^2}$$

(4.15)

The value of $\Delta K$ associated with this $da/dN$ value is computed using the fitted crack length, $\hat{a}_i$, corresponding to $N_i$.

4.6.2 $K$ calibration

As shown in the figures presented in section (4.5), three different types of crack growth were observed:

I) one crack during all the crack growth process, observed for the cold worked specimens fatigue tested at $\sigma_{\text{max}} = 120$, 140 and 160 MPa;

II) begin with one crack during part of the crack growth life, followed by two asymmetrical cracks until rupture, observed for normal open hole specimens fatigue tested at $\sigma_{\text{max}} = 120$ and 140 MPa;

III) two symmetrical cracks during all the crack growth life, observed for normal open hole specimens fatigue tested at $\sigma_{\text{max}} = 160$, 180 and 200 MPa and cold worked open hole specimens fatigue tested at $\sigma_{\text{max}} = 180$ and 200 MPa.
These three situations involve the $K$ calibration for the three cases in Figure (4.20). In the case of two symmetrical cracks Figure (4.20) the calibration was taken from references [38, 34] and a small part not covered by those references, was calculated using the software CRACKER based on the DBEM, developed by Professor Artur Portela and described in reference [39]. In the cases of one crack or two asymmetrical cracks the $K$ calibration was calculated using the software CRACKER.

![diagram](image)

Figure 4.20: Crack growth models used in $K$ calibration: a) two symmetrical cracks; b) one crack; c) two asymmetrical cracks.

In case II) when a second crack appears Figure (4.20-c), the $K$ calibration is done for the larger crack taking into consideration the presence of a smaller crack in the opposite side. Of course this procedure requires a particular $K$ calibration in each different moment of crack growth. Figure (4.21-d) shows an example of the mesh used in the software CRACKER, for the case of two asymmetrical cracks. In order to test the accuracy of the $K$ results obtained using CRACKER, for a plate with central hole and two symmetrical cracks a comparison of results was done. The boundary elements results were compared with results obtained using ABAQUS for a refined mesh of 1900 elements Figure (4.21-b) [55] and references [38, 34].
Figure 4.21: a) Boundary elements mesh of 2 asymmetrical cracks; b) FEM quarter of plate mesh.

Table (4.1) presents the data used in the DBEM models.

<table>
<thead>
<tr>
<th></th>
<th>Number of parabolic elements</th>
<th>Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hole</td>
<td>Crack faces</td>
</tr>
<tr>
<td>1 Crack</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>2 As. cracks</td>
<td>40</td>
<td>20</td>
</tr>
</tbody>
</table>
Figure (4.22) shows that the results obtained are approximately all of the same precision. In Figure (4.22) $Y$ is defined as $Y = K/\sigma \sqrt{\pi a}$.

![Graph showing comparison between analytical and numerical calibrations.](image)

Figure 4.22: Comparison of results between analytical and numerical calibrations.

Table (4.2) presents the $K$ calibration for the case of a finite plate with a central hole and one crack.

<table>
<thead>
<tr>
<th>$c$ [mm]</th>
<th>$K$ [Pa.m$^{0.5}$]</th>
<th>$Y = \frac{K}{\sigma \sqrt{\pi a}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.127</td>
<td>5.749</td>
<td>2.878</td>
</tr>
<tr>
<td>0.254</td>
<td>8.040</td>
<td>2.846</td>
</tr>
<tr>
<td>0.508</td>
<td>9.800</td>
<td>2.453</td>
</tr>
<tr>
<td>1.000</td>
<td>10.949</td>
<td>1.953</td>
</tr>
<tr>
<td>1.500</td>
<td>11.483</td>
<td>1.673</td>
</tr>
<tr>
<td>2.000</td>
<td>11.901</td>
<td>1.501</td>
</tr>
<tr>
<td>2.500</td>
<td>12.316</td>
<td>1.390</td>
</tr>
<tr>
<td>3.000</td>
<td>12.762</td>
<td>1.315</td>
</tr>
<tr>
<td>3.500</td>
<td>13.248</td>
<td>1.263</td>
</tr>
<tr>
<td>4.000</td>
<td>13.780</td>
<td>1.229</td>
</tr>
<tr>
<td>5.000</td>
<td>15.008</td>
<td>1.197</td>
</tr>
<tr>
<td>6.000</td>
<td>16.515</td>
<td>1.203</td>
</tr>
<tr>
<td>7.000</td>
<td>18.396</td>
<td>1.241</td>
</tr>
</tbody>
</table>

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Table (4.3) and (4.4) present the $K$ calibration for the left crack of the specimens 8.1 and 7.8 (Figure(4.7)) and 7.5 (Figure(4.9)) fatigue tested at 120 and 140 MPa. In both cases the calibration was done taking into account the presence of a smaller crack in the opposite side.

Table 4.3: $K$ calibration, hole with 2 asymmetrical cracks, normal hole specimen 8.1 fatigue tested at $\sigma_{\text{max}}=120$ MPa

<table>
<thead>
<tr>
<th>$c_{\text{left}}$ [mm]</th>
<th>$c_{\text{right}}$ [mm]</th>
<th>$K_{\text{left}}$ [Pa.m$^{0.5}$]</th>
<th>$Y = \frac{K}{\sigma(\tau_0)^{0.5}}$</th>
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<tbody>
<tr>
<td>3.943</td>
<td>0.229</td>
<td>14.104</td>
<td>1.267</td>
</tr>
<tr>
<td>4.171</td>
<td>0.600</td>
<td>14.649</td>
<td>1.280</td>
</tr>
<tr>
<td>4.629</td>
<td>1.000</td>
<td>15.655</td>
<td>1.298</td>
</tr>
<tr>
<td>4.914</td>
<td>1.200</td>
<td>16.301</td>
<td>1.312</td>
</tr>
<tr>
<td>4.943</td>
<td>1.229</td>
<td>16.379</td>
<td>1.314</td>
</tr>
<tr>
<td>5.057</td>
<td>1.314</td>
<td>16.660</td>
<td>1.322</td>
</tr>
<tr>
<td>5.343</td>
<td>1.400</td>
<td>17.265</td>
<td>1.333</td>
</tr>
<tr>
<td>5.771</td>
<td>1.486</td>
<td>18.231</td>
<td>1.354</td>
</tr>
<tr>
<td>6.171</td>
<td>2.171</td>
<td>20.017</td>
<td>1.438</td>
</tr>
<tr>
<td>6.429</td>
<td>2.486</td>
<td>21.141</td>
<td>1.488</td>
</tr>
</tbody>
</table>

Table 4.4: $K$ calibration, hole with 2 asymmetrical cracks, normal hole specimen 7.5 fatigue tested at $\sigma_{\text{max}}=140$ MPa

<table>
<thead>
<tr>
<th>$c_{\text{left}}$ [mm]</th>
<th>$c_{\text{right}}$ [mm]</th>
<th>$K_{\text{left}}$ [Pa.m$^{0.5}$]</th>
<th>$Y = \frac{K}{\sigma(\tau_0)^{0.5}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.438</td>
<td>0.250</td>
<td>11.724</td>
<td>1.744</td>
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<tr>
<td>1.875</td>
<td>0.438</td>
<td>12.225</td>
<td>1.593</td>
</tr>
<tr>
<td>2.334</td>
<td>0.750</td>
<td>12.864</td>
<td>1.502</td>
</tr>
<tr>
<td>2.969</td>
<td>1.063</td>
<td>13.733</td>
<td>1.422</td>
</tr>
<tr>
<td>3.438</td>
<td>1.406</td>
<td>14.554</td>
<td>1.400</td>
</tr>
<tr>
<td>3.906</td>
<td>1.813</td>
<td>15.516</td>
<td>1.401</td>
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<tr>
<td>4.156</td>
<td>2.063</td>
<td>16.101</td>
<td>1.409</td>
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</tr>
<tr>
<td>4.469</td>
<td>2.375</td>
<td>16.876</td>
<td>1.424</td>
</tr>
<tr>
<td>5.563</td>
<td>3.063</td>
<td>19.616</td>
<td>1.484</td>
</tr>
</tbody>
</table>

The stress intensity factor calibration for the case of two symmetrical cracks was previously presented in chapter 3 section 3.6, which presents the $K$ calibration for two small symmetrical cracks (reference [38]) and two long cracks (reference [34]). It must be mentioned that $K$ calibration for one or two small cracks is the same.

The $K$ calibration used in both types of specimens is presented in Figure (4.23). Two figures are presented because different hole diameters were taken into account. The hole diameter considered in normal and cold worked hole specimens was 5.00 and 4.83 mm respectively.

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Figure 4.23: $K$ calibration used in the different crack growth models: a) normal hole specimens; b) cold worked specimens not taking into account the residual stress effect.

For the cold worked specimens it was necessary to take into account the presence of the residual stress field. This was done calculating the residual stress intensity factors due to the present residual stress field and take them into account in $\Delta K$ as following:

$$\Delta K = \Delta K_{app} - K_{res}. \tag{4.16}$$

Figure (4.24) presents the residual stress intensity factors for both specimens faces considering the existence of one crack or two symmetrical cracks.
Figure 4.24: Residual stress intensity factor in cold worked specimens considering the different crack growth models: a) on the entrance face; b) exit face.

It must be mentioned that the present work only takes into account the smaller (in module) residual stress intensity factors, i.e., entrance face $K_{res}$.

The equations of the comparison curves shown in Figures (4.25) to (4.31) were used in the European Union Structural Maintenance of Ageing Aircraft (SMAAC) project, see for example reference [56]:

SMAAC/IDMEC TP5: \( da/dN = 7 \times 10^{-8} \Delta K^{3.1266}, [\text{mm/cycle}] \)
SMAAC/IDMEC TP6: \( da/dN = 7 \times 10^{-8} \Delta K^{3.208}, [\text{mm/cycle}] \)
SMAAC/IDMEC TP8: \( da/dN = 2 \times 10^{-8} \Delta K^{3.6668}, [\text{mm/cycle}] \)
Aerospatiale: \( da/dN = 3 \times 10^{-7} \Delta K^{2.4454}, [\text{mm/cycle}] \)
Aermacchi: \( da/dN = 3 \times 10^{-7} \Delta K^{2.5233}, [\text{mm/cycle}] \)
4.6.3 Normal open hole specimens, $da/dN \ vs \ \Delta K$

Figure (4.25) shows the $da/dN \ vs \ \Delta K$ for specimen 8.1 from data points in Figure (4.7) considering symmetrical crack growth (Figure (4.20) - a). Figure (4.26) presents the $da/dN \ vs \ \Delta K$ obtained for the data points in Figure (4.7) considering asymmetrical crack growth (Figure (4.20) - b and c)).

Figure 4.25: $da/dN \ vs \ \Delta K$. Specimen 8.1 tested at $\sigma_{max} = 120$ MPa. Symmetric crack growth.

Figure 4.26: $da/dN \ vs \ \Delta K$. Specimen 8.1 fatigue tested at $\sigma_{max} = 120$ MPa. Asymmetrical crack growth.
Figure (4.27) shows the da/dN vs $\Delta K$ for specimen 7.5 from data points in Figure (4.9) considering symmetrical crack growth (Figure (4.20) - a)).

![Graph showing da/dN vs $\Delta K$ for symmetrical cracks](image)

$da/dN = 6E-11 \Delta K^{1.1517}$  
$R^2 = 0.641$

Figure 4.27: da/dN vs $\Delta K$. Specimen 7.5 fatigue tested at $\sigma_{max} = 140$ MPa. Symmetrical crack growth.

Figure (4.28) presents the da/dN vs $\Delta K$ for specimen 7.5 from data points in Figure (4.9) considering asymmetrical crack growth (Figure (4.20) - b) and c)).

![Graph showing da/dN vs $\Delta K$ for asymmetrical cracks](image)

$da/dN = 8E-11 \Delta K^{4.4621}$  
$R^2 = 0.483$

Figure 4.28: da/dN vs $\Delta K$. Specimen 7.5 fatigue tested at $\sigma_{max} = 140$ MPa.
Figures (4.29) and (4.30) present the $da/dN$ vs $\Delta K$ for specimens 7.3 and 8.4 from data points in Figure (4.11) and (4.13) considering symmetrical crack growth (Figure 4.20 - a)).

![Graph showing $da/dN$ vs $\Delta K$ for Specimen 7.3 fatigue tested at $\sigma_{max} = 160$ MPa.]

**Figure 4.29**: $da/dN$ vs $\Delta K$. Specimen 7.3 fatigue tested at $\sigma_{max} = 160$ MPa.

![Graph showing $da/dN$ vs $\Delta K$ for Specimen 8.4 fatigue tested at $\sigma_{max} = 180$ MPa.]

**Figure 4.30**: $da/dN$ vs $\Delta K$. Specimen 8.4 fatigue tested at $\sigma_{max} = 180$ MPa.
Figure (4.31) shows the $\frac{da}{dN}$ vs $\Delta K$ for specimen 6.4 from data points in Figure (4.15) considering symmetrical crack growth (Figure (4.20) - a).

![Figure 4.31: $\frac{da}{dN}$ vs $\Delta K$. Specimen 6.4 fatigue tested at $\sigma = 200$ MPa.](image)

Figure (4.32) shows the $\frac{da}{dN}$ vs $\Delta K$, considering the asymmetrical crack growth for the stress levels of 120 and 140 MPa, and symmetrical crack growth for the maximum stress levels of 160, 180 and 200 MPa.

![Figure 4.32: $\frac{da}{dN}$ vs $\Delta K$ considering symmetrical and asymmetrical crack growth. Specimens fatigue tested at $\sigma_{max} = 120$ to 200 by 20 MPa.](image)
Figure (4.33) shows the same information than the previous figure, but with a fitted curve for the data.

Figure 4.33: $\frac{da}{dN}$ vs $\Delta K$ considering symmetrical and asymmetrical crack growth. Specimens fatigue tested at $\sigma_{max} = 120$ to 200 by 20 MPa - with regression line.

Figure (4.34) shows the $\frac{da}{dN}$ assuming symmetrical crack growth for all stress levels.

Figure 4.34: $\frac{da}{dN}$ vs $\Delta K$ considering symmetrical crack growth. Specimens fatigue tested at $\sigma_{max} = 120$ to 200 by 20 MPa.
4.6.4 Cold worked open hole specimens, \( \text{da/dN} \ vs \ \Delta K \)

Figure (4.35) shows the \( \text{da/dN} \ vs \ \Delta K \) for specimen 7.3 CW from data points in Figure (4.8) considering one crack (Figure (4.20) - b). Figure (4.36) presents the \( \text{da/dN} \ vs \ \Delta K \) for specimen 7.1 CW from data points in Figure (4.10) considering one crack (Figure (4.20) - b) and c).

Figure 4.35: \( \text{da/dN} \ vs \ \Delta K \). Specimen 7.3 CW fatigue tested at \( \sigma_{\text{max}} = 120 \) MPa.

Figure 4.36: \( \text{da/dN} \ vs \ \Delta K \). Specimen 7.1 CW fatigue tested at \( \sigma_{\text{max}} = 140 \) MPa.
Figure (4.37) presents the $da/dN \, vs \, \Delta K$ for specimen 6.1 CW from data points in Figure (4.12) considering one crack (Figure (4.20) - b)).

![Figure 4.37: da/dN vs ΔK. Specimen 6.1 CW fatigue tested at $\sigma_{\text{max}} = 160$ MPa.](image)

Figure (4.38) presents the $da/dN \, vs \, \Delta K$ obtained for the data points in Figure (4.14) considering symmetrical crack growth (Figure (4.20) - a)).

![Figure 4.38: da/dN vs ΔK. Specimen 6.2 CW fatigue tested at $\sigma_{\text{max}} = 180$ MPa.](image)
Figure (4.39) presents the da/dN vs ΔK obtained for the data points in Figure (4.16) considering symmetrical crack growth (Figure (4.20) - a)).

![Graph showing da/dN vs ΔK for different materials](image)

Figure 4.39: da/dN vs ΔK. Specimen 8.4 CW fatigue tested at σ = 200 MPa.

Figure (4.40) shows the da/dN vs ΔK, considering the one crack growth for the stress levels of 120, 140 and 160 MPa, and symmetrical crack growth for the maximum stress levels of 180 and 200 MPa.

![Graph showing da/dN vs ΔK for the specimens](image)

Figure 4.40: da/dN vs ΔK for the specimens fatigue tested at σ_{max} = 120 to 200 by 20 MPa.
It must be mentioned that for the lower values of $\Delta K$ in Figures (4.35) to (4.37) a behaviour of increasing $da/dN$ with the decreasing of $\Delta K$ was found, similar to that reported in the literature [50, 57] as typical in short fatigue cracks.

### 4.6.5 Comparison of $da/dN$ vs $\Delta K$ results between normal and cold worked hole specimens

From section (4.6.3) and (4.6.4) it was seen that $da/dN$ vs $\Delta K$ results are directly comparable between normal and cold worked hole specimens for the stress levels of 120, 140 and 160 MPa because the main part of data for the stress levels of 180 and 200 MPa was not strictly valid according to standard [54] used as a guideline in the present test. In Figures (4.41), (4.42) and (4.42) are shown the comparison of results for $\sigma_{max} = 120$, 140 and 160 MPa, respectively.

![Comparison of da/dN vs ΔK results](image)

**Figure 4.41**: $da/dN$ vs $\Delta K$, comparison results between normal and cold worked hole fatigue tested at $\sigma_{max} = 120$ MPa.
Figure 4.42: $\frac{da}{dN}$ vs $\Delta K$, comparison results between normal and cold worked hole fatigue tested at $\sigma_{max} = 140$ MPa.

Figure 4.43: $\frac{da}{dN}$ vs $\Delta K$, comparison results between normal and cold worked hole fatigue tested at $\sigma_{max} = 160$ MPa.
Figure (4.44) shows the comparison of macroscopic crack growth measurements $da/dN$ vs $\Delta K$, between the specimens with normal and cold worked hole.

Figure 4.44: $da/dN$ vs $\Delta K$. Comparison results between normal and cold worked specimens. Considering all valid measurements.

Figure (4.44) shows that cold worked specimens measurements have larger scatter than normal hole specimens and the cold work specimens straight line slope is smaller. Although it is noticed that the bigger part of the points which move away the trend line of the cold worked specimens are from crack growth measurements performed in specimen 7.1 CW fatigue tested at $\sigma_{max} = 140$ MPa. Removing these points the results obtained are presented in Figure (4.45). The results presented in Figure (4.45) seems more accurate because crack propagation depends on $\Delta K$ and similar $da/dN$ is expected for the same $\Delta K$ as shows Figure (4.45).
Figure 4.45: $\frac{da}{dN}$ vs $\Delta K$, comparison results between normal and cold worked specimens. Considering all valid measurements, without specimen 7.1 CW fatigue tested at $\sigma_{max} = 140$ MPa.
4.7 Summary

1. Crack propagation measurements based on macroscopic techniques were presented.

2. Although this type of narrow specimens is not designed for CGR measurements, an attempt to evaluate the crack growth rate was performed using data obtained with a recording camera.

3. CGR obtained in the present work differ from values in the SMAAC European Union research project; this may result from variation on the material properties and also from the crack length measurements, which are obtained in a different way for the present narrow specimens.

4. For the lower values of ΔK in the specimens with cold work a behaviour of increasing da/dN with decreasing ΔK was found. Similar behaviour is reported in the literature [50, 57] as typical in short fatigue cracks.
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Chapter 5

Fractography analysis

5.1 Introduction

This chapter presents the fractography work performed by SEM in Centro de Materiais da Universidade do Porto, Portugal (CEMUP) for ten open hole specimens, five normal and five cold worked. The main task dealt with in this chapter is fatigue striations spacing measurements. It starts with an introduction to fractography mentioning some relevant previous works. The specimens were divided in 5 batches in order to test 2 specimens for each stress level 120, 140, 160, 180 and 200 MPa. This way the effect of stress level and cold work on the fatigue striation spacing could be assessed. For each one of the analyzed specimens the CGR is calculated. The fatigue crack history reconstitution is performed for one specimen with and one without residual stresses. CGR based on striation spacing is compared with CGR based on macro measurements. Finally the chapter is summarized and some conclusions are stated.

5.2 Fractography of fatigue failures

A concise description of fractography of fatigue failures is given by Nedbal et al. [58]. Sections 5.2.1 to 5.2.3 are essentially transcriptions of relevant parts of that reference.

5.2.1 General concept

From [58], "... Fractography is a [...] tool for the study of failure processes in a broad spectrum of applications - from the fundamental research of relations between failure micromechanisms and microstructure of materials to the practical failure analysis of service events. General fractography is based on the following simple axiomatic presumption: The information on a failure process course is encoded in the rupture surface (and sometimes in the adjacent layers of material). The task of fractography is to decode this information, and to apply it in the frame of Fracture and Damage Mechanics, Materials Science and other linked disciplines. The most significant source of fractography information is the morphology of fracture surfaces. That is why the introduction of SEM in fractographic laboratories has induced an
5.2.2 General fractography of fatigue fractures

"Fatigue crack propagation can be brought about by many various fracture micromechanisms. The character of failure processes is controlled by local conditions on the crack front, before all by the properties of microstructure, local level of stress and strain fields (e.g., by the local level of stress intensity factor range ΔK), and by environmental conditions. [...]"

Important structural materials displaying striations include Al-alloys and Ti-alloys for space and aircraft structures, Ni-alloys, austenitic and duplex steels for nuclear reactors, common unalloyed carbon steels and a broad range of engineering plastics [59]) during the fatigue process they form fatigue striations.

"... The first communication about striations is usually attributed to C. Zappfe and C. Worden [60]. Since then (1951), the mechanism of striation forming has been described by many authors and models (e.g. [61, 62, 63]), the most popular is the oldest Laird’s model from 1962 [64]; the most convenient for fractographic interpretation is the simple schematic of François et al. [65] in Figure (5.1), describing the formation of the fatigue crack growth process passes from stage I to stage II of propagation. From the direct application of the schematic description of striation forming [...] it is evident, eq., why fatigue striations cannot intersect one another [...], and why the local vector of crack growth rate is always perpendicular to the striation.

The local direction of FCG can be determined either from a general view of striations patches or from micromorphologic details."

![Figure 5.1: Schematic description of the striation forming due to repeated local plastic deformation on & before crack front, (After [65]).](image)

5.2.3 Fractographic reconstitution of fatigue crack history

As previously stated the fractography is based on the objective of interpretation the information encoded in fracture surfaces. From [58], "... However, the utilization of this valuable and irreplaceable information in engineering problems presents two main problems: in the first step, the acquisition of selected fractographic data, and, in the second step, the data
processing and interpretation. The complexity of both steps is accentuated in fractographic reconstitution of fatigue crack growth, a method that can yield an information unobtainable so far by any other means." Methods of fractographic reconstitution have been developed by Nedbal et al (e.g., [66, 67, 68, 69, 70]). "... An overview is presented in Figure (5.2): the first step, fractographic data acquisition, is schematically described in upper part. The processing of fractographic data, on the lower part, is based on the fundamental equation

\[ N_s = \int_{a_i}^{a_f} \frac{da}{D(s)s(a)} + N_i \]  

(5.1)

where the unknown crack length \( a_s \) corresponds to the cycle number \( N_s \), \((a_i, N_i)\) is an a priori known couple of corresponding data, \( s(a) \) is the fractographic input (a result of the striation spacing measurement) and \( D(s) \) (D-factor course)[...].

[...] The fractographic reconstitution of fatigue crack history is conditioned by the existence of a fractographic feature whose measurable characteristic depends on the macroscopic FCG rate."

"... So the main input of the contemporary reconstitution methods is the dependence of striation spacing \( s \) on the fatigue crack length \( a \), i.e., \( s(a) \). Besides the measurable striations, an appropriate method of measurement and a big portion of patience, we need two transformations. [...] A transfer from the space (where the crack length and striation spacing are measured), performed by equation (5.1) to the time (usually expressed by the number of cycles \( N \)). In the second transfer, the microfractographic data have to be passed from microlvolume to macrovolume. Thus we need a relation between striation spacing \( s \) and macroscopic FCG \( v = da/dN \). This relation is expressed in equation (5.1) by the factor \( D \).

For purposes of applied fractography, in the sense of a link between microscopic and macroscopic characteristics of the fatigue process, factor \( D \) can be represented as a simple ratio \( D = v/s \).

A very brief [...] summarization can contribute to a deeper knowledge of the factor \( D \) concept, a surface of a fatigue fracture of a simple prismatic body is schematically shown in Figure (5.3). On the right side, a detail of the crack front is presented - note that index \( i \) is reserved for crack front propagation, while index \( j \) defines the location of a chosen microscopic area along the crack front. This area (of a width \( \Delta \ell_{i,j} \), where \( \ell_i \) is the total length of the crack front under observation [...] is magnified in Figure (5.4) in two phases, separated in time by \( \Delta N \) cycles necessary for the local crack growth \( \Delta a_{i,j} \) [...] Nevertheless, some fractographic facts schematically summed up in the diagrams presented can be pointed out:

- From the microscopic point of view, the real crack front is a complicated system of distorted boundaries between new fracture surfaces and the non-cracked part of a body. A 2D planar projection of the 3D reality can be observed;

- Local crack growth rate \( v_{i,j} \), characterizing a chosen area \( [\Delta \ell_{i,j} \times \Delta a_{i,j}] \), is the weighted average of microscopic FCG vectors \( v_m \), whose values and orientations are stochastic;

- In the observed part \( \Delta \ell_{i,j} \) of the crack front, we must distinguish microscopic sections defined by the actual state of a striation patch, and other sections, where the growth of crack is realized by other micromechanisms (e.g., ductile fracture or cleavage);
Figure 5.2: Fractographic reconstitution of fatigue crack history, ref. [58].
• In sections with striations, the information on microscopic FCG rate $v_m$ can be extracted from the value of striation spacing $s$. In general the equivalence $v_m = s$ is not valid;

• In sections without striations, no quantitative information about $v_m$ is available;

• The fractography data acquisition is schematically sketched on the right side of Figure (5.4). The mean striation spacing $\bar{s}_{i,j}$ corresponding to the crack length $a_i$ is one point of the $s = s(a)$ dependence in Figure (5.2). Generally, more areas (more SEM screens) are measured for every value of the crack length $a_i$, and then $\bar{s}_{i,j}$ is replaced by the average value $\bar{s}_i$.

The growth of macroscopic fatigue crack in a body is realized by stochastic interaction of local microscopic processes. The qualitatively and/or differing micromechanisms of fatigue crack front propagation are governed by properties of heterogeneous microstructure and by the corresponding local redistribution of the externally induced stress and strain fields. As the nature of these complex processes is encoded in the micromorphology of the rupture surface, the local value of $D_{i,j}$ reflects the result of stochastic interactions among different failure micromechanisms in the chosen microscopic area, then the mean value $D_i$ characterizes the crack propagation on the actual front of the crack with length $a_i$. The course of $D$ (e.g., its change with $\Delta K$ or with FCG rate) depends on the microstructure characteristics and must be experimentally determined.

Figure 5.3: Macroscopic crack front.
According to experimental results of Nedbal et al. [58] for two structural materials: Al-alloys 2024 and 2124, and Ni-alloy El 437B, the $D$ course has three different characteristic sections as shown schematically in Figure (5.5).

"... The shape of $D=D(\Delta K_{eff})$ was interpreted as a simultaneous influence of three basic factors [68]:

a) Existence of idle cycles, i.e., the load cycles which did not produce a stration on the fracture surface. In the range of low $\Delta K_{eff}$, it is necessary to apply $n$ load cycles for one stration to form. [...] The possible existence of idle cycles was taken in account in the relation defining the size of microscopic FCG vector $v_m$ (see figure (5.4)), $v_m=k.s$ where $k=1/n$, and $n \geq 1$ is an integer quoting the number of load cycles, necessary for the formation of the stration observed [71]. [...] So the macroscopic effect of idle cycles can be expressed as

$$v = da/dN \approx (1/n').\bar{s}$$

(5.2)
where \( n' \) (generally is no more an integer) is a weighted mean value of local values \( n \) in the individual striation patches (\( n'\approx5 \) Al-alloy);

b) Spatial dispersion of local directions of the crack growth. The vector divergence can be evaluated by angles \( \theta' \) between the projection vectors in the picture plane and the direction of macroscopic FCG (see schematic representation in Figure 5.6). The isolated effect of the vector divergence can be expressed as

\[
v = \frac{da}{dN} \approx \bar{s}\cos(\theta')
\]

(5.3)

\( \theta' \) is a weighted mean value of local values \( \theta \);

c) Influence of FCG micromechanisms other than the striating one. The information on the contribution of these "non-striating" mechanisms is recorded in fracture morphology and its proportion can be quantified by means of area percentage (\( 1-p_s \)), where \( p_s \) corresponds to the area of striation patches [...]. In the course of crack growth, striations are gradually replaced by ductile dimples. These areas correspond to the local jumps of small sections of the crack front whose instantaneous local FCG rate is known. These randomly spaced jumps increase the average of the macroscopic FCG rate and their effect can be formally expressed as

\[
v = \frac{da}{dN} \approx \bar{s}f(p_s)
\]

(5.4)

where the function \( f(p_s) \) (unknown in general) increases with \( p_s \).

Figure 5.6: Influence of idle cycles and divergence of vector FCG vectors, ref. [67].

"... The course of factor \( D \) is a result of simultaneous influence of three factors a), b) and c) mentioned above. The importance these factors varies as the crack growth, with the rise of FCG rate. In Figure (5.5), section A is mainly controlled by the occurrence of idle cycles, section B (\( D \approx \text{const} \)) is influenced mainly by the divergence of local FCG vectors, the section C is controlled by (1-\( p_s \)), i.e., by the increasing contribution of non-striating mechanisms of the crack front propagation."
"... Consequently, the course of factor D may be described on the basis of equations (5.2, 5.3 and 5.4) as
\[ D(\Delta K) = (v/s)\Delta K = F_{\Delta K}[(1/n').\cos(\phi').f(p_s)] \] (5.5)
where the unknown function \( F_{\Delta K} \) implies changes of the relative importance of three simultaneously operating factors. Function \( F_{\Delta K} \) is to be determined experimentally.

"... The main purpose of factor D is to facilitate the reconstitution of fatigue failure history. For the direct application of the method summarized in Figure (5.2), it is useful to transform experimental data from the relationship \( D = D(\Delta K_{eff}) \) to "fractographic" coordinates \( D = D(s) \). This transformation transformation enables the link between factor D course and the fractographic input \( s = s(a) \).[...].

For the Al-alloy 2024, \( D = D(s) \) is given by Nedbal et al. in reference [58], and is presented in Table (5.1).

<table>
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<tr>
<th>( \bar{s} , [\mu m] )</th>
<th>D</th>
<th>( \bar{s} , [\mu m] )</th>
<th>D</th>
<th>( \bar{s} , [\mu m] )</th>
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<td>1,031</td>
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</table>
5.3 Fatigue striation spacing measurements

5.3.1 Procedure

Fatigue striation measurements were performed according to reference [72]. Two perpendicular directions, crack length and crack depth, Figure (5.7-a), were analyzed by SEM. Despite the specimens’ symmetry the fatigue crack didn’t start from both sides of the hole at the same time, consequentially the fatigue crack was not symmetrical. The fatigue crack limits suggested in Figure (5.7) are dependent on the person that inspects the specimen. SEM measurements were performed for each specimen on the side with larger fatigue crack. In the case presented in Figure (5.7) it is the left side. Fractographic data acquisition was performed doing five measurements in each SEM screen (see Figure (5.8)). For each crack length \( a_i \) and crack depth \( t_i \) the striation spacing mean value was calculated.

![Figure 5.7: Specimen 7.5 fatigue tested at \( \sigma_{max} = 140MPa \). a) Longitudinal and transversal directions of measurement; b) Fatigue crack, left side; c) Fatigue crack, right side.](image)

The fatigue striation measurements were carried out in two specimens for each stress level, one without cold work and other with cold work. The specimens used for striation measurements are presented in Table 5.2.

<table>
<thead>
<tr>
<th>( \sigma_{max} ) [MPa]</th>
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<th>cold worked hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>8.5</td>
<td>10.1</td>
</tr>
<tr>
<td>140</td>
<td>7.5</td>
<td>7.1</td>
</tr>
<tr>
<td>160</td>
<td>7.3</td>
<td>10.3</td>
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<tr>
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<td>4.2</td>
<td>7.5</td>
</tr>
<tr>
<td>200</td>
<td>7.1</td>
<td>8.6</td>
</tr>
</tbody>
</table>

As an example of the striation spacing data obtained is following presented for specimen 7.5 fatigue tested at \( \sigma_{max} = 140MPa \). All the other measurements (values) obtained for the
remaining specimens are presented in Appendix D. Graphical results are presented for all specimens examined by SEM in section 5.3.2.
Specimen 7.5 measurements were done on the left side crack, Figure (5.7-b). The measurements performed along the crack length are presented in Tables (5.3) and (5.4), the measurements along crack depth are presented in Tables (5.5) and (5.6).

Table 5.3: Fatigue striation spacing measurements along crack length, specimen 7.5 fatigue tested at \( \sigma_{\text{max}} = 140 \) MPa

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [( \mu \text{m} )]</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1 x= 0.21 y= 0.87</td>
<td>0.1328</td>
<td>0.1143</td>
</tr>
<tr>
<td>2 x= 0.29 y= 0.89</td>
<td>0.0948</td>
<td>0.0882</td>
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<tr>
<td>3 x= 0.39 y= 0.88</td>
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<td>0.1139</td>
</tr>
<tr>
<td>4 x= 0.49 y= 0.84</td>
<td>0.1752</td>
<td>0.1846</td>
</tr>
<tr>
<td>5 x= 0.58 y= 0.85</td>
<td>0.1303</td>
<td>0.1304</td>
</tr>
<tr>
<td>6 x= 0.76 y= 0.86</td>
<td>0.1226</td>
<td>0.1203</td>
</tr>
<tr>
<td>7 x= 0.95 y= 0.86</td>
<td>0.2245</td>
<td>0.2214</td>
</tr>
<tr>
<td>8 x= 1.15 y= 0.88</td>
<td>0.2252</td>
<td>0.2297</td>
</tr>
<tr>
<td>9 x= 1.35 y= 0.85</td>
<td>0.3540</td>
<td>0.3572</td>
</tr>
<tr>
<td>10 x= 1.54 y= 0.85</td>
<td>0.3072</td>
<td>0.3080</td>
</tr>
<tr>
<td>11 x= 1.76 y= 0.84</td>
<td>0.3237</td>
<td>0.3151</td>
</tr>
<tr>
<td>12 x= 1.89 y= 0.82</td>
<td>0.4075</td>
<td>0.4120</td>
</tr>
<tr>
<td>13 x= 2.04 y= 0.79</td>
<td>0.3113</td>
<td>0.2989</td>
</tr>
<tr>
<td>14 x= 2.31 y= 0.76</td>
<td>0.3681</td>
<td>0.3571</td>
</tr>
<tr>
<td>15 x= 2.49 y= 0.77</td>
<td>0.2829</td>
<td>0.2829</td>
</tr>
<tr>
<td>16 x= 2.71 y= 0.74</td>
<td>0.4122</td>
<td>0.4105</td>
</tr>
<tr>
<td>17 x= 2.87 y= 0.70</td>
<td>0.5490</td>
<td>0.5384</td>
</tr>
</tbody>
</table>
Table 5.4: Fatigue striation spacing measurements along crack length, cont.

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [μm]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>x= 3.06</td>
<td>y= 0.66</td>
<td>0.3486</td>
<td>0.3445</td>
<td>0.3453</td>
<td>0.3491</td>
<td>0.3484</td>
<td>0.3472</td>
</tr>
<tr>
<td>x= 3.20</td>
<td>y= 4.18</td>
<td>0.3430</td>
<td>0.3492</td>
<td>0.3477</td>
<td>0.3452</td>
<td>0.3460</td>
<td>0.3462</td>
</tr>
<tr>
<td>x= 3.28</td>
<td>y= 4.06</td>
<td>0.4606</td>
<td>0.4572</td>
<td>0.4577</td>
<td>0.4596</td>
<td>0.4562</td>
<td>0.4583</td>
</tr>
<tr>
<td>x= 3.40</td>
<td>y= 4.11</td>
<td>0.4593</td>
<td>0.4466</td>
<td>0.4633</td>
<td>0.4513</td>
<td>0.4435</td>
<td>0.4528</td>
</tr>
<tr>
<td>x= 3.48</td>
<td>y= 4.16</td>
<td>0.4796</td>
<td>0.4800</td>
<td>0.4802</td>
<td>0.4632</td>
<td>0.4737</td>
<td>0.4753</td>
</tr>
<tr>
<td>x= 3.85</td>
<td>y= 4.18</td>
<td>0.7238</td>
<td>0.7181</td>
<td>0.7231</td>
<td>0.7135</td>
<td>0.7078</td>
<td>0.7173</td>
</tr>
</tbody>
</table>

Table 5.5: Fatigue striation spacing measurements along crack depth, specimen 7.5 fatigue tested at $\sigma_{\text{max}} = 140$ MPa

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [μm]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>x= 0.00</td>
<td>y= 0.22</td>
<td>0.1092</td>
<td>0.0951</td>
<td>0.0985</td>
<td>0.0993</td>
<td>0.0921</td>
<td>0.0988</td>
</tr>
<tr>
<td>x= -0.04</td>
<td>y= 0.30</td>
<td>0.0489</td>
<td>0.0488</td>
<td>0.0487</td>
<td>0.0484</td>
<td>0.0488</td>
<td>0.0487</td>
</tr>
<tr>
<td>x= -0.16</td>
<td>y= 0.44</td>
<td>0.1559</td>
<td>0.1577</td>
<td>0.1542</td>
<td>0.1557</td>
<td>0.1535</td>
<td>0.1554</td>
</tr>
<tr>
<td>x= -0.42</td>
<td>y= 0.56</td>
<td>0.0879</td>
<td>0.0885</td>
<td>0.0856</td>
<td>0.0856</td>
<td>0.0828</td>
<td>0.0861</td>
</tr>
<tr>
<td>x= -0.27</td>
<td>y= 0.72</td>
<td>0.0838</td>
<td>0.0814</td>
<td>0.0845</td>
<td>0.0860</td>
<td>0.0872</td>
<td>0.0846</td>
</tr>
<tr>
<td>x= -0.21</td>
<td>y= 0.87</td>
<td>0.1328</td>
<td>0.1143</td>
<td>0.1175</td>
<td>0.1353</td>
<td>0.1301</td>
<td>0.1260</td>
</tr>
<tr>
<td>x= -0.25</td>
<td>y= 1.02</td>
<td>0.0720</td>
<td>0.0810</td>
<td>0.0752</td>
<td>0.0808</td>
<td>0.0749</td>
<td>0.0768</td>
</tr>
<tr>
<td>x= -0.46</td>
<td>y= 1.13</td>
<td>0.1115</td>
<td>0.1140</td>
<td>0.1174</td>
<td>0.1153</td>
<td>0.1155</td>
<td>0.1147</td>
</tr>
<tr>
<td>x= -0.43</td>
<td>y= 1.24</td>
<td>0.0827</td>
<td>0.0826</td>
<td>0.0778</td>
<td>0.0778</td>
<td>0.0835</td>
<td>0.0809</td>
</tr>
<tr>
<td>x= -0.36</td>
<td>y= 1.34</td>
<td>0.1087</td>
<td>0.1048</td>
<td>0.1083</td>
<td>0.1084</td>
<td>0.1076</td>
<td>0.1076</td>
</tr>
</tbody>
</table>
Table 5.6: Fatigue striation spacing measurements along crack depth, specimen 7.5 fatigue tested at a $\sigma_{\text{max}}=140$ MPa, cont.

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [$\mu$m]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>11  x= -0,31</td>
<td></td>
<td>0,1045</td>
<td>0,1038</td>
<td>0,1019</td>
<td>0,1015</td>
<td>0,1019</td>
<td>0,1027</td>
</tr>
<tr>
<td>y= 1,44</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12  x= -0,05</td>
<td></td>
<td>0,0863</td>
<td>0,0878</td>
<td>0,0924</td>
<td>0,0829</td>
<td>0,0795</td>
<td>0,0858</td>
</tr>
<tr>
<td>y= 1,54</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13  x= -0,02</td>
<td></td>
<td>0,1223</td>
<td>0,1261</td>
<td>0,1258</td>
<td>0,1255</td>
<td>0,1258</td>
<td>0,1251</td>
</tr>
<tr>
<td>y= 1,62</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14  x= 0,01</td>
<td></td>
<td>0,1983</td>
<td>0,1883</td>
<td>0,1977</td>
<td>0,1970</td>
<td>0,1963</td>
<td>0,1955</td>
</tr>
<tr>
<td>y= 1,68</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure (5.8) shows two fractographs taken with SEM+FEG for this specimen at different crack length coordinates.

![Fractographs](image1.jpg)

Figure 5.8: Specimen 7.5: a) point 1, $x=0,21$ and $y=0,87$ mm; b) point 21, $x=0,66$ and $y=3,06$ mm.
5.3.2 Fatigue striation spacing measurement results

Figure (5.9) presents the fatigue striation spacing measurements along the crack length and crack depth, for the normal open hole specimen 8.5 and the cold worked specimen 10.1 CW. Both specimens were fatigue tested at $\sigma_{\text{max}}=120\text{MPa}$.

Figure 5.9: Specimens fatigue tested at $\sigma_{\text{max}}=120\text{MPa}$: a1) striation spacing along crack length, specimen 8.5 with normal hole; b1) striation spacing along crack length, specimen 10.1 CW with cold worked hole; a2) striation spacing along crack depth, specimen 8.5 with normal hole; b2) striation spacing along crack depth, specimen 10.1 CW with cold worked hole.
Figure (5.10) presents the fatigue striation spacing measurements along the crack length and crack depth, for the normal open hole specimen 7.5 and the cold worked specimen 7.1 CW. Both specimens were fatigue tested at $\sigma_{\text{max}}=140$ MPa.

![Graphs](image)

Figure 5.10: Specimens fatigue tested at $\sigma_{\text{max}}=140$ MPa: 
- a1) striation spacing along crack length, specimen 7.5 with normal hole; 
- b1) striation spacing along crack length, specimen 7.1 CW with cold worked hole; 
- a2) striation spacing along crack depth, specimen 7.5 with normal hole; 
- b2) striation spacing along crack depth, specimen 7.1 CW with cold worked hole.
Figure (5.11) presents the fatigue striation spacing measurements along the crack length and crack depth, for the normal open hole specimen 7.3 and the cold worked specimen 10.3 CW. Both specimens were fatigue tested at $\sigma_{max}=160$MPa.

Figure 5.11: Specimens fatigue tested at $\sigma_{max}=160$ MPa: a1) striation spacing along crack length, specimen 7.3 with normal hole; b1) striation spacing along crack length, specimen 10.3 CW with cold worked hole; a2) striation spacing along crack depth, specimen 7.3 with normal hole; b2) striation spacing along crack depth, specimen 10.3 CW with cold worked hole.
Figure (5.12) presents the fatigue striation spacing measurements along the crack length and crack depth, for the normal open hole specimen 4.2 and the cold worked specimen 7.5 CW. Both specimens were fatigue tested at $\sigma_{\text{max}}=180$ MPa.

Figure 5.12: Specimens fatigue tested at $\sigma_{\text{max}}=180$ MPa: a1) striation spacing along crack length, specimen 4.2 with normal hole; b1) striation spacing along crack length, specimen 7.5 CW with cold worked hole; a2) striation spacing along crack depth, specimen 4.2 with normal hole; b2) striation spacing along crack depth, specimen 7.5 CW with cold worked hole.
Figure (5.13) presents the fatigue striation spacing measurements along the crack length and crack depth, for the normal open hole specimen 7.1 and the cold worked specimen 8.6 CW. Both specimens were fatigue tested at a $\sigma_{\text{max}}=200\text{MPa}$.

Figure 5.13: Specimens fatigue tested at $\sigma_{\text{max}}=200\text{MPa}$: a$_1$) striation spacing along crack length, specimen 7.1 with normal hole; b$_1$) striation spacing along crack length, specimen 8.6 CW with cold worked hole; a$_2$) striation spacing along crack depth, specimen 7.1 with normal hole; b$_2$) striation spacing along crack depth, specimen 8.6 CW with cold worked hole.
Figure (5.14) shows the fatigue striation spacing mean values comparison of results along the crack length between normal and cold worked hole specimens for all the stress levels tested.

\[ a_1 \] \( \sigma_{max} = 120 \text{ MPa}; \]

\[ a_2 \] \( \sigma_{max} = 140 \text{ MPa}; \]

\[ a_3 \] \( \sigma_{max} = 160 \text{ MPa}; \]

\[ a_4 \] \( \sigma_{max} = 180 \text{ MPa}; \]

\[ a_5 \] \( \sigma_{max} = 200 \text{ MPa}; \)

Figure 5.14: Fatigue striation spacing along the crack length, comparison of results between normal and cold worked hole specimens.
Figure (5.15) compares fatigue striation spacing along the crack length with the stress level increasing. Figure (5.15) $a_1$ and $b_1$ present the experimental results. Figure (5.15) $a_2$ and $b_2$ present suggest an exponential fitting of the experimental results. Reference [73] reports the exponential fitting of fatigue striation spacing measurements in a longitudinal fuselage lap joint as a good approximation for this type of measurements.

![Graphs showing fatigue striation spacing](image)

**Figure 5.15:** Fatigue striations spacing along crack length: $a_1$) normal hole specimens; $b_1$) cold worked hole specimens; $a_2$) normal hole specimens using exponential fitting; $b_2$) cold worked hole specimens using exponential fitting.

### 5.3.3 SEM measurements, comments

The previous results showed the effect of the stress level and cold work on fatigue striation spacing along the crack length and crack depth of a fatigue crack. Fatigue striation spacing rise along the crack length, this is comprehensible because as the crack length increase during the fatigue test the local stress field on the crack front increase and consequently the deformation field makes larger striations. For specimens with cold work a similar trend was found along the crack length but in this case with smaller values of striation spacing.
As shown in chapter 3, cold work introduce a residual stress field making the effective stress field \( \sigma_{eff} = \sigma_{app} - \sigma_{res} \) on the crack front smaller than without cold work. As a consequence the deformation field on the crack front is not so high as without cold work producing smaller striations. Along crack depth it was shown that striation spacing for specimens with cold work was also lower than for normal hole specimens. For both types of specimens the crack initiate preferentially on one of the specimens side (crack depth equal to 0 or 2mm). In the case of the specimens with normal hole it is reasonable that the crack initiates randomly, depending on the existence of material or manufacturing defects. For specimens with cold work it should be expected that the crack initiate on the depth side with lower residual stress. Unfortunately, this hypothesis could not be confirmed by the present experimental results because the specimen depth side with lower residual stress was not marked by the specimens’ manufacturer DASA.

5.4 Fatigue crack history reconstitution

The present section intends to describe the fatigue crack history reconstitution of two specimens. This analysis was performed on two open hole specimens (with and without cold worked hole) fatigue tested at \( \sigma_{max} = 140 \) MPa. These two specimens were selected because they are the only pair of specimens with both types of crack growth measurements, surface crack growth performed with video and fatigue striation measurements performed with SEM. A comparison between both techniques is presented.

Surface crack growth measurements were presented in chapter 4 and are shown in Figure (5.16) and (5.17).

![Figure 5.16: Surface crack growth, normal hole specimen (left side crack).](image)

Figure (5.18) shows both specimens just before rupture moment. Fractographic measurements were performed as presented in section 5.3. The fatigue striation spacing measurements are presented in Figure (5.14 - a2) for both specimens. Fatigue
crack history reconstitution was performed according to section 5.2.3. The integration of equation (5.1) was done using the numerical integration, rectangle rule,

\[ \Delta N = \frac{\Delta a_i}{v_i} = \frac{\Delta a_i}{D_i(s) \cdot s_i} \]  \hspace{1cm} (5.6)\]

The values of factor \( D \) used in the present work are presented in Table (5.1). The striation spacing measurements are interpreted according two different approaches: (i) the view that striation spacing \( s \) is equivalent to the macroscopic rate \( v \) \((D=1)\) of the fatigue crack front, which was supported by a number of authors (e.g., \([74]\)) and (ii), in the view that the ratio \( v/s \) changes with the crack growth rate (e.g., \([75, 76, 77]\)), or the concept \( D = D(s) \) in \([66, 67, 68, 78]\). In Figure (5.20 a) and b) the fractographic crack reconstitution using \( D=1 \) and \( D = D(s) \) \([58]\) are compared with results based on surface macroscopic observations, for the specimen with and without hole treatment respectively. Figure (5.20 - a) shows results for the specimen without cold expansion, with a fatigue life of 70986 cycles. Macroscopic measurements were performed in an interval of 3840 cycles before the final rupture, which means approximately 5% of the specimen fatigue life. Figure (5.20 - b) presents results for the specimen with cold expanded hole, with a fatigue life of 200224 cycles. Macroscopic measurements were performed in a short interval of 2840 cycles before the rupture, i.e. during approximately 1.5% of the specimen life.
Fractographic reconstitution of crack growth in time, \( a = a(N) \), illustrates the following experience: for a given alloy, the importance of D-factor knowledge depends on the range of striation spacing used as the input for fractographic reconstitution - compare Figure (5.20 - a and b), in relation to input data in Figure (5.14 - a2). In the case of cold expanded hole (Figure (5.20 - a)), the assumption \( v = s \) (i.e., \( D = 1 \)) leads to a misguided result of fractographic reconstitution: the evolution of time necessary for crack growth until a 0.35 mm (which can be considered as a practical engineering initialization time) is unjustifiably overestimated. If we use the actual knowledge of the course of \( D = D(s) \) [58], the very important difference of results attains approximately 50% of the specimen life. Figure (5.20 - c) shows results obtained for both specimens using fractographic crack reconstitution with \( D = D(s) \), in comparison with the surface macroscopic measurements. Figure (5.19) shows the fractographic reconstitution of crack growth rate in time \( v = v(N) \) (see Figure(5.19)) and quantifies the braking efficiency of the hole treatment: the crack initiated in the cold expanded hole needs about 125000 cycles more before the CGR of \( v = 0.1 \) \( \mu \text{m/cycle} \) is attained. This difference represents nearly 180% of fatigue life of the specimen with untreated hole.

![Graph showing crack growth rate vs. number of cycles](image)

Figure 5.19: Crack growth rate \( v \) as function of number of cycles \( N \) (normal and cold worked hole).

In Figure (5.20- a to c), the macroscopic crack length resulting from the surface measurements in the final stage of fatigue life (Figure (5.21)), is larger than a considered in fractographic measurements, because using a recording camera the surface crack length before the rupture moment (Figure(5.22 - b)) is assessed. In the fractographic analysis, the measurements were just performed in the part of the crack that was evaluated as a fatigue crack. Figure(5.22 - a) suggests that during the fatigue crack growth, the visible surface crack length (SCL) underestimate the total fatigue crack length (TFCCL) inside the specimen. Before the rupture moment, there is a period of time in which SCL is bigger than total fatigue crack length because the crack part with plastic deformation was not taken into account in SEM measurements.
Figure 5.20: Fatigue crack history using $D=1$ and $D = D(s)$: a) normal hole specimen; b) cold worked hole; c) normal and cold worked hole using $D = D(s)$.  

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Figure 5.21: Specimen fatigue life, different stages.

---

Surface measurements

A—A (x2)

Legend:
S. C. L. - surface crack length
T.F.C. L. - total fatigue crack length

Surface measurements

B—B (x2)

Fatigue test begin

Crack propagation with plastic deformation

Specimen rupture

Fatigue life without crack propagation

Fat. crack propagation

---

Figure 5.22: Difference between surface crack measurements (macroscopic), and microscopic measurements of striation spacing along the longitudinal axis of fatigue crack: a) during fatigue crack growth; b) in the final stage of cracking.

Surface measurement describes the rapid cracking of a "shell" created by foregone failure inside, i.e., by propagation of the crack with heavily pronounced convexity. It cannot be directly compared with results of the fractographic reconstitution, which offers a plausible evaluation of the movement of a short segment of the crack front propagating along the longitudinal axis of bearing section of the specimen. This difference of information source is the origin of substantial differences in values of the CGR. Figure (5.23 - a and b) show the difference found between macroscopic surface crack growth rate, and the macroscopic CGR reconstructed from striation spacings, considering all the measurements judge as valid. It must be mentioned that the surface macroscopic CGR was calculated as described in chapter 4. Large differences were found in both types of specimens, although differences
are much bigger in the specimen with hole treatment. It may suggest that those macroscopic measurements were performed during the period of crack growth with plastic deformation. This is known that in this final fatigue stage other phenomena than fatigue are present, e.g., ductile fracture and accentuated plastic deformation. In the specimen with normal hole, this effect is also present but it is not so accentuated.

Figure 5.23: Difference between surface crack growth rate measurements (macroscopic) and CGR reconstructed inside fatigue crack from striation spacing: a) normal hole specimen; b) cold worked hole.

5.5 Crack growth rate using SEM measurements

This section presents the crack growth rate measurements based on fatigue striations measured by SEM. Two different approaches are compared, (i) view that striation spacing $s$ is equivalent to the macroscopic rate $v$ ($D=1$) and (ii) the view that ratio $v/s$ changes with the crack growth rate $v$ ($D = D(s)$). Figure (5.24) presents the $da/dN \text{ vs } \Delta K$ for all the stress levels tested in normal hole specimens.
Figure 5.24: $da/dN$ vs $\Delta K$ for all stress levels considering $D=1$ and $D = D(s)$, normal hole specimens.
Figure (5.24) presents the da/dN vs \( \Delta K \) in cold worked hole specimens.

\[
\begin{align*}
\text{a1) } \sigma_{\text{max}} & = 120 \text{ MPa;} \\
\text{a2) } \sigma_{\text{max}} & = 140 \text{ MPa;} \\
\text{a3) } \sigma_{\text{max}} & = 160 \text{ MPa;} \\
\text{a4) } \sigma_{\text{max}} & = 180 \text{ MPa;} \\
\text{a5) } \sigma_{\text{max}} & = 200 \text{ MPa;} \\
\text{a6) } \sigma_{\text{max}} & = 120 - 200 \text{ MPa;}
\end{align*}
\]

Figure 5.25: da/dN vs \( \Delta K \) for all stress levels considering \( D=1 \) and \( D = D(s) \), cold worked hole specimens.
Figure (5.26) shows the comparison of crack growth rate measurements between normal and cold worked hole specimens in comparison with references presented in chapter 4, end of section 4.6.2. Figure (5.26 - a) shows the comparison of results considering \( D = 1 \) and Figure (5.26 - b) shows the comparison of results considering \( D = D(s) \).

Figure 5.26: Comparison of CGR measurements between normal and cold worked hole specimens and other references: a) \( D = 1 \); b) \( D = D(s) \).
In the previous two figures no big differences were found between $D=1$ and $D = D(s)$ CGR measurements from fatigue striations judge as valid. The scatter of data presented is larger than this difference. It must be mentioned that the major part of the fatigue striation spacing measurements were performed between $0.1 \leq s \leq 1$ (μm) (see Figure (5.27 - PW). According to Figure (5.27) this means that when we use $D = D(s)$ is used CGR is reduced 16.1%. In both figures CGR obtained using SEM measurements are very close of the literature references presented.

![Figure 5.27: $D = D(s)$ used in the present work.](image)

### 5.6 Comparison of crack growth rate results between macro and micro measurements

In the previous section it was shown that CGR results obtained using $D = D(s)$ in the striation spacing measurements judged as valid are not very different than those obtained using $D = 1$. Because of this reason the second option is used in the present section. Figures (5.28) and (5.29) present the $da/dN$ vs $\Delta K$ obtained using macroscopic measurement techniques (video recording) and microscopic measurement techniques (striations spacing) for normal hole specimens. Figures (5.30) and (5.31) present the same kind of results considering all video measurements judged as valid for cold worked specimens in chapter 4, section 4.6.4. Although a more detailed discussion was presented in section 4.6.5 of the same chapter and for this case the comparison is done in Figures (5.32) and (5.33).
Figure 5.28: Normal hole specimens CGR measurements. Comparison of results between surface measurements (using video) and striation spacing measurements (using SEM).

Figure 5.29: Normal hole specimens CGR measurements. Comparison of results between surface measurements (using video) and striation spacing measurements (using SEM). Comparison with other references.
Figure 5.30: Cold worked hole specimens CGR measurements. Comparison of results between surface measurements (using video) and striation spacing measurements (using SEM).

Figure 5.31: Cold worked hole specimens CGR measurements. Comparison of results between surface measurements (using video) and striation spacing measurements (using SEM). Comparison with other references.
Figure 5.32: Cold worked hole specimens CGR measurements. Comparison of results between surface measurements (using video) and striation spacing measurements (using SEM).

Figure 5.33: Cold worked hole specimens CGR measurements. Comparison of results between surface measurements (using video) and striation spacing measurements (using SEM). Comparison with other references.
5.6.1 Comments

- Micro and macro crack growth measurements are not in perfect agreement but they show the trend reported in literature [79, 71, 58], that \( s < \text{CGR} \) in the region of high crack grow rate, which is the case of the present work because macro measurements were just possible to perform in a very short period close to the rupture moment;

- The same type of results were obtained in normal and cold worked hole specimens as presented in Figure (5.28) and Figure (5.32) respectively.

5.7 Specimens residual strength

The residual strength of a structure, which is the failure strength as a function of crack size, decreases with increasing of crack size. After a time the residual strength becomes so low that the structure may fail in service. In order to evaluate the specimens behaviour and estimate the maximum load, specimens data were analyzed using residual strength diagrams. In order to construct residual strength diagrams, the first step was the measurement of fatigue crack areas. Crack areas and crack lengths measurements are presented in Appendix E. Figure (5.34) represents schematically the cracked area and crack length considered in the measurements.

![Diagram of fatigue crack area and crack length measurements.]

Figure 5.34: Fatigue crack area and crack length measurements.

The notation in Figure (5.34) means: \( a_{\text{left}} \) is the fatigue crack on the left, \( a_{\text{right}} \) is the right side fatigue crack, \( \Omega_{\text{left}} \) is the left side final fatigue crack area, \( \Omega_{\text{right}} \) is the right side final fatigue crack area, D is the hole diameter, t is thickness, W is the width and ligament is the ligament area.

The collapse mechanism used is schematized in Figure (5.35). Maximum load net section collapse criterion [80], was calculated using equation (5.7).

\[
\sigma_{\text{net}} W = \bar{\sigma}(W - D) \\
\sigma_{\text{net}} = \bar{\sigma}(1 - \frac{D}{W})
\]  

Different ways of representing data results are possible. Two of those possible ways are suggested in equations (5.8) and (5.9).

\[
\text{% of non resistant area} = \frac{\Omega_{\text{left}} + D \cdot t + \Omega_{\text{right}}}{W \cdot t} \times 100
\]  

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\[
\% \text{ of cracked area} = \frac{\Omega_{\text{left}} + \Omega_{\text{right}}}{(W - D) \cdot t} \times 100
\]

In order to avoid errors is convenient to remember equation (5.10):

0\% of non resistant area \Rightarrow \text{residual strength} = \sigma_{\text{yield}} \text{ or } \sigma_{\text{flow}}, \quad (\sigma_{\text{flow}} = (\sigma_y + \sigma_u)/2)

0\% of cracked area \Rightarrow \text{residual strength} = (1 - \frac{d}{W}) \cdot (\sigma_{\text{yield}} \text{ or } \sigma_{\text{flow}})

(5.10)

Residual strength diagrams were complemented with the representation of minimum and maximum \(K_c\). Critical toughness estimation is presented in Appendix F. The representation of these curves was done using equation (5.11). In the case of normal hole specimens \(K_{\text{res}}\) is zero.

\[
\sigma_c = \frac{K_c - K_{\text{res}}}{Y\sqrt{\pi a_c}}
\]

(5.11)

In the previous equation \(\sigma_c\) is the critical tensile stress and \(a_c\) is the critical crack size.

Residual strength diagrams using the two ways of representing data mentioned above are presented in Figures (5.36) to (5.39). Experimental data points, minimum and maximum \(K_c\) lines (from eq. (5.11)) and net section collapse are compared. In the normal hole specimens (see Figures (5.36 and 5.37)) the maximum tensile stress lines estimated based on \(K_c\) are presented for the case of two symmetrical cracks. In the cold cold worked hole specimens (see Figures (5.36 and 5.37)) the maximum tensile stress lines estimated based on \(K_c\) are presented considering one crack and two symmetrical cracks for minimum values of \(K_c\) and two symmetrical cracks for maximum \(K_c\). This procedure was adopted because it was noticed that some cold worked specimens tested at 120 MPa broke due to the crack growth of one fatigue crack only. In both types of specimens the region between minimum and maximum critical tensile curves is presented.
In Figures (5.36) and (5.37) the estimated $K_c \text{ min} = 17.9 \text{ MPa.m}^{0.5}$ and estimated $K_c \text{ max} = 26.91 \text{ MPa.m}^{0.5}$.

Figure 5.36: Residual strength diagram, normal hole specimens. Representation as function of the % of non-resistant area.

Figure 5.37: Residual strength diagram, normal hole specimens. Representation as function of the % of non resistant area.
In Figures (5.38) and (5.39) the estimated $K_c$ min, 1 crack = 15.98 MPa.m^{0.5}$, $K_c$ min, 2 cracks = 15.6 MPa.m^{0.5}$ and estimated $K_c$ max = 23.12 MPa.m^{0.5}$.

Figure 5.38: Residual strength diagram, specimens without cold work. Representation as function of the % of non-resistant area.

Figure 5.39: Residual strength diagram, specimens without cold work. Representation as function of the % of cracked area.
5.7.1 Comments

- In the case of normal hole specimens the residual strength values are below the net section yield lines, which implies the failure criterion is therefore in the field of Fracture Mechanics. For the data presented the net section collapse procedure could be taken as a rough estimation of the specimens' behaviour which improves for the higher stress levels tested;

- In the case of cold worked hole specimens the net section collapse procedure would be a reasonable estimation for the higher stress levels tested.
5.8 Summary

1. Fatigue striation spacing measurements for normal and cold worked hole were presented. It was observed that fatigue striation spacing increase with the increase in crack length;

2. Fatigue striations spacing for specimens with cold work are smaller along the crack length and depth, by comparison with normal hole specimens. However it was not possible with the presented data to state a general quantitative law for all the specimens measured;

3. Micro and macro crack growth measurements are not in perfect agreement but they show the trend reported in literature [79, 71, 58], that s<CG in the region of high crack grow rate (region of the present work, because macro measurements were possible just in a very short period close to the final rupture moment);

4. The quantitative microfractography of fracture surfaces was used: the SEM measurements of striation spacing afforded the input data for fractographic reconstitution of fatigue crack growth. Two different approaches were confronted: a simplified presumption \( v = \frac{da}{dN} = s \) (i.e., \( D=1 \)), and more realistic supposition that the ratio \( \frac{v}{s} \) is not constant, i.e., \( D=D(s) \);

5. Results of fractographic reconstitution of the fatigue crack growth offers a plausible evaluation of the movement of a short segment of crack front propagating along the longitudinal axis of bearing section of the specimen. This information, attainable only by help of fractography, yields a new piece of knowledge about the effect of the hole cold expansion: it seems that the main source of specimen life prolongation is not a longer crack initiation time, but an intensive braking of early crack growth stage, by effect of the field of residual stresses;

6. Large differences were not found between \( D=1 \) and \( D=D(s) \) CGR measurements from fatigue striations judged as valid;

7. CGR measurements obtained using SEM measurements are very close to data of the literature references presented;

8. In the case of normal hole specimens the residual strength values are bellow the net section yield lines, which implies the failure criterion is therefore in the field of Fracture Mechanics. For the data presented the net section collapse procedure could be taken as a rough estimation of the specimens’ behaviour which improves for the higher stress levels tested. In the case of cold worked hole specimens the net section collapse procedure would be a reasonable estimation for the higher stress levels tested.
Chapter 6

Statistical analysis of fatigue tests

6.1 Introduction

The aim of the present work is the statistical analysis of the fatigue life and critical crack size for a particular type of specimens, open hole specimens with and without residual stress.

In order to use the test data for probabilistic methods, the results were fitted to a distribution function. There are many distribution types (e.g. Normal, Lognormal, Weibull etc.) and the goal of this work is to determine the distribution type that best fits the test data. This work was based on the use of two software tools, SuperSMITH Weibull and an Excel worksheet. The software SuperSMITH Weibull allow us to compare the results for the following distributions: Normal, Lognormal, Weibull with two parameters (Weibull 2P) and Weibull with three parameters (Weibull 3P). Based on the goodness of fit criterium described in section 6.2.4, the distribution witch fits best is selected. The Excel worksheet allow us to plot the PDF (probability density function) and CDF (cumulative distribution function) for the selected distribution based on the parameters estimated with the software SuperSMITH Weibull. This graphical representation of the PDF and CDF allow the simultaneous presentation of both curves.

6.2 Theory survey

In this section, some basic theoretical principles of the distribution types used in the present work are presented.

6.2.1 Weibull distribution

Often the Weibull distribution is used to model the time until failure of many different physical systems, references [81, 82, 83].

For a random variable following three-parameter Weibull distribution, the probability distribution function is given by,

\[ f(x) = \frac{\beta}{\eta} \left( \frac{x - x_0}{\eta} \right)^{\beta - 1} \cdot e^{-\left( \frac{x - x_0}{\eta} \right)^{\beta}} \]  

(6.1)
with,

\[ x > x_0; \quad -\infty < x_0 > \infty; \quad \eta > 0; \quad \beta > 0 \]

where \( \eta \) is the scale parameter, \( \beta \) is the shape parameter, \( x_0 \) is the expected minimum value of \( x \) and is also referred to as correction parameter and \( x \) is the variable, which in the present case is the fatigue life of the specimens.

The Weibull distribution is very flexible, and by appropriate choice of \( \beta \) the distribution can assume a wide variety of shapes, reference [82]. It is often proposed that the Weibull distribution with a value of \( \beta \) lying between 3 and 4 gives a fair approximation to the normal distribution. However, the approximation is not mathematical. The most commonly used value of \( \beta \) to approximate the normal is \( \beta = 3.44 \). Values of \( \beta = 2.5 \) and \( \beta < 1 \) give the exponential and lognormal distribution curves, respectively. For \( \beta = 2 \) the shape of the Weibull distribution becomes identical to that of the Rayleigh distribution. The different shapes that the Weibull distribution assumes for different values of \( \beta \) are shown in Figure(6.1).

The shape parameter \( \beta \), also referred to as the Weibull modulus, is a measure of width of the fatigue life or scatter in the fatigue life data. In other words, the shape parameter is related with the specimens fatigue life. For a large value of the scatter in the fatigue life the fatigue life is narrow and more reliable.

The correction parameter \( x_0 \) is the value of fatigue life below which the probability of failure is zero, i.e. \( x_0 \) is the fatigue bellow which the specimen never fails. If we neglect the correction parameter, the expression for the probability distribution function takes the form

\[ f(x) = \frac{\beta}{\eta} \left( \frac{x}{\eta} \right)^{\beta-1} e^{-\left( \frac{x}{\eta} \right)^{\beta}} \tag{6.2} \]

This form of Weibull distribution has two adjustable parameters \( \eta \) and \( \beta \).

The cumulative distribution function is expressed in terms of the probability density function as

\[ F(x) = \int f(x)dx \tag{6.3} \]

Therefore, the expression for the probability of failure in the case of three-parameter Weibull distribution can be written as equation (6.4). In the case of two parameter, Weibull distribution can be written as equation (6.5).

\[ F(x) = 1 - e^{-\left( \frac{x-x_0}{\eta} \right)^{\beta}} \tag{6.4} \]

\[ F(x) = 1 - e^{-\left( \frac{x}{\eta} \right)^{\beta}} \tag{6.5} \]

The different shapes of the cumulative distribution function assumes for different values of \( \beta \) are shown in Figure(6.2).

The following four criteria should always be met before using the three-parameter Weibull, reference [83]:

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1. The Weibull plot should show concave downward curvature;

2. There should be a physical explanation of why failures cannot occur before $x_0$;

3. A larger sample size, at least 20 failures should be available. If there is a prior knowledge from earlier Weibulls that the third parameter is appropriate, a smaller sample size, say eight to ten may be acceptable;

4. The correlation coefficient should significantly increase to be above the required CCC (critical correlation coefficient) for the three parameter Weibull.

The life values obtained are arranged in an increasing order such that the $N$th value correspond to the the highest fatigue life. For each fatigue life a probability of failure using one estimator is assigned. There is more than one definition for the fatigue life estimators. According to reference [84], four of the most common are,

\[ F(x_i) = \frac{i}{1 + N} \quad (6.6) \]

\[ F(x_i) = \frac{i - 1/2}{N} \quad (6.7) \]

\[ F(x_i) = \frac{i - 0.3}{N + 0.4} \quad (6.8) \]

\[ F(x_i) = \frac{i - 3/4}{N + 1/4} \quad (6.9) \]

Among these estimators the estimator $F(x_i) = i/(1 + N)$ gives a conservative failure probability (low value of Weibull modulus) and from the reliability point of view is the best choice, references [85, 84], and is used in the software SuperSmith.

Knowing $\beta$ and $\alpha$, the Weibull mean and standard of the fatigue life distribution is calculated according equation (6.10).

\[ \mu = \eta \Gamma \left( 1 + \frac{1}{\beta} \right) \quad (6.10) \]

The standard deviation is given by equation (6.11), reference [82],

\[ \sigma = \left\{ \eta^2 \Gamma \left( 1 + \frac{2}{\beta} \right) - \eta^2 \left[ \Gamma \left( 1 + \frac{1}{\beta} \right) \right]^2 \right\}^{1/2} \quad (6.11) \]

In Figures (6.1) and (6.2) are presented the Weibull PDF and CDF respectively for different values of $\beta$. 

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Figure 6.1: Weibull probability density function for different values of $\beta$, ref. [86].

Figure 6.2: Weibull cumulative distribution function for different values of $\beta$, ref. [86].
6.2.2 Normal distribution

According to reference [87], Normal distribution is the most frequent to describe phenomena expressed by random variables. Normal distribution is characterized by two parameters: the expected value $\mu$ and variance $\sigma^2$; $x \rightarrow N(\mu, \sigma^2)$.

The Normal probability density function is defined by equation (6.12).

$$f(x) = \frac{1}{\sqrt{2\pi} \cdot \sigma^2} \cdot e^{-\frac{1}{2} \left( \frac{x-\mu}{\sigma} \right)^2}$$ (6.12)

The cumulative distribution function, equation (6.13)

$$F(x) = \int_{-\infty}^{x_1} f(x)dx$$ (6.13)

can't be analytically integrated, can only be numerically integrated.

6.2.3 Lognormal distribution

According to reference [87], if $V = \ln(x)$ follow a normal distribution with parameters $N(\mu_V, \sigma_V^2)$, the $x$ variable follow a Lognormal distribution with parameters $\mu$ and $\sigma$.

The Lognormal probability density function is defined by equation (6.11).

$$f(x) = \frac{1}{\sqrt{2\pi} \cdot \sigma_V} \cdot e^{-\frac{1}{2} \left( \frac{\ln x - \mu_V}{\sigma_V} \right)^2}$$ (6.14)

The expected value of $x$ and variance expressed as function of $V$, $\mu_V$ and $\sigma_V$ are:

$$\mu_x = e^{\mu_V + \sigma_V^2/2}$$ (6.15)

$$\sigma_x^2 = e^{2(\mu_V + \sigma_V^2)} - e^{2\mu_V + \sigma_V^2}$$ (6.16)

Using equations (6.15) and (6.16) we can obtain $V$ parameters as function of $\mu_x$ and $\sigma_x$

$$\mu_V = \frac{1}{2} \cdot \ln \left( \frac{\mu_x^4}{\sigma_x^2 + \mu_x^2} \right)$$ (6.17)

$$\sigma_V^2 = \ln \left( \frac{\sigma_x^2 + \mu_x^2}{\mu_x^2} \right).$$ (6.18)

6.2.4 Goodness of fit

According to reference reference [88], graphical methods of assessing fit require skill to correct interpretation and provide no quantitative measure of lack of conformance of the data to the hypothesized distribution. These disadvantages can be overcome by the use of formal goodness of fit tests. These are a type of hypothesis test. The hypothesis being tested is that the sample originated from a population with a specified distributional form, the alternative being that it did not.

A very large number of different goodness of fit testes is available. The most widely used is the Chi-Squared and Kolmonov-Smirnov tests. There are however also many newer tests.
that are usually considered more powerful.  
For many engineering applications the Anderson-Darling test can be recommended, since it is a very powerful test, versions are available for testing a wide variety of distributional forms and it is particularly sensitive to discrepancies in the tail regions, about which engineering interferences often need to be made.

The goodness of fit parameter employed in the software SuperSimth, used in this work was the simple correlation factor, reference [83]. It is ideal for testing the goodness of fit to a straight line. as stated in reference [83], "Mathematicians object to the use of the correlation coefficient on probability plots because the assignment of median ranks artificially increases the observed correlation. To overcome this objection, the author employed Monte Carlo simulation to approximate the distribution of simulation to approximate the distribution of the correlation coefficient from ideal Weibulls based on median rank plotting positions. The 90% critical correlation coefficient (CCC) provides a measure of goodness of fit. The CCC is found by ranking the "r" values for the correlation coefficient from 1000 MonteCarloSMITH™ trails and choosing the highest value of the 100 values. Thus the 90% CCC is the tenth percentile, the "10P" of the 1000 values. If your "r" is larger than the CCC, the 10P, you have a good fit."

The correlation coefficient squared is called the coefficient of determination ,"r²", [83]. Many statisticians prefer r² to r as a measure of goodness of fit. The coefficient of determination is equal to the percentage of the variation in the data that is explained by the fit to the distribution. Although this is not precisely true on probability , r² is still a good indicator of goodness of fit.

To compare the fit of one distribution with another, say a Weibull with a Lognormal or Normal, we need a moderate size sample, and the P values for the correlation coefficient, r, for each distribution. The larger positive difference, (r²-CCC²), the highest P value of the observed r wins.
6.3 Fatigue data statistical analysis

In this section the statistical fatigue data results is presented. In spite of the results obtained for the Weibull 3P being presented that distribution was not considered due the application criteria being out of range, see section 6.2.1. Notice that the graphical PDF representation in the following figures is normalized.

6.3.1 Normal open hole specimens

6.3.1.1 $\sigma_{\text{max}} = 120$ MPa

Table (6.1) presents statistical parameters estimated in software SuperSMITH Weibull, for the fatigue life of the specimens tested at $\sigma_{\text{max}} = 120$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$-CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>129083,6</td>
<td>3,280</td>
<td>115757</td>
<td>38827</td>
<td>0,957</td>
<td>0,814</td>
<td>0,101</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>81192,5</td>
<td>39950,4</td>
<td>0,773</td>
<td>46453</td>
<td>60816</td>
<td>0,999</td>
<td>0,909</td>
<td>0,089</td>
</tr>
<tr>
<td>LogNormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>119318</td>
<td>43065</td>
<td>0,981</td>
<td>0,821</td>
<td>0,142</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>115360</td>
<td>42793</td>
<td>0,964</td>
<td>0,821</td>
<td>0,109</td>
</tr>
</tbody>
</table>

Figure (6.3) presents the PDF and CDF for the best distribution fits, Lognormal.

Figure 6.3: Lognormal distribution PDF and CDF, specimens tested at $\sigma_{\text{max}} = 120$ MPa.
Figure (6.4) presents the CDF with a confidence interval of 95 % for the Lognormal distribution.

![Lognormal distribution CDF with confidence interval](image)

Figure 6.4: Lognormal distribution, CDF with a confidence interval of 95 %. \( \sigma_{max} = 120 \) MPa.

6.3.1.2 \( \sigma_{max} = 140 \) MPa

Table (6.2) presents the statistical parameters estimated in software SuperSMITH Weibull, for the fatigue life of the specimens, \( \sigma_{max} = 140 \) MPa.

<table>
<thead>
<tr>
<th></th>
<th>( \eta_0 )</th>
<th>( \eta )</th>
<th>( \beta )</th>
<th>( \mu )</th>
<th>( \sigma )</th>
<th>( r )</th>
<th>CCC2</th>
<th>( r^2 )-CCC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>68072,8</td>
<td>3,817284</td>
<td>61540</td>
<td>18007</td>
<td>0,974</td>
<td>0,814</td>
<td>0,135</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>43704,3</td>
<td>21695,96</td>
<td>0,842577</td>
<td>23735</td>
<td>28304</td>
<td>0,986</td>
<td>0,909</td>
<td>0,064</td>
</tr>
<tr>
<td>LogNormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>63245</td>
<td>19771</td>
<td>0,983</td>
<td>0,821</td>
<td>0,146</td>
</tr>
<tr>
<td>Normal</td>
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<td>...</td>
<td>...</td>
<td>61610</td>
<td>18788</td>
<td>0,982</td>
<td>0,821</td>
<td>0,143</td>
</tr>
</tbody>
</table>

In Figure (6.5) are presented the PDF and CDF for the best distribution fits at \( \sigma_{max} = 140 \) MPa, Lognormal distribution. Figure (6.6) presents the CDF with a confidence interval of 95 %.

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Figure 6.5: Lognormal distribution PDF and CDF, specimens tested at $\sigma_{max} = 140$ MPa.

Figure 6.6: Lognormal distribution, CDF with a confidence interval of 95%. $\sigma_{max} = 140$ MPa.
6.3.1.3 $\sigma_{\text{max}} = 160$ MPa

Table (6.3) presents statistical parameters estimated in software SuperSMITH Weibull, for the fatigue life of the specimens tested at $\sigma_{\text{max}} = 160$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$-CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>38679.8</td>
<td>8.917</td>
<td>36613</td>
<td>4906</td>
<td>0.993</td>
<td>0.814</td>
<td>0.173</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>295.5</td>
<td>33832.8</td>
<td>8.848</td>
<td>36319</td>
<td>4902</td>
<td>0.993</td>
<td>0.909</td>
<td>0.078</td>
</tr>
<tr>
<td>LogNormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>37067</td>
<td>4956</td>
<td>0.985</td>
<td>0.821</td>
<td>0.149</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>36882</td>
<td>4803</td>
<td>0.989</td>
<td>0.821</td>
<td>0.158</td>
</tr>
</tbody>
</table>

Figure (6.7) presents the PDF and CDF for the best distribution fits, Weibull with two parameters. The parameters $\eta$ and $\beta$ of the Weibull distribution are presented in Table (6.3).

![Graph](image.png)

Figure 6.7: Weibull 2P distribution, PDF and CDF, specimens tested at $\sigma_{\text{max}} = 160$ MPa.
Figure (6.8) presents the CDF with a confidence interval of 95% for the Weibull 2P distribution.

![Graph showing Weibull 2P distribution]

Figure 6.8: Weibull 2P distribution, CDF with a confidence interval of 95%. $\sigma_{max}=160$ MPa.

### 6.3.1.4 $\sigma_{max} = 180$ MPa

Table (6.4) presents the statistical parameters estimated in software SuperSMITH Weibull, for the fatigue life of the specimens tested at $\sigma_{max}=180$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC²</th>
<th>$r^2$-CCC²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>29274.9</td>
<td>5.348</td>
<td>26984</td>
<td>5811</td>
<td>0.950</td>
<td>0.814</td>
<td>0.088</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>-48347.52</td>
<td>77591.8</td>
<td>15.898</td>
<td>75063</td>
<td>5803</td>
<td>0.961</td>
<td>0.909</td>
<td>0.015</td>
</tr>
<tr>
<td>LogNormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>27582</td>
<td>6401</td>
<td>0.913</td>
<td>0.821</td>
<td>0.012</td>
</tr>
<tr>
<td>Normal</td>
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<td>...</td>
<td>...</td>
<td>27123</td>
<td>5675</td>
<td>0.928</td>
<td>0.821</td>
<td>0.040</td>
</tr>
</tbody>
</table>

In Figure (6.9) are presented the PDF and CDF for the best distribution fits at $\sigma_{max}=180$ MPa, Lognormal distribution. Figure (6.10) presents the CDF with a confidence interval of 95%.

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Figure 6.9: Weibull 2P distribution PDF and CDF, specimens tested at $\sigma_{max} = 180$ MPa.

Figure 6.10: Weibull 2P distribution, CDF with a confidence interval of 95%. $\sigma_{max} = 180$ MPa.
6.3.1.5 $\sigma_{\text{max}} = 200$ MPa

Table (6.5) presents statistical parameters estimated in software SuperSMITH Weibull, for the fatigue life of the specimens tested at $\sigma_{\text{max}} = 200$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$.CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>20405.7</td>
<td>6,294</td>
<td>18981</td>
<td>3518</td>
<td>0,896</td>
<td>0,796</td>
<td>0,007</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>17071,0</td>
<td>2286.4</td>
<td>0,567</td>
<td>3721</td>
<td>7032</td>
<td>0,998</td>
<td>0,900</td>
<td>0,097</td>
</tr>
<tr>
<td>LogNormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>19317</td>
<td>3482</td>
<td>0,932</td>
<td>0,801</td>
<td>0,068</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>19117</td>
<td>3612</td>
<td>0,920</td>
<td>0,801</td>
<td>0,047</td>
</tr>
</tbody>
</table>

Table 6.5: Statistical parameters, normal hole specimens, $\sigma_{\text{max}} = 200$ MPa

Figure (6.11) presents the PDF and CDF for the best distribution fits, Lognormal.

![Figure 6.11: Lognormal distribution PDF and CDF, specimens tested at $\sigma_{\text{max}} = 200$ MPa.](image)

Figure 6.11: Lognormal distribution PDF and CDF, specimens tested at $\sigma_{\text{max}} = 200$ MPa.
Figure (6.10) presents the CDF with a confidence interval of 95% for the Lognormal distribution.

Figure 6.12: Lognormal distribution, CDF with a confidence interval of 95%. $\sigma_{max}=200$ MPa.

In Figures (6.13) and (6.14) are presented one general overview of the PDF and CDF respectively, for the different stress levels tested.
Figure 6.13: PDF for the stress levels, \( \sigma_{\text{max}} = 120, 140, 160, 180 \text{ and } 200 \text{ MPa.} \)
6.3.2 Cold worked open hole specimens

6.3.2.1 $\sigma_{\max} = 120$ MPa

Table (6.6) presents the statistical parameters estimated in software SuperSMITH Weibull, for the fatigue life of the specimens tested at $\sigma_{\max} = 120$ MPa.

Table 6.6: Statistical parameters, cold worked hole specimens, $\sigma_{\max} = 120$ MPa

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>r$^2$-CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>913427.6</td>
<td>1,500004</td>
<td>824594</td>
<td>559878</td>
<td>0.994</td>
<td>0.796</td>
<td>0.192</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>-1411152</td>
<td>2345980</td>
<td>4,90732</td>
<td>2151705</td>
<td>501253</td>
<td>1,000</td>
<td>0.900</td>
<td>0.100</td>
</tr>
<tr>
<td>LogNormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>927576</td>
<td>864445</td>
<td>0.980</td>
<td>0.801</td>
<td>0.161</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>754801</td>
<td>508870</td>
<td>0.999</td>
<td>0.801</td>
<td>0.199</td>
</tr>
</tbody>
</table>

Figure (6.15) presents the PDF and CDF for the best distribution fits, Normal.

![Figure 6.15: Normal distribution, PDF and CDF. Specimens tested at $\sigma_{\max} = 120$ MPa.](image)

As shown in Figure (6.15) this distribution does not seem to be the most suitable because it has the left tail in the negative side of the scale. Of course this behavior is not the most suitable to describe the specimens fatigue life. Because of this the use of the Weibull 2P which has the second best fit was adopted.
Figure (6.16) presents the PDF and CDF for Weibull 2P. The parameters $\eta$ and $\beta$ of the Weibull distribution are presented in Table (6.8).

In Figure (6.17) is shown the PDF and CDF comparison for the Normal and Weibull 2P distributions.

Figure 6.16: Weibull 2P distribution, PDF and CDF, specimens tested at $\sigma_{max} = 120$ MPa.

Figure 6.17: Weibull 2P versus Normal distribution. PDF and CDF, $\sigma_{max} = 120$ MPa.
The observation of the two last figures allow us to say that the Weibull 2P is the most suitable distribution because the Normal distribution has a residual failure life for 0 cycles.

Figure (6.18) presents the CDF with a confidence interval of 95 % for the Weibull 2P distribution.

Figure 6.18: Weibull 2P distribution, CDF with a confidence interval of 95 %. $\sigma_{\text{max}} = 120$ MPa.

6.3.2.2 $\sigma_{\text{max}} = 140$ MPa

Table (6.7) presents statistical parameters estimated in software SuperSMITH Weibull, for the fatigue life of the specimens tested at $\sigma_{\text{max}} = 140$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$-CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>225684,6</td>
<td>1,280765</td>
<td>209080</td>
<td>164483</td>
<td>0,973</td>
<td>0,814</td>
<td>0,133</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>-54198,01</td>
<td>282200,5</td>
<td>1,831881</td>
<td>250757</td>
<td>141882</td>
<td>0,977</td>
<td>0,909</td>
<td>0,046</td>
</tr>
<tr>
<td>Lognormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>243332</td>
<td>285830</td>
<td>0,960</td>
<td>0,821</td>
<td>0,101</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>185026</td>
<td>148166</td>
<td>0,965</td>
<td>0,821</td>
<td>0,110</td>
</tr>
</tbody>
</table>

In Figure (6.19) are presented the PDF and CDF for the best distribution fits at $\sigma_{\text{max}} = 140$ MPa, Weibull 2P distribution. Figure (6.20) presents the CDF with a confidence interval of 95 %.
Figure 6.19: Weibull 2P distribution PDF and CDF, specimens tested at $\sigma_{max} = 140$ MPa.

Figure 6.20: Weibull 2P distribution, CDF with a confidence interval of 95 %. $\sigma_{max} = 140$ MPa.
6.3.2.3 $\sigma_{max} = 160$ MPa

Table (6.8) presents statistical parameters estimated in software SuperSMITH Weibull, for the fatigue life of the specimens tested at $\sigma_{max} = 160$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$.CCC$^2$</th>
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</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>136628.6</td>
<td>3.269</td>
<td>122501</td>
<td>41219</td>
<td>0.979</td>
<td>0.796</td>
<td>0.163</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>47078</td>
<td>88649.8</td>
<td>1.900</td>
<td>78665</td>
<td>43071</td>
<td>0.980</td>
<td>0.900</td>
<td>0.060</td>
</tr>
<tr>
<td>Lognormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>85215</td>
<td>58880</td>
<td>0.969</td>
<td>0.801</td>
<td>0.138</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>122032</td>
<td></td>
<td>0.972</td>
<td>0.801</td>
<td>0.143</td>
</tr>
</tbody>
</table>

Figure (6.21) presents the PDF and CDF for the best distribution fits, Weibull with two parameters. The parameters $\eta$ and $\beta$ of the Weibull distribution are presented in Table (6.8).

![Weibull 2P distribution, PDF and CDF, specimens tested at $\sigma_{max} = 160$ MPa.](image)

Figure 6.21: Weibull 2P distribution, PDF and CDF, specimens tested at $\sigma_{max} = 160$ MPa.
Figure (6.22) presents the CDF with a confidence interval of 95 % for the Weibull 2P distribution.

![Graph showing CDF with confidence interval]

Figure 6.22: Weibull 2P distribution, CDF with a confidence interval of 95 %. $\sigma_{max} = 160$ MPa.

### 6.3.2.4 $\sigma_{max} = 180$ MPa

Table (6.9) presents statistical parameters estimated in software SuperSMITH Weibull, for the fatigue life of the specimens tested at $\sigma_{max} = 180$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$-CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>$\ldots$</td>
<td>58768,5</td>
<td>7,641</td>
<td>55221</td>
<td>8549</td>
<td>0,981</td>
<td>0,796</td>
<td>0,167</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>$\ldots$</td>
<td>136291,6</td>
<td>18,973</td>
<td>132504</td>
<td>8638</td>
<td>0,991</td>
<td>0,900</td>
<td>0,082</td>
</tr>
<tr>
<td>Lognormal</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>56120</td>
<td>8830</td>
<td>0,961</td>
<td>0,801</td>
<td>0,123</td>
</tr>
<tr>
<td>Normal</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>55678</td>
<td>8336</td>
<td>0,970</td>
<td>0,801</td>
<td>0,140</td>
</tr>
</tbody>
</table>

In Figure (6.23) are presented the PDF and CDF for the best distribution fits at $\sigma_{max} = 180$ MPa, Weibull 2P distribution. Figure (6.24) presents the CDF with a confidence interval of 95 %.
Figure 6.23: Weibull 2P distribution PDF and CDF, specimens tested at $\sigma_{max} = 180$ MPa.

Figure 6.24: Weibull 2P distribution, CDF with a confidence interval of 95 %. $\sigma_{max} = 180$ MPa.
6.3.2.5 \( \sigma_{\text{max}} = 200 \text{ MPa} \)

Table (6.10) presents the statistical parameters estimated in software SuperSMITH Weibull, for the fatigue life of the specimens tested at \( \sigma_{\text{max}} = 200 \text{ MPa} \).

Table 6.10: Statistical parameters, cold worked hole specimens, \( \sigma_{\text{max}} = 200 \text{ MPa} \)

<table>
<thead>
<tr>
<th></th>
<th>( \eta_0 )</th>
<th>( \eta )</th>
<th>( \beta )</th>
<th>( \mu )</th>
<th>( \sigma )</th>
<th>( r )</th>
<th>CCC(^2)</th>
<th>r(^2)-CCC(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>\ldots</td>
<td>31301,1</td>
<td>2,494</td>
<td>27771</td>
<td>11909</td>
<td>0,866</td>
<td>0,796</td>
<td>-0,046</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>-45869,0</td>
<td>76964,9</td>
<td>7,581</td>
<td>72290</td>
<td>11274</td>
<td>0,872</td>
<td>0,900</td>
<td>-0,139</td>
</tr>
<tr>
<td>Lognormal</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
<td>29598</td>
<td>15618</td>
<td>0,820</td>
<td>0,801</td>
<td>-0,129</td>
</tr>
<tr>
<td>Normal</td>
<td>\ldots</td>
<td>\ldots</td>
<td>\ldots</td>
<td>26950</td>
<td>11240</td>
<td>0,831</td>
<td>0,801</td>
<td>-0,110</td>
</tr>
</tbody>
</table>

Figure (6.25) presents the PDF and CDF for the best distribution fits, Weibull 2P.

![Figure 6.25: Lognormal distribution PDF and CDF, specimens tested at \( \sigma_{\text{max}} = 200 \text{ MPa} \).](image-url)
Figure (6.26) presents the CDF with a confidence interval of 95 % for the Weibull 2P distribution.

Figure 6.26: Weibull distribution, CDF with a confidence interval of 95 %. $\sigma_{max} =$ 200 MPa.

In Figures (6.27) and (6.28) are presented one general overview of the PDF and CDF respectively, for the different stress levels tested.
Figure 6.27: PDF for the stress levels, $\sigma_{\text{max}} = 120, 140, 160, 180$ and 200 MPa.
Figure 6.28: CDF for the stress levels, $\sigma_{max} = 120, 140, 160, 180$ and $200$ MPa.
6.4 Critical crack size statistical data analysis

6.4.1 Normal open hole specimens

6.4.1.1 $\sigma_{\text{max}} = 120$ MPa

Table (6.11) presents statistical parameters estimated in software SuperSMITH Weibull, for the critical crack size of the specimens tested at $\sigma_{\text{max}} = 120$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$-CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>14,161</td>
<td>10,458</td>
<td>13,500</td>
<td>1,556</td>
<td>0,954</td>
<td>0,814</td>
<td>0,096</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>-18,760</td>
<td>32,914</td>
<td>25,606</td>
<td>32,220</td>
<td>1,570</td>
<td>0,959</td>
<td>0,909</td>
<td>0,011</td>
</tr>
<tr>
<td>LogNormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>13,645</td>
<td>1,587</td>
<td>0,926</td>
<td>0,821</td>
<td>0,037</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>13,588</td>
<td>1,502</td>
<td>0,936</td>
<td>0,821</td>
<td>0,056</td>
</tr>
</tbody>
</table>

Figure (6.29) presents the PDF and CDF for the best distribution fits, Lognormal.

![Figure 6.29: Weibull 2P distribution PDF and CDF, specimens tested at $\sigma_{\text{max}} = 120$ MPa.](image-url)
Figure (6.30) presents the CDF with a confidence interval of 95 % for the Weibull 2P distribution.

![Graph showing CDF with a confidence interval](image)

Figure 6.30: Lognormal distribution, CDF with a confidence interval of 95 %. $\sigma_{\text{max}}$=120 MPa.

### 6.4.1.2 $\sigma_{\text{max}}$ = 140 MPa

Table (6.12) presents statistical parameters estimated in software SuperSMITH Weibull, for the critical crack size of the specimens tested at $\sigma_{\text{max}}$ = 140 MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>$\text{CCC}^2$</th>
<th>$r^2$-$\text{CCC}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>$\ldots$</td>
<td>12,826</td>
<td>13,799</td>
<td>12,350</td>
<td>1,094</td>
<td>0.976</td>
<td>0.814</td>
<td>0.139</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>0.589</td>
<td>12,236</td>
<td>13,141</td>
<td>11,760</td>
<td>1,092</td>
<td>0.977</td>
<td>0.909</td>
<td>0.045</td>
</tr>
<tr>
<td>Lognormal</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>12,453</td>
<td>1,080</td>
<td>0.962</td>
<td>0.821</td>
<td>0.105</td>
</tr>
<tr>
<td>Normal</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>$\ldots$</td>
<td>12,426</td>
<td>1,061</td>
<td>0.964</td>
<td>0.821</td>
<td>0.109</td>
</tr>
</tbody>
</table>

In Figure (6.31) are presented the PDF and CDF for the best distribution fits at $\sigma_{\text{max}}$ = 140 MPa, Weibull 2P distribution. Figure (6.32) presents the CDF with a confidence interval of 95 %.
Figure 6.31: Weibull 2P distribution PDF and CDF, specimens tested at $\sigma_{\text{max}} = 140$ MPa.

Figure 6.32: Weibull 2P distribution, CDF with a confidence interval of 95%. $\sigma_{\text{max}} = 140$ MPa.
6.4.1.3 \( \sigma_{\text{max}} = 160 \text{ MPa} \)

Table (6.13) presents statistical parameters estimated in software SuperSMITH Weibull, for the critical crack size of the specimens tested at \( \sigma_{\text{max}} = 160 \text{ MPa} \).

<table>
<thead>
<tr>
<th></th>
<th>( \eta_0 )</th>
<th>( \eta )</th>
<th>( \beta )</th>
<th>( \mu )</th>
<th>( \sigma )</th>
<th>( r )</th>
<th>CCC(^2)</th>
<th>r(^2)-CCC(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>11,135</td>
<td>8,031</td>
<td>10,490</td>
<td>1,550</td>
<td>0.980</td>
<td>0.814</td>
<td>0.146</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>8,469</td>
<td>2,508</td>
<td>1,448</td>
<td>2,275</td>
<td>1,596</td>
<td>0.997</td>
<td>0.909</td>
<td>0.086</td>
</tr>
<tr>
<td>Lognormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>10,627</td>
<td>1,545</td>
<td>0.993</td>
<td>0.821</td>
<td>0.165</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>10,566</td>
<td>1,545</td>
<td>0.990</td>
<td>0.821</td>
<td>0.159</td>
</tr>
</tbody>
</table>

Figure (6.33) presents the PDF and CDF for the best distribution fits, Lognormal.

Figure 6.33: Lognormal distribution, PDF and CDF, specimens tested at \( \sigma_{\text{max}} = 160 \text{ MPa} \).
Figure (6.34) presents the CDF with a confidence interval of 95% for the Weibull 2P distribution.

![Graph showing CDF with confidence interval]

Figure 6.34: Weibull 2P distribution, CDF with a confidence interval of 95%. $\sigma_{\text{max}} = 160$ MPa.

### 6.4.1.4 $\sigma_{\text{max}} = 180$ MPa

Table (6.14) presents statistical parameters estimated in software SuperSMITH Weibull, for the critical crack size of the specimens tested at $\sigma_{\text{max}} = 180$ MPa.

| Table 6.14: Statistical parameters, normal hole specimens, 180 MPa |
|---|---|---|---|---|---|---|---|
|   | $\eta_0$ | $\eta$ | $\beta$ | $\mu$ | $\sigma$ | $r$ | CCC$^2$ | $r^2$-CCC$^2$ |
| Weibull 2P | … | 10,831 | 19,758 | 10,540 | 0.661 | 0.964 | 0.814 | 0.115 |
| Weibull 3P | -18,060 | 28,892 | 54,586 | 28,600 | 0.663 | 0.970 | 0.909 | 0.032 |
| Lognormal | … | … | … | 10,602 | 0.649 | 0.939 | 0.821 | 0.060 |
| Normal | … | … | … | 10,590 | 0.636 | 0.942 | 0.821 | 0.067 |

In Figure (6.35) are presented the PDF and CDF for the best distribution fits at $\sigma_{\text{max}} = 180$ MPa, Weibull 2P distribution. Figure (6.36) presents the CDF with a confidence interval of 95%.
Figure 6.35: Weibull 2P distribution PDF and CDF, specimens tested at $\sigma_{\text{max}} = 180$ MPa.

Figure 6.36: Weibull 2P distribution, CDF with a confidence interval of 95%. $\sigma_{\text{max}} = 180$ MPa.
6.4.1.5 $\sigma_{\text{max}} = 200$ MPa

Table (6.15) presents statistical parameters estimated in software SuperSMITH Weibull, for the fatigue life of the specimens tested at $\sigma_{\text{max}} = 200$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$-CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>10,589</td>
<td>8,125</td>
<td>9,980</td>
<td>1,459</td>
<td>0.973</td>
<td>0.796</td>
<td>0.151</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>8,260</td>
<td>2,186</td>
<td>1,359</td>
<td>2,002</td>
<td>1,359</td>
<td>0.995</td>
<td>0.900</td>
<td>0.091</td>
</tr>
<tr>
<td>LogNormal</td>
<td>...</td>
<td>...</td>
<td>10,125</td>
<td>1,443</td>
<td>0.988</td>
<td>0.801</td>
<td>0.175</td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>10,063</td>
<td>1,456</td>
<td>0.982</td>
<td>0.801</td>
<td>0.165</td>
<td></td>
</tr>
</tbody>
</table>

Figure (6.37) presents the PDF and CDF for the best distribution fits, Lognormal.

![Figure 6.37: Lognormal distribution PDF and CDF, specimens tested at $\sigma_{\text{max}} = 200$ MPa.](image)

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Figure (6.38) presents the CDF with a confidence interval of 95 % for the Lognormal distribution.

Figure 6.38: Lognormal distribution, CDF with a confidence interval of 95 %. $\sigma_{\text{max}}=200 \text{ MPa}$.

A general overview of PDF and CDF for the different stress levels tested, is presented in Figures (6.39) and (6.40) respectively.
Figure 6.39: Normalized PDF for the stress levels, $\sigma_{max} = 120, 140, 160, 180$ and 200 MPa.
Figure 6.40: CDF for the stress levels, $\sigma_{\text{max}} = 120, 140, 160, 180$ and $200$ MPa.
6.4.2 Cold worked open hole specimens

6.4.2.1 $\sigma_{\text{max}} = 120$ MPa

Table (6.16) presents statistical parameters estimated in software SuperSMITH Weibull, for the critical crack size of the specimens tested at $\sigma_{\text{max}} = 120$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$-CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>14,395</td>
<td>10,062</td>
<td>13,700</td>
<td>1,638</td>
<td>0,949</td>
<td>0,773</td>
<td>0,128</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>-73,040</td>
<td>87,426</td>
<td>65,898</td>
<td>86,680</td>
<td>1,668</td>
<td>0,961</td>
<td>0,887</td>
<td>0,037</td>
</tr>
<tr>
<td>LogNormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>13,893</td>
<td>1,664</td>
<td>0,925</td>
<td>0,773</td>
<td>0,083</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>13,820</td>
<td>1,609</td>
<td>0,929</td>
<td>0,773</td>
<td>0,090</td>
</tr>
</tbody>
</table>

Figure (6.41) presents the PDF and CDF for the best distribution fits, Weibull 2P.

Figure 6.41: Weibull 2P distribution PDF and CDF, specimens tested at $\sigma_{\text{max}} = 120$ MPa.
Figure (6.42) presents the CDF with a confidence interval of 95% for the Weibull 2P distribution.

![Graph showing CDF and Weibull 2P distribution](image)

Figure 6.42: Lognormal distribution, CDF with a confidence interval of 95%. $\sigma_{\text{max}}$=120 MPa.

### 6.4.2.2 $\sigma_{\text{max}} = 140$ MPa

Table (6.17) presents statistical parameters estimated in software SuperSMITH Weibull, for the critical crack size of the specimens tested at $\sigma_{\text{max}} = 140$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$-CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>13,253</td>
<td>3,818</td>
<td>11,980</td>
<td>3,505</td>
<td>0,942</td>
<td>0,814</td>
<td>0,073</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>-242.8</td>
<td>256,013</td>
<td>95,655</td>
<td>254,500</td>
<td>3,386</td>
<td>0,985</td>
<td>0,909</td>
<td>0,061</td>
</tr>
<tr>
<td>Lognormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>12,371</td>
<td>4,065</td>
<td>0,907</td>
<td>0,821</td>
<td>0,002</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>11,968</td>
<td>3,522</td>
<td>0,912</td>
<td>0,821</td>
<td>0,011</td>
</tr>
</tbody>
</table>

In Figure (6.43) are presented the PDF and CDF for the best distribution fits at $\sigma_{\text{max}} = 140$ MPa, Weibull 2P distribution. Figure (6.32) presents the CDF with a confidence interval of 95%.
Figure 6.43: Weibull 2P distribution PDF and CDF, specimens tested at $\sigma_{max} = 140$ MPa.

Figure 6.44: Weibull 2P distribution, CDF with a confidence interval of 95 %. $\sigma_{max} = 140$ MPa.
6.4.2.3 $\sigma_{\text{max}} = 160$ MPa

Table 6.18 presents statistical parameters estimated in software SuperSMITH Weibull, for the critical crack size of the specimens tested at $\sigma_{\text{max}} = 160$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$-CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>12,902</td>
<td>20,787</td>
<td>12,570</td>
<td>0,750</td>
<td>0,914</td>
<td>0,796</td>
<td>0,039</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>12,110</td>
<td>0,643</td>
<td>0,823</td>
<td>0,714</td>
<td>0,873</td>
<td>0,989</td>
<td>0,900</td>
<td>0,078</td>
</tr>
<tr>
<td>LogNormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>12,647</td>
<td>0,690</td>
<td>0,943</td>
<td>0,801</td>
<td>0,089</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>12,635</td>
<td>0,700</td>
<td>0,940</td>
<td>0,801</td>
<td>0,083</td>
</tr>
</tbody>
</table>

Figure (6.45) presents the PDF and CDF for the best distribution fits, Lognormal.

![Lognormal distribution, PDF and CDF, specimens tested at $\sigma_{\text{max}} = 160$ MPa.](image-url)

Figure 6.45: Lognormal distribution, PDF and CDF, specimens tested at $\sigma_{\text{max}} = 160$ MPa.
Figure (6.46) presents the CDF with a confidence interval of 95 % for the Lognormal distribution.

![Lognormal Distribution Graph](image)

Figure 6.46: Lognormal distribution, CDF with a confidence interval of 95 %. $\sigma_{max}=160$ MPa.

### 6.4.2.4 $\sigma_{max} = 180$ MPa

Table (6.4) presents statistical parameters estimated in software SuperSMITH Weibull, for the critical crack size of the specimens tested at $\sigma_{max} = 180$ MPa.

<table>
<thead>
<tr>
<th></th>
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<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$.CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>12,290</td>
<td>9,943</td>
<td>11,690</td>
<td>1,413</td>
<td>0,865</td>
<td>0,796</td>
<td>-0,047</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>11,120</td>
<td>0,619</td>
<td>0,406</td>
<td>1,973</td>
<td>6,040</td>
<td>0,999</td>
<td>0,900</td>
<td>0,099</td>
</tr>
<tr>
<td>Lognormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>11,825</td>
<td>1,332</td>
<td>0,907</td>
<td>0,801</td>
<td>0,022</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>11,775</td>
<td>1,370</td>
<td>0,901</td>
<td>0,801</td>
<td>0,011</td>
</tr>
</tbody>
</table>

In Figure (6.47) are presented the PDF and CDF for the best distribution fits at $\sigma_{max} = 180$ MPa, Lognormal distribution. Figure (6.48) presents the CDF with a confidence interval of 95 %.
Figure 6.47: Lognormal distribution PDF and CDF, specimens tested at $\sigma_{\text{max}}=180$ MPa.

Figure 6.48: Lognormal distribution, CDF with a confidence interval of 95 %. $\sigma_{\text{max}}=180$ MPa.
$\sigma_{\text{max}} = 200$ MPa

Table (6.20) presents statistical parameters estimated in software SuperSMITH Weibull, for the fatigue life of the specimens tested at $\sigma_{\text{max}} = 200$ MPa.

<table>
<thead>
<tr>
<th></th>
<th>$\eta_0$</th>
<th>$\eta$</th>
<th>$\beta$</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>$r$</th>
<th>CCC$^2$</th>
<th>$r^2$-CCC$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weibull 2P</td>
<td>...</td>
<td>12,202</td>
<td>25,202</td>
<td>11,940</td>
<td>0,591</td>
<td>0,970</td>
<td>0,796</td>
<td>0,144</td>
</tr>
<tr>
<td>Weibull 3P</td>
<td>1,475</td>
<td>10,726</td>
<td>22,076</td>
<td>10,470</td>
<td>0,589</td>
<td>0,970</td>
<td>0,900</td>
<td>0,040</td>
</tr>
<tr>
<td>LogNormal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>12,001</td>
<td>0,573</td>
<td>0,944</td>
<td>0,801</td>
<td>0,090</td>
</tr>
<tr>
<td>Normal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>11,993</td>
<td>0,565</td>
<td>0,946</td>
<td>0,801</td>
<td>0,095</td>
</tr>
</tbody>
</table>

Figure (6.49) presents the PDF and CDF for the best distribution fits, Weibull 2P.

Figure 6.49: Weibull 2P distribution PDF and CDF, specimens tested at $\sigma_{\text{max}} = 200$ MPa.
Figure (6.50) presents the CDF with a confidence interval of 95% for the Weibull 2P distribution.

![Weibull 2P CDF](image)

Figure 6.50: Lognormal distribution, CDF with a confidence interval of 95%. $\sigma_{max} = 200$ MPa.

A general overview of PDF and CDF for the different stress levels tested, is presented in Figures (6.51) and (6.52) respectively.
Figure 6.51: Normalized PDF for the stress levels, $\sigma_{max} = 120, 140, 160, 180$ and $200 \text{ MPa}$. 
Figure 6.52: CDF for the stress levels, $\sigma_{\text{max}} = 120, 140, 160, 180$ and 200 MPa.
6.5 Summary

1. For both open hole specimens with and without residual stresses, Lognormal and Weibull 2P distributions were applied to all tested stress levels in order to analyze fatigue life and critical crack size data.

2. The Weibull distribution showed good versatility, due to its good adjustment to different shapes.

3. The results obtained are in agreement with literature, because these two distribution types are the most commonly used to statistically analyze fatigue test data analysis.

4. The Weibull 3P distribution was not considered because in fatigue life problems a minimum life limit cannot be imposed and also because the number of samples required is at least 20, larger than that available in the present test program.
Chapter 7

Conclusions and future work

7.1 Conclusions

Along the present work several conclusions were drawn. The most relevant are the following:

- Basic fatigue S-N test results were presented for normal and cold worked open hole specimens of Al alloy 2024 T3-Alclad;

- For each stress level, fatigue lives of cold worked specimens are higher than those of non-cold worked specimens. Larger differences were found for lower stress levels. For higher stress levels the fatigue lives of cold worked and normal specimens are very similar. The trend is the decrease of the beneficial effect of the residual stress as the stress level increase;

- The residual stress effect consists on the increase of the fatigue life. This effect decreases with increasing external applied stress level. In the present tests, a factor of approximately 1.5 to 6.5 was found when comparing cold worked specimens with specimens of the same geometry without residual stresses;

- An empirical correlation between the maximum applied stress level and fatigue life increase in cold worked specimens was proposed;

- Two and three dimensional finite element analyses of the hole cold expansion process were presented, using two different types of material behaviour: elastic perfectly plastic and hardening material;

- Experimental measurements of the residual stress field profile were performed using the X-ray technique;

- An axisymmetric finite element simulation of cold working with different boundary conditions was presented. The bending effect has larger influence at the entrance face, being almost inexistent in the mid-thickness plane, as expected. The radial and axial deformation of the hole surface were presented and quantified for the uniform hole expansion and the cold working process;
• Two dimensional analyses showed that the residual stresses in the region near the hole predicted using the real geometry model or a cylindrical 2D model simulating an "infinite" domain are very close;

• The results of the cold working simulation were compared with the simplified uniform hole cold expansion applied to the hole surface, and it was concluded that the residual stresses due to the hole cold expansion can be estimated accurately only by using a realistic simulation of the cold working process;

• Agreement between 3D and 2D analysis was found for the mid-thickness plane of the plate only;

• 2D axisymmetric FEA overestimates maximum tensile and compressive stress values in the near hole. Larger differences between 2D axisymmetric model and 3D real model were found at the entrance face;

• 2D axisymmetric FEA overestimates the permanent hole enlargement and axial deformation by comparison with the 3D real model;

• Using the experimental X-ray technique inevitably the stresses are averaged over the irradiated volume. Therefore it is not possible to resolve the steep stress gradients in the vicinity of the hole, and the peak values predicted by finite element simulation result underestimated;

• The results from the cold working finite element simulations presented seem to be in general agreement with experimental results;

• The weight function technique was used for the calculation of the residual stress intensity factors, which are used for the $\Delta K$ calculation in the crack growth process;

• Crack propagation measurements based on macroscopic techniques were presented;

• For the lower values of $\Delta K$ in the specimens with cold work a behaviour of increasing $da/dN$ with the decreasing of $\Delta K$ was found. Similar behaviour is reported in the literature as typical in short fatigue cracks;

• Fatigue striation spacing measurements for normal and cold worked hole were presented. It was observed that fatigue striation spacing increase with the increase in crack length;

• Fatigue striations spacing for specimens with cold work are smaller along the crack length and depth, by comparison with normal hole specimens. With the presented data it was possible to state a general quantitative law for all the specimens measured;

• Micro and macro crack growth measurements are not in perfect agreement but they show the trend reported in literature [79, 71, 58], that $s<\text{CGR}$ in the region of high crack grow rate, which is the case of the present work because macro measurements were possible just in a very short period close to the final rupture moment;
• The quantitative microfractography of fracture surfaces was used: the SEM measurements of striation spacing have afforded the input data for fractographic reconstitution of fatigue crack growth. Two different approaches were confronted: a simplified presumption \( v = da/dN = s \) (i.e., \( D=1 \)), and more realistic supposition that the ratio \( v/s \) is not constant, i.e., \( D=D(s) \);

• Results of fractographic reconstitution of the fatigue crack growth offers a plausible evaluation of the movement of a short segment of crack front propagating along the longitudinal axis of bearing section of the specimen. This information, attainable only by help of fractography, yields a new piece of knowledge about the effect of the hole cold expansion: it seems that the main source of specimen life prolongation is not a longer crack initiation time, but an intensive braking of early crack growth stage, by effect of the field of residual stresses;

• Large differences were not found between \( D=1 \) and \( D = D(s) \) CGR measurements from fatigue striations judged as valid;

• CGR measurements obtained using SEM measurements are very close to data of the literature references presented;

• In the case of normal hole specimens the residual strength values are bellow the net section yield lines, which implies the failure criterion is therefore in the field of Fracture Mechanics. For the data presented the net section collapse procedure could be taken as a rough estimation, of the specimens' behaviour, which improves for the higher stress levels tested. In the case of cold worked hole specimens the net section collapse procedure would be a reasonable estimation for the higher stress levels tested;

• For both open hole specimens with and without residual stresses, Lognormal and Weibull 2P distributions were applied to all tested stress levels in order to analyze fatigue life and critical crack size data;

• The Weibull distribution showed good versatility, due to its good adjustment to different shapes;

• The results obtained are in agreement with literature, because these two distribution types are the most commonly used to statistically analyze fatigue test data.
7.2 Future work

During the course of this work, the following items were considered worthy of future work:

- The use of friction in the 3D FEA analysis of the cold-working process;

- The use of other experimental techniques as the Sachs method or neutron diffraction method for the residual stress profile measurement;

- The use of a more powerful video technique for the crack growth measurement;

- Although SEM, as used in this work, provides some insight into the initial fatigue cracking stage, a more detailed study of fatigue short cracks behaviour should be carried out. (in some cases of CGR measurements for the lower values of $\Delta K$ a behaviour of increasing $da/dN$ with the decreasing of $\Delta K$ was found, similar to that reported in the literature [50, 57] as typical in short fatigue cracks);

- The use of R-curve concepts for more accurate $K_c$ estimation.
Bibliography


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Appendix A

Tensile tests

A.1 Introduction

Four tensile tests were performed in order to determine the tensile properties of the material (0.2% yield strength, rupture strength and Young modulus). The tensile test specimens were manufactured from specimens 4.4, 4.5, 7.6, 10.5 previously fatigue tested. The Portuguese standard NP EN 10002-1 was used. The specimen geometry and dimensions are shown in Figure (A.1).

Figure A.1: Tensile specimen geometry.
A.2 Tensile tests results

Figure (A.2) shows the record of $\sigma$ vs $\varepsilon$ for the specimen 4.4.

![Graph showing tensile test results](image)

Figure A.2: Record $\sigma$ vs $\varepsilon$, specimen 4.4.

The tensile tests results are presented in Table (A.1).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Modulus of Elasticity [MPa]</th>
<th>Rupture strength [MPa]</th>
<th>Yield strength $0.2%$ [MPa]</th>
<th>Elongation [%]</th>
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</thead>
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<tr>
<td>4.4</td>
<td>78366</td>
<td>440</td>
<td>311</td>
<td>18</td>
</tr>
<tr>
<td>4.5</td>
<td>78425</td>
<td>438</td>
<td>311</td>
<td>17</td>
</tr>
<tr>
<td>7.6</td>
<td>83285</td>
<td>436</td>
<td>310</td>
<td>17</td>
</tr>
<tr>
<td>10.5</td>
<td>82259</td>
<td>440</td>
<td>311</td>
<td>16</td>
</tr>
</tbody>
</table>

Table A.1: Tensile test properties
Appendix B

Specimens geometric characterization

B.1 Introduction

In order to have detailed information on the specimens geometry, specimens were measured in three sections as shown in Figure (B.1). Measurements on sections 1 and 3 give information about the specimen alignment with the load cell and the actuator. Measurements in section 2 give information about the hole dimension and alignment.

B.1.1 Normal open hole specimens

Table (B.1) presents the values of $A_2$, $\phi_2$ and $B_2$ measured on section 2 (Figure (B.1)) on the normal open hole specimens.

<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>Dimensions [mm]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_2$</td>
<td>$\phi_2$</td>
</tr>
<tr>
<td>4.1</td>
<td>10,208</td>
<td>5,015</td>
</tr>
<tr>
<td>4.2</td>
<td>10,145</td>
<td>5,018</td>
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<td>10,135</td>
<td>5,040</td>
</tr>
<tr>
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<td>10,025</td>
<td>4,996</td>
</tr>
<tr>
<td>4.5</td>
<td>9,904</td>
<td>5,018</td>
</tr>
<tr>
<td>5.1</td>
<td>10,128</td>
<td>5,009</td>
</tr>
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<td>10,155</td>
<td>5,012</td>
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<td>10,111</td>
<td>5,013</td>
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<td>10,386</td>
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<td>10,421</td>
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<td>6.5</td>
<td>10,363</td>
<td>5,020</td>
</tr>
</tbody>
</table>
Figure B.1: Geometric characterization of the sections 1, 2 and 3.

Table B.2: Normal open hole specimens dimensions, section 2 (cont.)

<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>Dimensions [mm]</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A₂</td>
<td>φ₂</td>
<td>B₂</td>
<td>Total</td>
</tr>
<tr>
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<td>10,473</td>
<td>5,075</td>
<td>9,548</td>
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</tr>
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</tr>
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<td>25,181</td>
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<td>5,071</td>
<td>9,984</td>
<td>24,802</td>
</tr>
</tbody>
</table>

Table (B.3) shows values of A₁, φ₁, B₁ and A₃, φ₃, B₃, measured on sections 1 and 3 (Figure (2.6)) on the normal open hole specimens.
<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>(section 1) Dimensions [mm]</th>
<th>(section 3) Dimensions [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A₁</td>
<td>φ₁</td>
</tr>
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<td>9,401</td>
<td>6,238</td>
</tr>
<tr>
<td>4.2</td>
<td>9,445</td>
<td>6,127</td>
</tr>
<tr>
<td>4.3</td>
<td>9,412</td>
<td>6,164</td>
</tr>
<tr>
<td>4.4</td>
<td>9,361</td>
<td>6,172</td>
</tr>
<tr>
<td>4.5</td>
<td>9,436</td>
<td>6,111</td>
</tr>
<tr>
<td>5.1</td>
<td>9,436</td>
<td>6,177</td>
</tr>
<tr>
<td>5.2</td>
<td>9,448</td>
<td>6,057</td>
</tr>
<tr>
<td>5.3</td>
<td>9,413</td>
<td>6,109</td>
</tr>
<tr>
<td>5.4</td>
<td>9,362</td>
<td>6,102</td>
</tr>
<tr>
<td>5.5</td>
<td>9,329</td>
<td>6,239</td>
</tr>
<tr>
<td>6.1</td>
<td>9,410</td>
<td>6,152</td>
</tr>
<tr>
<td>6.2</td>
<td>9,399</td>
<td>6,141</td>
</tr>
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<td>9,417</td>
<td>6,173</td>
</tr>
<tr>
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<tr>
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</tr>
<tr>
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</tr>
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<td>5.1</td>
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<td>6,102</td>
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<td>6,239</td>
</tr>
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<td>6.1</td>
<td>9,410</td>
<td>6,152</td>
</tr>
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<td>6.2</td>
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<td>6,173</td>
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<td>6,130</td>
</tr>
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<td>6.5</td>
<td>9,444</td>
<td>6,128</td>
</tr>
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</tr>
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</tr>
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</table>
B.1.2 Cold worked open hole specimens

Table (B.4) presents the values of $A_2$, $\phi_2$ and $B_2$ measured on section 2 (Figure (B.1)) on the cold worked open hole specimens.

<table>
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<th>Specimen Nr.</th>
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<th>B_2</th>
<th>Total</th>
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<td>4,808</td>
<td>9,924</td>
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<tr>
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<td>9,970</td>
<td>25,079</td>
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<td>4,823</td>
<td>9,974</td>
<td>25,118</td>
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<tr>
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<td>9,952</td>
<td>25,097</td>
</tr>
<tr>
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<td>4,989</td>
<td>9,786</td>
<td>25,022</td>
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<td>4,773</td>
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<td>25,012</td>
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</table>

Table (B.5) shows values of $A_1$, $\phi_1$, $B_1$ and $A_3$, $\phi_3$, $B_3$, measured on sections 1 and 3 (Figure (2.6)) on the cold worked open hole specimens.
<table>
<thead>
<tr>
<th>Specimen Nr.</th>
<th>(section 1) Dimensions [mm]</th>
<th>(section 3) Dimensions [mm]</th>
</tr>
</thead>
<tbody>
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<td>A1</td>
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<td>6,364</td>
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<td>9,252</td>
<td>6,113</td>
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<td>6,073</td>
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<td>6,161</td>
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<tr>
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<td>6,136</td>
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<td>6,090</td>
</tr>
<tr>
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<td>9,373</td>
<td>6,108</td>
</tr>
</tbody>
</table>
Appendix C

Clad thickness measurements using metallographic techniques

C.1 Introduction

The aim of this work is the determination of the clad (pure Al) thickness in the open hole specimens represented in Figure (2.1). The specimens material is the Alclad aluminium alloy 2024-T3.

C.2 Metallographic procedure

In the metallographic analysis of clad thickness was cut a piece of material from the open hole specimen - part A, Figure (C.1) was cut. This part A was divided in two pieces to use two different etchants.

According to reference [89] there are several etchants that can be used to identify and differentiate the microstructure of aluminium alloys. In Table (C.1) the etchants used in this work are presented.

<table>
<thead>
<tr>
<th>Etchant</th>
<th>Composition</th>
<th>Procedure for use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - HF etch</td>
<td>1 mL HF (48%), 200mL H₂O</td>
<td>immerse for 30-45 s</td>
</tr>
<tr>
<td>2 - Keller’s reagent</td>
<td>2 mL HF (48%), 3mL HCl (conc), 5 mL HNO₃(conc), 190 mL H₂O</td>
<td>immerse for 8-15 s, wash in stream of warm water, blow dry.</td>
</tr>
</tbody>
</table>

In reference [89] the etchant 2, Table (C.1), is specified as having special application for the examination of the clad thickness in the Alclad Aluminum alloy 2024-T3. The etchant 1 can be used in general examination of constituent size and distribution.

C.2.1 Results obtained with HF etchant

Figures (C.2) and (C.3) present the results obtained using the HF etchant. In both figures we can identify two different regions can be identified: a light grey region corresponding to
the layer of Alclad (pure Al) and a darker region corresponding to the attacked aluminium alloy. The boundary grain between the two parts is also visible.

Figure C.2: Metallographic observation of the specimen with the HF etchant. ×20 amplification.

For each one of the last two figures the measurement of the clad layer thickness was done in three different points. The results are presented in Table (C.2).
Figure C.3: Metallographic observation of the specimen with the HF etchant. ×50 amplification.

<table>
<thead>
<tr>
<th>Measurement Nr.</th>
<th>Figure (C.2) [μm]</th>
<th>Figure (C.3) [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41,724</td>
<td>39,200</td>
</tr>
<tr>
<td>2</td>
<td>42,261</td>
<td>42,667</td>
</tr>
<tr>
<td>3</td>
<td>38,255</td>
<td>40,533</td>
</tr>
<tr>
<td>Mean values</td>
<td>40,747</td>
<td>40,800</td>
</tr>
</tbody>
</table>

From Table (C.2) we can conclude that using the HF etchant the clad thickness is approximately 41 μm.

### C.2.2 Results obtained with Keller’s reagent

In Figures (C.4) and (C.5) are presented the observations made with Keller’s etchant. As in the HF etchant, we can differentiate two main regions. Using this etchant the boundary grain between this regions is not so pronounced.
Figure C.4: Metallographic observation of the specimen with Keller's etchant. ×20 amplification.

Figure C.5: Metallographic observation of the specimen with Keller's etchant. ×50 amplification.
The measurement of the clad layer thickness of Figures (C.4) and (C.5) was also done in three different points. The results are presented in Table (C.3).

Table C.3: Measurements of the clad thickness in the Figures (C.4) and (C.5).

<table>
<thead>
<tr>
<th>Measurement Nr.</th>
<th>Figure (C.4) [µm]</th>
<th>Figure (C.5) [µm]</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>42,149</td>
<td>40,533</td>
</tr>
<tr>
<td>3</td>
<td>44,040</td>
<td>41,600</td>
</tr>
<tr>
<td>Mean value</td>
<td>44,327</td>
<td>41,422</td>
</tr>
</tbody>
</table>

From Table (C.3) we can conclude that using the Keller’s etchant the clad thickness is approximately 43 µm.

C.2.3 Discussion and conclusions

The metallographic observation of the clad thickness in the open hole specimens was well succeeded. The layer of clad was observed with two etchants. In reference [89] the Keller’s reagent is specified as being the appropriate etchant for examination of the clad thickness. However that observation was more evident using the HF etchant. Using the HF etchant the chemical attack of Aluminium alloy was stronger. Consequently the contrast between the Aluminium alloy and the Aluminium clad was more pronounced.

After this work we estimate that the Alclad thickness in the open hole specimens is approximately 41µm.
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Appendix D

SEM analysis

D.1 Introduction

The Scanning Electron Microscopy (SEM) + Field Emission Gun (FEG) analysis was carried out at CEMUP, a laboratory of the University of Porto dedicated to electron microscopy.

D.2 Fatigue striation measurements

Figure (D.1) presents schematically of the measurements performed in the fatigue crack area for determination of fatigue striation spacing, reference [72].

![Figure D.1: Longitudinal and transversal directions of measurement.](image)

The fatigue striation measurements were carried out in two specimens for each stress level, one without cold work and other with cold work. Table (D.1) presents the specimens used.

<table>
<thead>
<tr>
<th>$\sigma_{max}$ [MPa]</th>
<th>without cold work</th>
<th>with cold work</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>8.5</td>
<td>10.1</td>
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<td>7.5</td>
<td>7.1</td>
</tr>
<tr>
<td>160</td>
<td>7.3</td>
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<td>7.5</td>
</tr>
<tr>
<td>200</td>
<td>7.1</td>
<td>8.6</td>
</tr>
</tbody>
</table>
D.2.1 Normal hole specimens

4.2.1.1 Specimen 8.5, $\sigma_{max} = 120$ MPa

In specimen 8.5 the measurements were done on the right side crack, Figure (D.2). Tables (D.2) to (D.4) present the coordinate values and the fatigue striation spacing in the points where the measurements were done. Figures (D.3) and (D.4) present some fractographs taken with SEM+FEG for this specimen.

![Fatigue crack right side, specimen 8.5.](image)

Table D.2: Fatigue striation spacing, specimen 8.5 without cold work. $\sigma_{max}$=120 MPa, measurements in the longitudinal direction

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [$\mu$m]</th>
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<tr>
<td></td>
<td>1</td>
</tr>
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<td>1 x= 0.03 y= 0.89</td>
<td>0.1273</td>
</tr>
<tr>
<td>2 x= 0.19 y= 0.91</td>
<td>0.1039</td>
</tr>
<tr>
<td>3 x= 0.16 y= 1.00</td>
<td>0.1375</td>
</tr>
<tr>
<td>4 x= 0.25 y= 0.90</td>
<td>0.1047</td>
</tr>
<tr>
<td>5 x= 0.28 y= 0.99</td>
<td>0.1308</td>
</tr>
<tr>
<td>6 x= 0.32 y= 0.91</td>
<td>0.0852</td>
</tr>
</tbody>
</table>
Table D.3: Fatigue striation spacing, specimen 8.5 tested at $\sigma_{max} = 120$ MPa. Measurements in the longitudinal direction, cont.

<table>
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<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [$\mu$m]</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Mean value</th>
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<td>0.5012</td>
<td>0.5003</td>
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Table D.4: Fatigue striation spacing, specimen 8.5 tested at $\sigma_{\text{max}} = 120$ MPa. Measurements in the transversal direction

<table>
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<tr>
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<th>Fatigue striation spacing [(\mu\text{m})]</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
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<td>0.0562</td>
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<td>0.0762</td>
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<td>0.0587</td>
<td>0.0643</td>
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<td>2</td>
<td></td>
<td>0.0512</td>
<td>0.0579</td>
<td>0.0580</td>
<td>0.0562</td>
<td>0.0524</td>
<td>0.0551</td>
</tr>
<tr>
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<td>0.0759</td>
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<td>0.0828</td>
<td>0.0782</td>
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<td>0.1100</td>
<td>0.1089</td>
<td>0.1037</td>
<td>0.1001</td>
<td>0.1045</td>
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<td>0.0931</td>
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<td>0.0898</td>
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<td>0.0922</td>
<td>0.0990</td>
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<tr>
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<td>0.0687</td>
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<td>0.0701</td>
<td>0.0751</td>
<td>0.0728</td>
</tr>
<tr>
<td>4</td>
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<td>0.1095</td>
<td>0.1015</td>
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<td>0.1092</td>
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<td>0.2332</td>
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<td>0.2125</td>
<td>0.2164</td>
<td>0.2133</td>
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<tr>
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<td>1.67</td>
<td>1.67</td>
<td>1.67</td>
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</tr>
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</table>
Figure D.3: Point 3, x=0.16 and y=1.00 mm. Specimen 8.5.

Figure D.4: Point 21, x=6.03 and y=1.05 mm. Specimen 8.5.
4.2.1.2 Specimen 7.5, $\sigma_{\text{max}} = 140$ MPa

In specimen 7.5 the measurements were done on the left side crack, Figure (D.5). Tables (D.5) to (D.7) present the coordinate values and the fatigue striation spacing in the points where the measurements were done. Figures (D.6) and (D.7) present some fractographs taken with SEM+FEG for this specimen.

![Figure D.5: Left side fatigue crack of specimen 7.5.](image)

Table D.5: Fatigue striation spacing, specimen 7.5 tested at $\sigma_{\text{max}} = 140$ MPa. Measurements in the longitudinal direction.

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [µm]</th>
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<th></th>
<th></th>
<th>Mean value</th>
</tr>
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<tbody>
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<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>1 x=0.21 y=0.87</td>
<td>0.1328</td>
<td>0.1143</td>
<td>0.1175</td>
<td>0.1353</td>
<td>0.1301</td>
</tr>
<tr>
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<td>0.0882</td>
<td>0.0875</td>
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<td>0.0762</td>
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<td>0.1139</td>
<td>0.1138</td>
<td>0.1122</td>
<td>0.1122</td>
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<tr>
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<td>0.1846</td>
<td>0.1746</td>
<td>0.1783</td>
<td>0.1801</td>
</tr>
<tr>
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<td>0.1304</td>
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<td>0.1297</td>
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<tr>
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</table>
Table D.6: Fatigue striation, specimen 7.5 $\sigma_{\text{max}}$ =140 MPa. Measurements in the longitudinal direction, cont.

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Table D.7: Fatigue striation spacing, specimen 7.5 tested at $\sigma_{max} = 140$ MPa. Measurements in the transversal direction.

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<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
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<td>0,0951</td>
<td>0,0985</td>
<td>0,0993</td>
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<td>0,0988</td>
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<td>0,0488</td>
<td>0,0487</td>
<td>0,0484</td>
<td>0,0488</td>
<td>0,0487</td>
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<td>0,1557</td>
<td>0,1535</td>
<td>0,1554</td>
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<td>0,0856</td>
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<td>0,0861</td>
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<td>0,1175</td>
<td>0,1353</td>
<td>0,1301</td>
<td>0,1260</td>
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<td>0,0768</td>
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<td>0,1153</td>
<td>0,1155</td>
<td>0,1147</td>
</tr>
<tr>
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<td>0,0826</td>
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<td>0,0778</td>
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<td>0,0809</td>
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<td>0,1083</td>
<td>0,1084</td>
<td>0,1076</td>
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<td>0,1015</td>
<td>0,1019</td>
<td>0,1027</td>
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<td>0,1258</td>
<td>0,1251</td>
</tr>
<tr>
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<td>0,1883</td>
<td>0,1977</td>
<td>0,1970</td>
<td>0,1963</td>
<td>0,1955</td>
</tr>
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</table>

234
Figure D.6: Point 1, x=0.21 and y=0.87 mm. Specimen 7.5.

Figure D.7: Point 21, x=0.66 and y=3.06 mm. Specimen 7.5.
4.2.1.3 Specimen 7.3, $\sigma_{\text{max}} = 160$ MPa

In specimen 7.3 the measurements were done on the right side crack, Figure (D.8). Tables (D.8) to (D.10) present the coordinate values and the fatigue striation spacing in the points where the measurements were done. Figures (D.9) and (D.10) present some fractographs taken with SEM+FEG for this specimen.

![Fatigue crack right side, specimen 7.3.](SE1_7_3_S_C_W_.jpg)

Figure D.8: Fatigue crack right side, specimen 7.3.

Table D.8: Fatigue striation spacing, specimen 7.3 tested at $\sigma_{\text{max}} = 160$ MPa. Measurements in the longitudinal direction

<table>
<thead>
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<td>y= 1,04</td>
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<td>y= 0,99</td>
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<td>y= 0,92</td>
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<tr>
<td>y= 0,99</td>
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Table D.9: Fatigue striation spacing, specimen 7.3 tested at $\sigma_{\text{max}} = 160$ MPa. Measurements in the longitudinal direction, cont.

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<td>0.2051</td>
<td>0.2022</td>
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<td>0.1972</td>
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<td>0.3194</td>
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<td>0.3151</td>
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<td>0.2670</td>
<td>0.2711</td>
<td>0.2719</td>
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<tr>
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Table D.10: Fatigue striation spacing, specimen 7.3 tested at $\sigma_{\text{max}} = 160$ MPa. Measurements in the transversal direction.

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<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
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<tr>
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<td>0.0776</td>
<td>0.0624</td>
<td>0.0787</td>
<td>0.0754</td>
</tr>
<tr>
<td>5</td>
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<td>0.0758</td>
<td>0.0758</td>
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<td>6</td>
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<td>0.0319</td>
</tr>
<tr>
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<td>0.0450</td>
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<td>0.0335</td>
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<td>0.0312</td>
<td>0.0317</td>
<td>0.0285</td>
<td>0.0312</td>
</tr>
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<td>0.0544</td>
<td>0.0506</td>
<td>0.0494</td>
<td>0.0514</td>
</tr>
<tr>
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<td>0.0359</td>
<td>0.0353</td>
<td>0.0341</td>
</tr>
<tr>
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<td>0.1106</td>
<td>0.1080</td>
<td>0.1371</td>
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Figure D.9: Point 3, $x=0.08$ and $y=0.99$ mm. Specimen 7.3.

Figure D.10: Point 23, $x=2.24$ and $y=0.94$ mm. Specimen 7.3.
4.2.1.4 Specimen 4.2, $\sigma_{\text{max}} = 180$ MPa

In specimen 4.2 the measurements were done on the right side crack, Figure (D.11). Tables (D.11) to (D.13) present the coordinate values and the fatigue striation spacing in the points where the measurements were done. Figures (D.12) and (D.13) present some fractographs taken with SEM+FEG for this specimen.

![Fatigue crack right side, specimen 4.2.](image)

**Figure D.11:** Fatigue crack right side, specimen 4.2.

**Table D.11:** Fatigue striation, specimen 4.2 $\sigma_{\text{max}}=180$[MPa]. Measurements in the longitudinal direction.

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td>2</td>
</tr>
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<td>1 $x=3.79$ $y=1.17$</td>
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<td>0.7965</td>
</tr>
<tr>
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<td>0.5565</td>
</tr>
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<td>0.7542</td>
</tr>
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<td>4 $x=3.14$ $y=1.18$</td>
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<td>0.8049</td>
</tr>
<tr>
<td>5 $x=2.92$ $y=1.31$</td>
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<td>0.6839</td>
</tr>
<tr>
<td>6 $x=2.79$ $y=1.15$</td>
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<td>0.7212</td>
</tr>
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<td>7 $x=2.51$ $y=0.82$</td>
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Table D.12: Fatigue striation spacing, specimen 4.2 tested at $\sigma_{\text{max}} = 180$ MPa. Measurements in the longitudinal direction, cont.

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<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
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Table D.13: Fatigue striation spacing, specimen 4.2 tested at $\sigma_{\text{max}} = 180$ MPa. Measurements in the transversal direction.

<table>
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<th></th>
<th>Mean value</th>
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<td>1</td>
<td>2</td>
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<td>5</td>
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242
Figure D.12: Point 24, x=0.25 and y=0.63 mm. Specimen 4.2.

Figure D.13: Point 6, x=2.79 and y=1.15 mm. Specimen 4.2.
4.2.1.5 Specimen 7.1, $\sigma_{max} = 200$ MPa

In specimen 7.1 the measurements were done on the right side crack, Figure (D.14). Tables (D.14) to (D.16) present the coordinate values and the fatigue striation spacing in the points where the measurements were done. Figures (D.15) and (D.16) present some fractographs taken with SEM+FEG for this specimen.

![Fatigue crack right side, specimen 7.1.](image)

Figure D.14: Fatigue crack right side, specimen 7.1.

Table D.14: Fatigue striation spacing, specimen 7.1 tested at $\sigma_{max} = 200$ MPa. Measurements in the longitudinal direction

<table>
<thead>
<tr>
<th>Point coordinates</th>
<th>Fatigue striation spacing [$\mu$m]</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
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<td></td>
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</tr>
<tr>
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<td>0.1548</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>0.1610</td>
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<td></td>
</tr>
<tr>
<td>3 X= 0.33 Y= 0.61</td>
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<td>0.1778</td>
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</tr>
<tr>
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<td>0.2155</td>
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</tr>
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<td>0.1545</td>
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</tr>
<tr>
<td>6 X= 0.66 Y= 0.57</td>
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Table D.15: Fatigue striation spacing specimen 7.1, tested at $\sigma_{\text{max}} = 200$ MPa. Measurements in the longitudinal direction, cont.

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<th>Mean value</th>
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<td>0.1985</td>
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<tr>
<td>8 X= 0.77 Y= 0.65</td>
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<td>0.3347</td>
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<tr>
<td>9 X= 0.86 Y= 0.79</td>
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<td>0.3175</td>
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Table D.16: Fatigue striation spacing specimen 7.1, tested at $\sigma_{\text{max}} = 200$ MPa. Measurements in the transversal direction

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<th>Mean value</th>
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<td>1</td>
<td>2</td>
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Figure D.15: Point 5, x=0.58 and y=0.49 mm. Specimen 7.1.

Figure D.16: Point 16, x=1.45 and y=0.87 mm. Specimen 7.1.
D.2.2 Specimens with cold work

4.2.2.1 Specimen 10.1 CW, $\sigma_{\text{max}} = 120$ MPa

In specimen 10.1 CW the measurements were done on the right side crack, Figure (D.17). Tables (D.17) to (D.19) present the coordinate values and the fatigue striation spacing in the points where the measurements were done. Figures (D.18) and (D.19) present some fractographs taken with SEM+FEG for this specimen.

![Fatigue crack right side, specimen 10.1 CW.](image)

Table D.17: Fatigue striation spacing specimen 10.1 CW tested at $\sigma_{\text{max}} = 120$ MPa. Measurements in the longitudinal direction

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [$\mu$m]</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
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Table D.18: Fatigue striation spacing, specimen 10.1 CW tested at $\sigma_{\text{max}} = 120$ MPa. Measurements in the longitudinal direction, cont.

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<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 (x=3.10) (y=0.92)</td>
<td>(0.1481) (0.1581) (0.1399) (0.1606) (0.1324)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 (x=3.24) (y=0.96)</td>
<td>(0.1768) (0.1658) (0.1521) (0.1658) (0.1656)</td>
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<td>0.1652</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>9 (x=3.38) (y=0.96)</td>
<td>(0.1144) (0.1162) (0.0989) (0.0952) (0.1024)</td>
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<td>0.1054</td>
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<tr>
<td>10 (x=3.63) (y=0.94)</td>
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<td>11 (x=3.89) (y=0.84)</td>
<td>(0.1156) (0.1076) (0.0967) (0.1032) (0.1063)</td>
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<td>14 (x=4.00) (y=0.89)</td>
<td>(0.1636) (0.1867) (0.1882) (0.1710) (0.1934)</td>
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<td>15 (x=4.45) (y=1.03)</td>
<td>(0.1290) (0.1470) (0.1513) (0.1483) (0.1317)</td>
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<td>0.1415</td>
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<td>16 (x=4.94) (y=0.89)</td>
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<tr>
<td>17 (x=5.35) (y=0.88)</td>
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<td>18 (x=5.83) (y=1.24)</td>
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<td>0,0894</td>
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<td>0,0932</td>
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<td>0,0941</td>
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<td>0,0701</td>
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<td>0,0690</td>
<td>0,0623</td>
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Figure D.18: Point 4, x=2,79 and y=1,06 mm. Specimen 10.1 CW.

Figure D.19: Point 18, x=1,24 and y=5,83 mm. Specimen 10.1 CW.
4.2.2.2 Specimen 7.1 CW, $\sigma_{\text{max}} = 140$ MPa

In specimen 7.1 CW the measurements were done on the right side crack, Figure (D.20). Tables (D.20) to (D.23) present the coordinate values and the fatigue striation spacing in the points where the measurements were done. Figures (D.21) and (D.22) present some fractographs taken with SEM+FEG for this specimen.

![Fatigue crack right side, specimen 7.1 CW.](image)

Table D.20: Fatigue striation spacing, specimen 7.1 CW tested at $\sigma_{\text{max}} = 140$ MPa. Measurements in the longitudinal direction.

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [$\mu$m]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
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<td>0.0255</td>
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<td>0.0323</td>
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<tr>
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<td></td>
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<td>0.0522</td>
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<tr>
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<td></td>
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<td>0.0339</td>
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<tr>
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<td>0.0580</td>
<td>0.0576</td>
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Table D.21: Fatigue striation spacing, specimen 7-1 CW tested at $\sigma_{\text{max}} = 140$ MPa. Measurements in the longitudinal direction, cont.

<table>
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<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [(\mu\text{m})]</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
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<tbody>
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Table D.22: Fatigue striation spacing, specimen 7-1 CW tested at $\sigma_{max} = 140$ MPa. Measurements in the longitudinal direction, cont.

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Table D.23: Fatigue striation spacing, specimen 7.1 CW tested at $\sigma_{\text{max}} = 140$ MPa. Measurements in the transversal direction.

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</tbody>
</table>
Figure D.21: Point 2, $x=0.50$ and $y=0.49$ mm. Specimen 7.1 CW.

Figure D.22: Point 31, $x=6.23$ and $y=1.28$ mm. Specimen 7.1 CW.
4.2.2.3 Specimen 10.3 CW, $\sigma_{\text{max}} = 160$ MPa

In specimen 10.3 CW the measurements were done on the left side crack, Figure (D.23). Tables (D.24) to (D.26) present the coordinate values and the fatigue striation spacing in the points where the measurements were done. Figures (D.24) and (D.25) present some fractographs taken with SEM+FEG for this specimen.

![Fatigue crack left side, specimen 10.3 CW.](image)

Figure D.23: Fatigue crack left side, specimen 10.3 CW.

Table D.24: Fatigue striation spacing, specimen 10.3 CW tested at $\sigma_{\text{max}} = 160$ MPa. Measurements in the longitudinal direction

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [$\mu$m]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
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<tbody>
<tr>
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</tr>
<tr>
<td>2 x= 1,07 y= 0,75</td>
<td>0,0338 0,0245 0,0374 0,0392 0,0361</td>
<td>0,0342</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>3 x= 9,57 y= 9,18</td>
<td>0,0403 0,0380 0,0346 0,0363 0,0376</td>
<td>0,0374</td>
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<td></td>
</tr>
<tr>
<td>4 x= 1,40 y= 0,68</td>
<td>0,0500 0,0475 0,0483 0,0542 0,0490</td>
<td>0,0498</td>
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</tr>
<tr>
<td>5 x= 1,43 y= 0,71</td>
<td>0,0314 0,0290 0,0279 0,0308 0,0291</td>
<td>0,0296</td>
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<td></td>
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</tr>
<tr>
<td>6 x= 1,50 y= 0,76</td>
<td>0,0505 0,0499 0,0526 0,0540 0,0546</td>
<td>0,0523</td>
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</table>
Table D.25: Fatigue striation spacing, specimen 10.3 CW tested at $\sigma_{\text{max}} = 160$ MPa. Measurements in the longitudinal direction, cont.

<table>
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<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [(\mu\m)]</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 (x=1.69, y=0.73)</td>
<td>0.0710, 0.0687, 0.0694, 0.0701, 0.0704</td>
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<td></td>
<td></td>
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<td>0.0699</td>
</tr>
<tr>
<td>8 (x=1.93, y=0.74)</td>
<td>0.0751, 0.0823, 0.0840, 0.0911, 0.0727</td>
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<td>0.0811</td>
</tr>
<tr>
<td>9 (x=2.03, y=0.70)</td>
<td>0.1113, 0.1056, 0.1087, 0.1215, 0.1108</td>
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<td>0.1116</td>
</tr>
<tr>
<td>10 (x=2.11, y=0.84)</td>
<td>0.1237, 0.1358, 0.1242, 0.1333, 0.1482</td>
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<td>0.1330</td>
</tr>
<tr>
<td>11 (x=2.29, y=0.89)</td>
<td>0.1329, 0.1540, 0.1275, 0.1655, 0.1610</td>
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<td></td>
<td>0.1482</td>
</tr>
<tr>
<td>12 (x=2.45, y=0.29)</td>
<td>0.1370, 0.1373, 0.1397, 0.1421, 0.1293</td>
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</tr>
<tr>
<td>13 (x=2.52, y=1.03)</td>
<td>0.1586, 0.1473, 0.1468, 0.1362, 0.1416</td>
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<td>0.1461</td>
</tr>
<tr>
<td>14 (x=2.90, y=0.97)</td>
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<td>0.1775</td>
</tr>
<tr>
<td>15 (x=2.80, y=0.78)</td>
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</tr>
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<td>16 (x=9.57, y=7.40)</td>
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<td></td>
<td></td>
<td></td>
<td>0.2762</td>
</tr>
<tr>
<td>17 (x=3.03, y=0.79)</td>
<td>0.2184, 0.2183, 0.2106, 0.2050, 0.1978</td>
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<td>0.2100</td>
</tr>
<tr>
<td>18 (x=3.23, y=0.77)</td>
<td>0.1080, 0.1031, 0.1064, 0.1034, 0.1033</td>
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<td></td>
<td>0.1049</td>
</tr>
<tr>
<td>19 (x=3.79, y=0.81)</td>
<td>0.2315, 0.2132, 0.2614, 0.2232, 0.2071</td>
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<td>0.2273</td>
</tr>
<tr>
<td>20 (x=4.16, y=0.89)</td>
<td>0.3393, 0.3521, 0.3293, 0.3353, 0.3398</td>
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<td>0.3392</td>
</tr>
<tr>
<td>21 (x=4.44, y=0.88)</td>
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<td>0.1479</td>
</tr>
<tr>
<td>22 (x=0.38, y=0.05)</td>
<td>0.4235, 0.3682, 0.4158, 0.4307, 0.3803</td>
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<td>0.4037</td>
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<tr>
<td>23 (x=1.05, y=1.81)</td>
<td>0.5796, 0.5983, 0.5543, 0.5479, 0.5844</td>
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</table>
Table D.26: Fatigue striation spacing, specimen 10.3 CW tested at $\sigma_{\text{max}} = 160$ MPa. Measurements in the transversal direction

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [$\mu$m]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 x= 0,38 y= 0,05</td>
<td>0,0501 0,0283 0,0371 0,0317 0,0386 0,0372</td>
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<td></td>
</tr>
<tr>
<td>2 x= 1,05 y= 1,81</td>
<td>0,1291 0,1282 0,1292 0,1274 0,1323 0,1292</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3 x= 0,94 y= 1,70</td>
<td>0,0998 0,0857 0,0863 0,0959 0,0971 0,0930</td>
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</tr>
<tr>
<td>4 x= 0,90 y= 1,60</td>
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</tr>
<tr>
<td>5 x= 0,85 y= 1,33</td>
<td>0,0306 0,0374 0,0347 0,0352 0,0361 0,0348</td>
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</tr>
<tr>
<td>6 x= 0,86 y= 1,09</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>7 x= 1,06 y= 1,01</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 x= 1,06 y= 0,81</td>
<td>0,0514 0,0529 0,0523 0,0514 0,0530 0,0522</td>
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<td></td>
</tr>
<tr>
<td>9 x= 1,20 y= 0,70</td>
<td>0,0783 0,0792 0,0842 0,0787 0,0814 0,0804</td>
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<td></td>
</tr>
<tr>
<td>10 x= 1,25 y= 0,49</td>
<td>0,0499 0,0414 0,0495 0,0444 0,0495 0,0469</td>
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<td></td>
</tr>
<tr>
<td>11 x= 1,14 y= 0,28</td>
<td>0,0592 0,0585 0,0614 0,0625 0,0624 0,0608</td>
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<td></td>
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</tr>
</tbody>
</table>
Figure D.24: Point 3, x=0.92 and y=0.76 mm. Specimen 10.3 CW.

Figure D.25: Point 17, x=2.80 and y=0.78 mm. Specimen 10.3 CW.
4.2.2.4 Specimen 7.5 CW, $\sigma_{\text{max}} = 180$ MPa

In specimen 7.5 CW the measurements were done on the left side crack, Figure (D.26). Tables (D.27) and (D.30) present the coordinate values to the fatigue striation spacing in the points where the measurements were done. Figures (D.27) and (D.28) present some fractographs taken with SEM+FEG for this specimen.

![Image](image.png)

Figure D.26: Fatigue crack left side, specimen 7.5 CW.

Table D.27: Fatigue striation spacing, specimen 7.5 CW tested at $\sigma_{\text{max}} = 180$ MPa. Measurements in the longitudinal direction

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [µm]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
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<tbody>
<tr>
<td>1 X= 0,17 Y= 0,50</td>
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<td>0,0388</td>
<td>0,0409</td>
<td>0,0349</td>
<td>0,0424</td>
<td>0,0372</td>
<td>0,0388</td>
</tr>
<tr>
<td>2 X= 0,32 Y= 0,77</td>
<td></td>
<td>0,0687</td>
<td>0,0774</td>
<td>0,0844</td>
<td>0,0740</td>
<td>0,0639</td>
<td>0,0737</td>
</tr>
<tr>
<td>3 X= 0,41 Y= 0,74</td>
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<td>0,0984</td>
<td>0,0930</td>
<td>0,1035</td>
<td>0,0762</td>
<td>0,1004</td>
<td>0,0943</td>
</tr>
<tr>
<td>4 X= 0,44 Y= 0,87</td>
<td></td>
<td>0,1030</td>
<td>0,1113</td>
<td>0,0934</td>
<td>0,1012</td>
<td>0,0935</td>
<td>0,1005</td>
</tr>
<tr>
<td>5 X= 0,51 Y= 0,73</td>
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<td>0,1141</td>
<td>0,1195</td>
<td>0,1183</td>
<td>0,1059</td>
<td>0,0651</td>
<td>0,1046</td>
</tr>
<tr>
<td>6 X= 0,62 Y= 0,84</td>
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<td>0,1821</td>
<td>0,1832</td>
<td>0,1726</td>
<td>0,1790</td>
<td>0,1850</td>
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</table>
Table D.28: Fatigue striation spacing, specimen 7.5 CW tested at $\sigma_{\text{max}} = 180$ MPa. Measurements in the longitudinal direction, cont.

<table>
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<th>Fatigue striation spacing [$\mu$m]</th>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>7  X= 0.66 Y= 0.80</td>
<td>0.1790</td>
<td>0.1829</td>
<td>0.1814</td>
<td>0.1708</td>
<td>0.1838</td>
<td>0.1796</td>
</tr>
<tr>
<td>8  X= 0.81 Y= 1.14</td>
<td>0.1821</td>
<td>0.1967</td>
<td>0.1870</td>
<td>0.1812</td>
<td>0.1630</td>
<td>0.1820</td>
</tr>
<tr>
<td>9  X= 0.88 Y= 1.14</td>
<td>0.1872</td>
<td>0.1826</td>
<td>0.1816</td>
<td>0.1812</td>
<td>0.1814</td>
<td>0.1828</td>
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<tr>
<td>10 X= 1.02 Y= 0.99</td>
<td>0.2075</td>
<td>0.2076</td>
<td>0.1995</td>
<td>0.1900</td>
<td>0.2025</td>
<td>0.2014</td>
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<td>11 X= 1.08 Y= 0.79</td>
<td>0.1967</td>
<td>0.1959</td>
<td>0.1963</td>
<td>0.2130</td>
<td>0.2097</td>
<td>0.2023</td>
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<tr>
<td>12 X= 1.19 Y= 0.83</td>
<td>0.2418</td>
<td>0.2333</td>
<td>0.2481</td>
<td>0.2400</td>
<td>0.2471</td>
<td>0.2421</td>
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<tr>
<td>13 X= 1.29 Y= 0.88</td>
<td>0.1308</td>
<td>0.1419</td>
<td>0.1441</td>
<td>0.1429</td>
<td>0.1383</td>
<td>0.1396</td>
</tr>
<tr>
<td>14 X= 1.42 Y= 0.80</td>
<td>0.3632</td>
<td>0.3805</td>
<td>0.2589</td>
<td>0.2744</td>
<td>0.2558</td>
<td>0.3065</td>
</tr>
<tr>
<td>15 X= 1.51 Y= 0.76</td>
<td>0.3340</td>
<td>0.3285</td>
<td>0.3420</td>
<td>0.3257</td>
<td>0.3424</td>
<td>0.3345</td>
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<tr>
<td>16 X= 1.55 Y= 0.79</td>
<td>0.3153</td>
<td>0.3445</td>
<td>0.3249</td>
<td>0.2953</td>
<td>0.3498</td>
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<td>0.3389</td>
<td>0.3056</td>
<td>0.3334</td>
<td>0.3276</td>
</tr>
<tr>
<td>18 X= 1.57 Y= 0.80</td>
<td>0.3712</td>
<td>0.3798</td>
<td>0.3700</td>
<td>0.3534</td>
<td>0.3535</td>
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</tr>
<tr>
<td>19 X= 1.55 Y= 0.79</td>
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<td>0.2545</td>
<td>0.2471</td>
<td>0.2390</td>
<td>0.2446</td>
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<td>0.3974</td>
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<td>0.3981</td>
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<td>0.3598</td>
<td>0.3187</td>
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<td>0.3563</td>
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<td>0.2887</td>
<td>0.3063</td>
<td>0.3070</td>
<td>0.3057</td>
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</tr>
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<td>0.3166</td>
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<td>0.3311</td>
<td>0.3298</td>
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Table D.29: Fatigue striation spacing, specimen 7.5 CW tested at $-180$ MPa. Measurements in the longitudinal direction, cont.

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<th>Fatigue striation spacing [μm]</th>
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<th></th>
<th></th>
<th></th>
<th>Mean value</th>
</tr>
</thead>
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<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>24 X= 2.30 Y= 1.10</td>
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<td>0.4439</td>
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<td>0.4566</td>
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<td>0.3405</td>
<td>0.3597</td>
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<td>0.3457</td>
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<td>0.3466</td>
</tr>
<tr>
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<td>0.3636</td>
<td>0.3729</td>
<td>0.3789</td>
<td>0.3844</td>
<td>0.3772</td>
</tr>
<tr>
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<td>0.4652</td>
<td>0.4811</td>
<td>0.4956</td>
<td>0.4942</td>
<td>0.4874</td>
</tr>
<tr>
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<td>0.6250</td>
<td>0.6706</td>
<td>0.6393</td>
<td>0.6257</td>
<td>0.6396</td>
</tr>
<tr>
<td>31 X= 3.11 Y= 0.91</td>
<td>0.8193</td>
<td>0.8952</td>
<td>0.8028</td>
<td>0.7963</td>
<td>0.8318</td>
<td>0.8291</td>
</tr>
<tr>
<td>23 X= 2.14 Y= 1.05</td>
<td>0.3180</td>
<td>0.3166</td>
<td>0.3077</td>
<td>0.3311</td>
<td>0.3298</td>
<td>0.3206</td>
</tr>
<tr>
<td>24 X= 2.30 Y= 1.10</td>
<td>0.4506</td>
<td>0.4593</td>
<td>0.4439</td>
<td>0.4627</td>
<td>0.4667</td>
<td>0.4566</td>
</tr>
</tbody>
</table>
Table D.30: Fatigue striation spacing, specimen 7.5 CW tested at $\sigma_{\text{max}} = 180$ MPa. Measurements in the transversal direction.

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [µm]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 X= 0,51 Y= 0,38</td>
<td></td>
<td>0,1197</td>
<td>0,1157</td>
<td>0,1182</td>
<td>0,1224</td>
<td>0,1129</td>
<td>0,1178</td>
</tr>
<tr>
<td>2 X= 0,50 Y= 0,55</td>
<td></td>
<td>0,1810</td>
<td>0,1863</td>
<td>0,1831</td>
<td>0,1881</td>
<td>0,1754</td>
<td>0,1828</td>
</tr>
<tr>
<td>3 X= 0,47 Y= 0,69</td>
<td></td>
<td>0,1282</td>
<td>0,1229</td>
<td>0,1289</td>
<td>0,1211</td>
<td>0,1249</td>
<td>0,1252</td>
</tr>
<tr>
<td>4 X= 0,51 Y= 0,88</td>
<td></td>
<td>0,0839</td>
<td>0,0916</td>
<td>0,0786</td>
<td>0,0777</td>
<td>0,0824</td>
<td>0,0829</td>
</tr>
<tr>
<td>5 X= 0,51 Y= 1,00</td>
<td></td>
<td>0,2113</td>
<td>0,2247</td>
<td>0,2044</td>
<td>0,2099</td>
<td>0,1939</td>
<td>0,2089</td>
</tr>
<tr>
<td>6 X= 0,90 Y= 1,20</td>
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<td>0,1361</td>
<td>0,1595</td>
<td>0,1628</td>
<td>0,1631</td>
<td>0,1550</td>
</tr>
<tr>
<td>7 X= 0,48 Y= 1,35</td>
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<td>0,0676</td>
<td>0,0664</td>
<td>0,0685</td>
<td>0,0698</td>
<td>0,0673</td>
</tr>
<tr>
<td>8 X= 0,42 Y= 1,52</td>
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<td>0,0559</td>
<td>0,0568</td>
<td>0,0524</td>
<td>0,0574</td>
<td>0,0547</td>
</tr>
<tr>
<td>9 X= 0,58 Y= 1,66</td>
<td></td>
<td>0,1119</td>
<td>0,1206</td>
<td>0,1169</td>
<td>0,1188</td>
<td>0,1166</td>
<td>0,1170</td>
</tr>
<tr>
<td>10 X= 0,41 Y= 1,83</td>
<td></td>
<td>0,1739</td>
<td>0,1696</td>
<td>0,1537</td>
<td>0,1677</td>
<td>0,1725</td>
<td>0,1675</td>
</tr>
<tr>
<td>11 X= 0,50 Y= 1,90</td>
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<td>0,1115</td>
<td>0,1084</td>
<td>0,1118</td>
<td>0,1107</td>
<td>0,1046</td>
<td>0,1094</td>
</tr>
</tbody>
</table>

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Figure D.27: Point 4, x=0.44 and y=0.87 mm. Specimen 7.5 CW.

Figure D.28: Point 29, x=2.42 and y=0.94 mm. Specimen 7.5 CW.
4.2.2.5 Specimen 8.6 CW, $\sigma_{max} = 200$ MPa

In specimen 8.6 CW the measurements were done on the right side crack, Figure (D.29). Tables (D.31) to (D.33) present the coordinate values and the fatigue striation spacing in the points where the measurements were done. Figures (D.30) and (D.31) present some fractographs taken with SEM+FEG for this specimen.

![Figure D.29: fatigue crack right side, specimen 8.6 CW.](image)

Table D.31: Fatigue striation spacing, specimen 8.6 CW tested at $\sigma_{max} = 200$ MPa. Measurements in the longitudinal direction

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1 X= 3,67 Y= 1,21</td>
<td>1,0532</td>
</tr>
<tr>
<td>2 X= 3,43 Y= 1,30</td>
<td>1,0790</td>
</tr>
<tr>
<td>3 X= 3,09 Y= 1,27</td>
<td>1,0125</td>
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<tr>
<td>4 X= 2,93 Y= 1,25</td>
<td>0,7170</td>
</tr>
<tr>
<td>5 X= 2,75 Y= 0,83</td>
<td>0,7446</td>
</tr>
<tr>
<td>6 X= 2,49 Y= 1,15</td>
<td>0,7210</td>
</tr>
</tbody>
</table>
Table D.32: Fatigue striation spacing, specimen 8.6 CW tested at $\sigma_{\text{max}} = 200$ MPa. Measurements in the longitudinal direction

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [$\mu$m]</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X= 2.09</td>
<td>Y= 1.22</td>
<td>0.3578</td>
<td>0.3549</td>
<td>0.3570</td>
<td>0.3551</td>
<td>0.3510</td>
<td>0.3552</td>
</tr>
<tr>
<td>X= 1.94</td>
<td>Y= 1.18</td>
<td>0.4060</td>
<td>0.4138</td>
<td>0.4099</td>
<td>0.4112</td>
<td>0.4120</td>
<td>0.4106</td>
</tr>
<tr>
<td>X= 1.85</td>
<td>Y= 1.17</td>
<td>0.3802</td>
<td>0.3807</td>
<td>0.3698</td>
<td>0.3692</td>
<td>0.3768</td>
<td>0.3754</td>
</tr>
<tr>
<td>X= 1.72</td>
<td>Y= 1.26</td>
<td>0.1013</td>
<td>0.1007</td>
<td>0.1029</td>
<td>0.1037</td>
<td>0.1021</td>
<td>0.1021</td>
</tr>
<tr>
<td>X= 1.60</td>
<td>Y= 1.30</td>
<td>0.1849</td>
<td>0.1835</td>
<td>0.1859</td>
<td>0.1854</td>
<td>0.1849</td>
<td>0.1849</td>
</tr>
<tr>
<td>X= 1.45</td>
<td>Y= 1.28</td>
<td>0.2650</td>
<td>0.2628</td>
<td>0.2652</td>
<td>0.2659</td>
<td>0.2602</td>
<td>0.2638</td>
</tr>
<tr>
<td>X= 1.22</td>
<td>Y= 1.20</td>
<td>0.1773</td>
<td>0.1663</td>
<td>0.1738</td>
<td>0.1745</td>
<td>0.1674</td>
<td>0.1719</td>
</tr>
<tr>
<td>X= 1.07</td>
<td>Y= 1.09</td>
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<td>0.2955</td>
<td>0.2990</td>
<td>0.2941</td>
<td>0.2962</td>
<td>0.2969</td>
</tr>
<tr>
<td>X= 1.02</td>
<td>Y= 1.23</td>
<td>0.1997</td>
<td>0.1993</td>
<td>0.1997</td>
<td>0.1993</td>
<td>0.1983</td>
<td>0.1993</td>
</tr>
<tr>
<td>X= 0.90</td>
<td>Y= 1.20</td>
<td>0.1688</td>
<td>0.1671</td>
<td>0.1667</td>
<td>0.1684</td>
<td>0.1700</td>
<td>0.1682</td>
</tr>
<tr>
<td>X= 0.71</td>
<td>Y= 1.19</td>
<td>0.1086</td>
<td>0.1030</td>
<td>0.1057</td>
<td>0.1006</td>
<td>0.1007</td>
<td>0.1037</td>
</tr>
<tr>
<td>X= 0.60</td>
<td>Y= 0.94</td>
<td>0.1552</td>
<td>0.1498</td>
<td>0.1562</td>
<td>0.1393</td>
<td>0.1453</td>
<td>0.1492</td>
</tr>
<tr>
<td>X= 0.49</td>
<td>Y= 0.95</td>
<td>0.1725</td>
<td>0.1736</td>
<td>0.1729</td>
<td>0.1727</td>
<td>0.1713</td>
<td>0.1726</td>
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<tr>
<td>X= 0.39</td>
<td>Y= 0.94</td>
<td>0.1156</td>
<td>0.1116</td>
<td>0.1122</td>
<td>0.1108</td>
<td>0.1119</td>
<td>0.1124</td>
</tr>
<tr>
<td>X= 0.31</td>
<td>Y= 0.85</td>
<td>0.1313</td>
<td>0.1243</td>
<td>0.1258</td>
<td>0.1311</td>
<td>0.1310</td>
<td>0.1287</td>
</tr>
<tr>
<td>X= 0.21</td>
<td>Y= 0.84</td>
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<td>0.0666</td>
<td>0.0663</td>
<td>0.0661</td>
<td>0.0664</td>
<td>0.0663</td>
</tr>
</tbody>
</table>

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Table D.33: Fatigue striation spacing, specimen 8.6 CW tested at $\sigma_{\text{max}} = 200$ MPa. Measurements in the transversal direction.

<table>
<thead>
<tr>
<th>Point coordinates [mm]</th>
<th>Fatigue striation spacing [$\mu$m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1 X= 0,27 Y= 0,17</td>
<td>0,1236</td>
</tr>
<tr>
<td>2 X= 0,28 Y= 0,44</td>
<td>0,0696</td>
</tr>
<tr>
<td>3 X= 0,29 Y= 0,54</td>
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<tr>
<td>4 X= 0,27 Y= 1,59</td>
<td>0,0879</td>
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<tr>
<td>5 X= 0,28 Y= 1,80</td>
<td>0,1555</td>
</tr>
<tr>
<td>6 X= 0,34 Y= 1,96</td>
<td>0,1194</td>
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<tr>
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<td>0,1088</td>
</tr>
<tr>
<td>8 X= 0,21 Y= 0,89</td>
<td>0,0971</td>
</tr>
<tr>
<td>9 X= 0,31 Y= 1,22</td>
<td>0,1313</td>
</tr>
<tr>
<td>10 X= 0,21 Y= 1,40</td>
<td>0,0662</td>
</tr>
</tbody>
</table>
Figure D.30: Point 5, x=2.75 and y=0.83 mm. Specimen 8.6 CW.

Figure D.31: Point 21, x=0.21 and y=1.40 mm. Specimen 8.6 CW.
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Appendix E

Crack areas and crack lengths measurements

E.1 Introduction

Crack areas and crack lengths were measured by SEM as follows. Figure (E.1) represents schematically the cracked area and crack length considered in the measurements.

![Diagram](image)

Figure E.1: Fatigue crack area and crack length measurements.

The nomenclature used in Figure (F.1) is presented in section 5.7.

E.2 Crack areas and crack lengths measurements

E.2.1 Specimens without cold work

Figure (E.2) presents the fatigue crack in the left and right sides of specimen 7.5 without cold work. These figures present the crack measurement as a dashed line around the bounds of the fatigue crack area.
Figure E.2: Fatigue crack, specimen 7.5 without cold work: a) left side; b) right side.

Tables (E.1) to (E.5) present the final fatigue crack area and crack length of the specimens without cold work. The measurements were done in both sides of the hole.

Table E.1: Crack area and crack lengths, specimens without cold work tested at $\sigma_{max} = 120$ MPa

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Crack area $[mm^2]$</th>
<th>Crack area + hole area$[mm^2]$</th>
<th>Crack length $[mm]$</th>
<th>Crack length + hole length$[mm]$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Omega_{left}$ $\Omega_{right}$ $\Omega_{total}$</td>
<td>$a_{left}$ $a_{right}$ $a_{total}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.5</td>
<td>1,460 8,946 10,406</td>
<td>20,406 2,402 6,443 8,844</td>
<td>13,844</td>
<td></td>
</tr>
<tr>
<td>8.2</td>
<td>4,810 5,518 10,327</td>
<td>20,327 3,015 3,831 6,845</td>
<td>11,845</td>
<td></td>
</tr>
<tr>
<td>8.3</td>
<td>7,202 3,714 10,916</td>
<td>20,916 5,425 3,084 8,510</td>
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</tr>
<tr>
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<td>5,655 6,813 12,467</td>
<td>22,467 4,233 5,435 9,668</td>
<td>14,668</td>
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</tr>
<tr>
<td>8.1</td>
<td>4,518 7,813 12,331</td>
<td>22,331 3,139 5,935 9,074</td>
<td>14,074</td>
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</table>
Table E.2: Crack area and crack lengths, specimens without cold work tested at $\sigma_{\text{max}} = 140$ MPa

<table>
<thead>
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<th>Specimen</th>
<th>Crack area [mm$^2$]</th>
<th>Crack area + hole area [mm$^2$]</th>
<th>Crack length [mm]</th>
<th>Crack length + hole length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Omega_{\text{left}}$</td>
<td>$\Omega_{\text{right}}$</td>
<td>$\Omega_{\text{total}}$</td>
<td>$\alpha_{\text{left}}$</td>
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<tr>
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<td>3,365</td>
<td>7,759</td>
<td>17,759</td>
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<tr>
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<td>21,038</td>
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<td>6,406</td>
<td>3,871</td>
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<td>5,963</td>
<td>5,171</td>
<td>11,134</td>
<td>21,134</td>
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</table>

Table E.3: Crack area and crack lengths, specimens without cold work tested at $\sigma_{\text{max}} = 160$ MPa

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Crack area [mm$^2$]</th>
<th>Crack area + hole area [mm$^2$]</th>
<th>Crack length [mm]</th>
<th>Crack length + hole length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Omega_{\text{left}}$</td>
<td>$\Omega_{\text{right}}$</td>
<td>$\Omega_{\text{total}}$</td>
<td>$\alpha_{\text{left}}$</td>
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<td>10,033</td>
<td>20,033</td>
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<td>4,300</td>
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<td>5.4</td>
<td>4,291</td>
<td>2,645</td>
<td>6,937</td>
<td>16,937</td>
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</tbody>
</table>

Table E.4: Crack area and crack lengths, specimens without cold work tested at $\sigma_{\text{max}} = 180$ MPa

<table>
<thead>
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<th>Specimen</th>
<th>Crack area [mm$^2$]</th>
<th>Crack area + hole area [mm$^2$]</th>
<th>Crack length [mm]</th>
<th>Crack length + hole length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Omega_{\text{left}}$</td>
<td>$\Omega_{\text{right}}$</td>
<td>$\Omega_{\text{total}}$</td>
<td>$\alpha_{\text{left}}$</td>
</tr>
<tr>
<td>5.1</td>
<td>3,133</td>
<td>4,251</td>
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<td>17,384</td>
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<tr>
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<td>3,117</td>
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</tr>
<tr>
<td>4.2</td>
<td>3,441</td>
<td>5,122</td>
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<td>18,563</td>
</tr>
<tr>
<td>6.3</td>
<td>3,417</td>
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<td>17,663</td>
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<td>3,973</td>
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Table E.5: Crack area and crack lengths, specimens without cold work tested at $\sigma_{\text{max}} = 200$ MPa

<table>
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<th>Specimen</th>
<th>Crack area [mm$^2$]</th>
<th>Crack area + hole area [mm$^2$]</th>
<th>Crack length [mm]</th>
<th>Crack length + hole length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Omega_{\text{left}}$</td>
<td>$\Omega_{\text{right}}$</td>
<td>$\Omega_{\text{total}}$</td>
<td>$\alpha_{\text{left}}$</td>
</tr>
<tr>
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<td>5,305</td>
<td>15,305</td>
</tr>
<tr>
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<td>1,450</td>
<td>3,790</td>
<td>5,240</td>
<td>15,240</td>
</tr>
<tr>
<td>4.3</td>
<td>2,178</td>
<td>2,504</td>
<td>4,681</td>
<td>14,681</td>
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<tr>
<td>6.4</td>
<td>3,576</td>
<td>3,963</td>
<td>7,539</td>
<td>17,539</td>
</tr>
</tbody>
</table>

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E.2.2 Specimens with cold work

Tables (E.6) to (E.10) present the final fatigue crack area and crack length of the specimens with cold work. The measurements were performed in both sides of the hole.

Table E.6: Crack area and crack lengths, specimens with cold work tested at $\sigma_{\text{max}} = 120$ MPa

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Crack area [mm$^2$]</th>
<th>Crack area + hole area [mm$^2$]</th>
<th>Crack length [mm]</th>
<th>Crack length + hole length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Omega_{\text{left}}$</td>
<td>$\Omega_{\text{right}}$</td>
<td>$\Omega_{\text{total}}$</td>
<td>$a_{\text{left}}$</td>
</tr>
<tr>
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<td>1.016</td>
<td>10.511</td>
<td>11.527</td>
<td>21.187</td>
</tr>
<tr>
<td>10.6</td>
<td>0.000</td>
<td>9.881</td>
<td>9.881</td>
<td>19.541</td>
</tr>
<tr>
<td>7.3</td>
<td>2.030</td>
<td>12.997</td>
<td>15.027</td>
<td>24.687</td>
</tr>
</tbody>
</table>

Table E.7: Crack area and crack lengths, specimens with cold work tested at $\sigma_{\text{max}} = 140$ MPa

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Crack area [mm$^2$]</th>
<th>Crack area + hole area [mm$^2$]</th>
<th>Crack length [mm]</th>
<th>Crack length + hole length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Omega_{\text{left}}$</td>
<td>$\Omega_{\text{right}}$</td>
<td>$\Omega_{\text{total}}$</td>
<td>$a_{\text{left}}$</td>
</tr>
<tr>
<td>7.1</td>
<td>7.678</td>
<td>1.444</td>
<td>9.122</td>
<td>18.762</td>
</tr>
<tr>
<td>8.5</td>
<td>13.299</td>
<td>0.000</td>
<td>12.299</td>
<td>21.959</td>
</tr>
</tbody>
</table>

Table E.8: Crack area and crack lengths, specimens with cold work tested at $\sigma_{\text{max}} = 160$ MPa

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Crack area [mm$^2$]</th>
<th>Crack area + hole area [mm$^2$]</th>
<th>Crack length [mm]</th>
<th>Crack length + hole length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Omega_{\text{left}}$</td>
<td>$\Omega_{\text{right}}$</td>
<td>$\Omega_{\text{total}}$</td>
<td>$a_{\text{left}}$</td>
</tr>
<tr>
<td>10.2</td>
<td>3.059</td>
<td>7.630</td>
<td>10.689</td>
<td>20.349</td>
</tr>
</tbody>
</table>

Table E.9: Crack area and crack lengths, specimens with cold work tested at $\sigma_{\text{max}} = 180$ MPa

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Crack area [mm$^2$]</th>
<th>Crack area + hole area [mm$^2$]</th>
<th>Crack length [mm]</th>
<th>Crack length + hole length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Omega_{\text{left}}$</td>
<td>$\Omega_{\text{right}}$</td>
<td>$\Omega_{\text{total}}$</td>
<td>$a_{\text{left}}$</td>
</tr>
<tr>
<td>7.5</td>
<td>5.041</td>
<td>3.504</td>
<td>8.544</td>
<td>18.204</td>
</tr>
</tbody>
</table>
Table E.10: Crack area and crack lengths, specimens with cold work tested at $\sigma_{max} = 200$ MPa

<table>
<thead>
<tr>
<th>Spec.</th>
<th>$\Omega_{\text{left}}$</th>
<th>$\Omega_{\text{right}}$</th>
<th>$\Omega_{\text{total}}$</th>
<th>Crack area + hole area [mm$^2$]</th>
<th>Crack length [mm]</th>
<th>Crack length + hole length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a_{\text{left}}$</td>
<td>$a_{\text{right}}$</td>
<td>$a_{\text{total}}$</td>
<td>$a_{\text{left}}$</td>
<td>$a_{\text{right}}$</td>
<td>$a_{\text{total}}$</td>
</tr>
<tr>
<td>10.5</td>
<td>5.593</td>
<td>2.096</td>
<td>7.689</td>
<td>17.349</td>
<td>3.854</td>
<td>1.607</td>
</tr>
</tbody>
</table>
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Appendix F

$K_c$ estimation

F.1 Introduction

A rough estimation of $K_c$ was performed based on the SEM final fatigue crack areas measured. The procedure is described in the following paragraphs.

F.2 $K_c$ calculation procedure

![Diagram of fatigue crack area and crack length measurements.](image)

Figure F.1: Fatigue crack area and crack length measurements.

The nomenclature used in Figure (F.1) is presented in section 5.7.

In order to estimate the critical toughness, the following approximations were done:

- specimens fracture, was evaluated as having two symmetrical cracks (2 sym. cracks) or having one crack;
- an equivalent crack length ($a_{eq}$) correspondent to the crack areas measured. A typical approximation is dividing the crack area by the thickness as presented in equation (F.1).

\[
a_{eq} = \frac{\Omega_{left} + \Omega_{right}}{N_{cracks} \cdot t}
\]  

(F.1)

After the equivalent crack length estimation the $K_c$ was calculated with equation (F.2) and (F.3) for specimens with and without cold work respectively.

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\[ K_c = \sigma_{\text{app}} Y \sqrt{\pi a_{eq}} \]  \hspace{1cm} (F.2)

\[ K_c = K_{\text{res}} + \sigma_{\text{app}} Y \sqrt{\pi a_{eq}} \]  \hspace{1cm} (F.3)

Stress intensity factor calibrations and residual stress intensity factor were presented in chapter 4, section 4.6.2.

## F.3 \( K_c \) results

In Tables (F.1) to (F.5) are the presented \( K_c \) estimation for all normal hole specimens measured by SEM.

### Table F.1: \( K_c \) estimation, normal hole specimens tested at \( \sigma_{\text{ma}x} = 120\text{MPa} \)

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Cracks</th>
<th>Fatigue area [mm(^2)]</th>
<th>( a_{eq} ) [mm]</th>
<th>( a/R )</th>
<th>Y</th>
<th>( K_c ) MPa.m(^{0.5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5</td>
<td>two sym.</td>
<td>10.406</td>
<td>2.602</td>
<td>1.041</td>
<td>1.654</td>
<td>17.943</td>
</tr>
<tr>
<td>8.2</td>
<td>two sym.</td>
<td>10.327</td>
<td>2.582</td>
<td>1.033</td>
<td>1.656</td>
<td>17.895</td>
</tr>
<tr>
<td>8.3</td>
<td>two sym.</td>
<td>10.916</td>
<td>2.729</td>
<td>1.092</td>
<td>1.643</td>
<td>18.251</td>
</tr>
<tr>
<td>4.4</td>
<td>two sym.</td>
<td>12.467</td>
<td>3.117</td>
<td>1.247</td>
<td>1.617</td>
<td>19.204</td>
</tr>
<tr>
<td>8.1</td>
<td>two sym.</td>
<td>12.331</td>
<td>3.083</td>
<td>1.233</td>
<td>1.619</td>
<td>19.119</td>
</tr>
</tbody>
</table>

### Table F.2: \( K_c \) estimation, normal hole specimens tested at \( \sigma_{\text{ma}x} = 140\text{MPa} \)

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Cracks</th>
<th>Fatigue area [mm(^2)]</th>
<th>( a_{eq} ) [mm]</th>
<th>( a/R )</th>
<th>Y</th>
<th>( K_c ) MPa.m(^{0.5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3</td>
<td>two sym.</td>
<td>8.977</td>
<td>2.244</td>
<td>0.898</td>
<td>1.694</td>
<td>19.914</td>
</tr>
<tr>
<td>7.2</td>
<td>two sym.</td>
<td>7.759</td>
<td>1.940</td>
<td>0.776</td>
<td>1.739</td>
<td>19.005</td>
</tr>
<tr>
<td>7.5</td>
<td>two sym.</td>
<td>11.038</td>
<td>2.759</td>
<td>1.104</td>
<td>1.640</td>
<td>21.379</td>
</tr>
<tr>
<td>4.5</td>
<td>two sym.</td>
<td>10.277</td>
<td>2.569</td>
<td>1.028</td>
<td>1.657</td>
<td>20.842</td>
</tr>
<tr>
<td>6.1</td>
<td>two sym.</td>
<td>11.134</td>
<td>2.783</td>
<td>1.113</td>
<td>1.638</td>
<td>21.447</td>
</tr>
</tbody>
</table>

### Table F.3: \( K_c \) estimation, normal hole specimens tested at \( \sigma_{\text{ma}x} = 160\text{MPa} \)

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Cracks</th>
<th>Fatigue area [mm(^2)]</th>
<th>( a_{eq} ) [mm]</th>
<th>( a/R )</th>
<th>Y</th>
<th>( K_c ) MPa.m(^{0.5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2</td>
<td>two sym.</td>
<td>10.033</td>
<td>2.508</td>
<td>1.003</td>
<td>1.663</td>
<td>23.623</td>
</tr>
<tr>
<td>7.3</td>
<td>two sym.</td>
<td>7.704</td>
<td>1.926</td>
<td>0.770</td>
<td>1.741</td>
<td>21.671</td>
</tr>
<tr>
<td>4.1</td>
<td>two sym.</td>
<td>9.122</td>
<td>2.281</td>
<td>0.912</td>
<td>1.689</td>
<td>22.879</td>
</tr>
<tr>
<td>6.2</td>
<td>two sym.</td>
<td>5.157</td>
<td>1.289</td>
<td>0.516</td>
<td>1.899</td>
<td>19.338</td>
</tr>
<tr>
<td>5.4</td>
<td>two sym.</td>
<td>6.937</td>
<td>1.734</td>
<td>0.694</td>
<td>1.777</td>
<td>20.986</td>
</tr>
</tbody>
</table>
Table F.4: $K_c$ estimation, normal hole specimens tested at $\sigma_{max} = 180$MPa

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Cracks</th>
<th>Fatigue area [mm$^2$]</th>
<th>$a_{eq}$ [mm]</th>
<th>$a/R$</th>
<th>$Y$</th>
<th>$K_c$ MPa.m$^{0.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>two sym.</td>
<td>7.384</td>
<td>1.846</td>
<td>0.738</td>
<td>1.755</td>
<td>24.061</td>
</tr>
<tr>
<td>7.4</td>
<td>two sym.</td>
<td>7.580</td>
<td>1.895</td>
<td>0.758</td>
<td>1.747</td>
<td>24.257</td>
</tr>
<tr>
<td>4.2</td>
<td>two sym.</td>
<td>8.563</td>
<td>2.141</td>
<td>0.856</td>
<td>1.708</td>
<td>25.213</td>
</tr>
<tr>
<td>6.3</td>
<td>two sym.</td>
<td>7.663</td>
<td>1.916</td>
<td>0.766</td>
<td>1.743</td>
<td>24.340</td>
</tr>
<tr>
<td>8.4</td>
<td>two sym.</td>
<td>7.249</td>
<td>1.812</td>
<td>0.725</td>
<td>1.762</td>
<td>23.926</td>
</tr>
</tbody>
</table>

Table F.5: $K_c$ estimation, normal hole specimens tested at $\sigma_{max} = 200$MPa

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Cracks</th>
<th>Fatigue area [mm$^2$]</th>
<th>$a_{eq}$ [mm]</th>
<th>$a/R$</th>
<th>$Y$</th>
<th>$K_c$ MPa.m$^{0.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>two sym.</td>
<td>5.305</td>
<td>1.326</td>
<td>0.530</td>
<td>1.886</td>
<td>24.345</td>
</tr>
<tr>
<td>7.1</td>
<td>two sym.</td>
<td>5.240</td>
<td>1.310</td>
<td>0.524</td>
<td>1.892</td>
<td>24.269</td>
</tr>
<tr>
<td>4.3</td>
<td>two sym.</td>
<td>4.681</td>
<td>1.170</td>
<td>0.468</td>
<td>1.947</td>
<td>23.615</td>
</tr>
<tr>
<td>6.4</td>
<td>two sym.</td>
<td>7.539</td>
<td>1.885</td>
<td>0.754</td>
<td>1.748</td>
<td>26.907</td>
</tr>
</tbody>
</table>

Table (F.6) presents $K_c$ mean values ($\mu(K_c)$) and standard deviation ($\sigma(K_c)$) for different stress levels in normal hole specimens.

Table F.6: $K_c$ estimation, mean values and standard deviation

<table>
<thead>
<tr>
<th>Stress level [MPa]</th>
<th>$\mu(K_c)$ MPa.m$^{0.5}$</th>
<th>$\sigma(K_c)$ MPa.m$^{0.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>17.935</td>
<td>1.974</td>
</tr>
<tr>
<td>140</td>
<td>18.225</td>
<td>2.349</td>
</tr>
<tr>
<td>160</td>
<td>17.259</td>
<td>2.012</td>
</tr>
<tr>
<td>180</td>
<td>17.095</td>
<td>2.458</td>
</tr>
<tr>
<td>200</td>
<td>19.919</td>
<td>2.467</td>
</tr>
<tr>
<td>120-200</td>
<td>18.087</td>
<td>1.125</td>
</tr>
</tbody>
</table>
In Tables (F.7) to (F.11) are the presented $K_c$ estimation for all cold worked hole specimens measured by SEM.

**Table F.7: $K_c$ estimation, cold worked hole specimens tested at $\sigma_{max} = 120\text{MPa}$**

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Cracks</th>
<th>Fatigue area [mm$^2$]</th>
<th>$a_{eq}$ [mm]</th>
<th>$a/R$</th>
<th>$Y$</th>
<th>$K_{app}$ [MPa.m$^{0.5}$]</th>
<th>$K_{res}$ [MPa.m$^{0.5}$]</th>
<th>$K_c$ [MPa.m$^{0.5}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>one</td>
<td>10.511</td>
<td>5.255</td>
<td>2.176</td>
<td>1.188</td>
<td>18.321</td>
<td>-1.829</td>
<td>16.491</td>
</tr>
<tr>
<td>10.6</td>
<td>one</td>
<td>9.881</td>
<td>4.941</td>
<td>2.046</td>
<td>1.189</td>
<td>17.770</td>
<td>-1.786</td>
<td>15.984</td>
</tr>
<tr>
<td>8.3</td>
<td>one</td>
<td>13.078</td>
<td>6.539</td>
<td>2.708</td>
<td>1.228</td>
<td>21.118</td>
<td>-1.357</td>
<td>19.761</td>
</tr>
<tr>
<td>7.3</td>
<td>one</td>
<td>12.997</td>
<td>6.498</td>
<td>2.691</td>
<td>1.227</td>
<td>21.034</td>
<td>-1.530</td>
<td>19.504</td>
</tr>
</tbody>
</table>

**Table F.8: $K_c$ estimation, cold worked hole specimens tested at $\sigma_{max} = 140\text{MPa}$**

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Cracks</th>
<th>Fatigue area [mm$^2$]</th>
<th>$a_{eq}$ [mm]</th>
<th>$a/R$</th>
<th>$Y$</th>
<th>$K_{app}$ [MPa.m$^{0.5}$]</th>
<th>$K_{res}$ [MPa.m$^{0.5}$]</th>
<th>$K_c$ [MPa.m$^{0.5}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.6</td>
<td>two sym.</td>
<td>13.396</td>
<td>3.349</td>
<td>1.387</td>
<td>1.606</td>
<td>23.058</td>
<td>-6.455</td>
<td>16.603</td>
</tr>
<tr>
<td>7.1</td>
<td>one</td>
<td>7.678</td>
<td>3.839</td>
<td>1.590</td>
<td>1.244</td>
<td>19.119</td>
<td>-2.958</td>
<td>16.162</td>
</tr>
<tr>
<td>8.5</td>
<td>one</td>
<td>12.222</td>
<td>6.111</td>
<td>2.530</td>
<td>1.214</td>
<td>23.551</td>
<td>-2.172</td>
<td>21.379</td>
</tr>
<tr>
<td>8.1</td>
<td>two sym.</td>
<td>13.597</td>
<td>3.399</td>
<td>1.408</td>
<td>1.605</td>
<td>23.217</td>
<td>-6.320</td>
<td>16.897</td>
</tr>
<tr>
<td>6.5</td>
<td>one</td>
<td>11.072</td>
<td>5.536</td>
<td>2.292</td>
<td>1.194</td>
<td>22.039</td>
<td>-1.952</td>
<td>20.087</td>
</tr>
</tbody>
</table>

**Table F.9: $K_c$ estimation, cold worked hole specimens tested at $\sigma_{max} = 160\text{MPa}$**

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Cracks</th>
<th>Fatigue area [mm$^2$]</th>
<th>$a_{eq}$ [mm]</th>
<th>$a/R$</th>
<th>$Y$</th>
<th>$K_{app}$ [MPa.m$^{0.5}$]</th>
<th>$K_{res}$ [MPa.m$^{0.5}$]</th>
<th>$K_c$ [MPa.m$^{0.5}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.2</td>
<td>two sym.</td>
<td>10.659</td>
<td>2.672</td>
<td>1.107</td>
<td>1.640</td>
<td>24.036</td>
<td>-8.422</td>
<td>15.614</td>
</tr>
<tr>
<td>6.6</td>
<td>two sym.</td>
<td>11.988</td>
<td>2.997</td>
<td>1.241</td>
<td>1.618</td>
<td>25.119</td>
<td>-7.471</td>
<td>17.648</td>
</tr>
<tr>
<td>6.1</td>
<td>two sym.</td>
<td>10.829</td>
<td>2.707</td>
<td>1.121</td>
<td>1.637</td>
<td>24.150</td>
<td>-8.324</td>
<td>15.826</td>
</tr>
</tbody>
</table>

**Table F.10: $K_c$ estimation, cold worked hole specimens tested at $\sigma_{max} = 180\text{MPa}$**

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Cracks</th>
<th>Fatigue area [mm$^2$]</th>
<th>$a_{eq}$ [mm]</th>
<th>$a/R$</th>
<th>$Y$</th>
<th>$K_{app}$ [MPa.m$^{0.5}$]</th>
<th>$K_{res}$ [MPa.m$^{0.5}$]</th>
<th>$K_c$ [MPa.m$^{0.5}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.4</td>
<td>two sym.</td>
<td>8.678</td>
<td>2.170</td>
<td>0.898</td>
<td>1.694</td>
<td>25.170</td>
<td>-9.551</td>
<td>15.619</td>
</tr>
<tr>
<td>7.5</td>
<td>two sym.</td>
<td>8.544</td>
<td>2.136</td>
<td>0.884</td>
<td>1.698</td>
<td>25.042</td>
<td>-9.599</td>
<td>15.443</td>
</tr>
<tr>
<td>7.4</td>
<td>two sym.</td>
<td>9.397</td>
<td>2.349</td>
<td>0.973</td>
<td>1.671</td>
<td>25.846</td>
<td>-9.226</td>
<td>16.620</td>
</tr>
</tbody>
</table>
Table F.11: \( K_c \) estimation, cold worked hole specimens tested at \( \sigma_{\text{max}} = 200\,\text{MPa} \)

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Cracks</th>
<th>Fatigue area [mm(^2)]</th>
<th>( a_{eq} ) [mm]</th>
<th>a/R</th>
<th>( Y )</th>
<th>( K_{\text{app}} ) MPa.m(^{0.5})</th>
<th>( K_{\text{res}} ) MPa.m(^{0.5})</th>
<th>( \bar{K}_c ) MPa.m(^{0.5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5</td>
<td>two sym.</td>
<td>7.689</td>
<td>1.922</td>
<td>0.796</td>
<td>1.731</td>
<td>26.898</td>
<td>-9.792</td>
<td>17.107</td>
</tr>
<tr>
<td>8.6</td>
<td>two sym.</td>
<td>9.504</td>
<td>2.376</td>
<td>0.984</td>
<td>1.668</td>
<td>28.828</td>
<td>-9.169</td>
<td>19.658</td>
</tr>
<tr>
<td>8.2</td>
<td>two sym.</td>
<td>11.541</td>
<td>2.885</td>
<td>1.195</td>
<td>1.624</td>
<td>30.927</td>
<td>-7.805</td>
<td>23.122</td>
</tr>
<tr>
<td>8.4</td>
<td>two sym.</td>
<td>9.585</td>
<td>2.396</td>
<td>0.992</td>
<td>1.666</td>
<td>28.912</td>
<td>-9.124</td>
<td>19.787</td>
</tr>
</tbody>
</table>

Table (F.6) presents \( K_c \) mean values (\( \mu(K_c) \)) and standard deviation (\( \sigma(K_c) \)) for different stress levels in cold worked hole specimens.

Table F.12: \( K_c \) estimation, mean values and standard deviation

<table>
<thead>
<tr>
<th>Stress level [MPa]</th>
<th>( \mu(K_c) ) MPa.m(^{0.5})</th>
<th>( \sigma(K_c) ) MPa.m(^{0.5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>18.482</td>
<td>0.636</td>
</tr>
<tr>
<td>140</td>
<td>20.517</td>
<td>1.044</td>
</tr>
<tr>
<td>160</td>
<td>21.699</td>
<td>1.672</td>
</tr>
<tr>
<td>180</td>
<td>24.359</td>
<td>0.504</td>
</tr>
<tr>
<td>200</td>
<td>24.784</td>
<td>0.126</td>
</tr>
<tr>
<td>120-200</td>
<td>21.968</td>
<td>2.645</td>
</tr>
</tbody>
</table>

It should be mentioned that reference [90], of the Advisory Group for Aerospace Research and Development (AGARD) presents \( K_{Ic} = 34 \) MPa.m\(^{0.5}\) for the thickness of 25.4 mm. The apparently low values of \( K_c \) obtained in the present work may result from the fact that fatigue tests were used to infer \( K_c \) data, using \( \sigma_{\text{max}} \) and critical crack size. However, it is known that thin sheet material presents R curve behaviour, and should be tested following specific guidelines that were not used here. The presented values of \( K_c \) are to be taken as an approximation only, and are in broad agreement with data presented by Lucas FM Silva in reference [56].