Effect of corrosion exposure on the mechanical properties of Electron Beam Welded (EBWed) joints of aeronautical Aluminum Alloy 2024

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“Impossible is a word to be found only in the dictionary of fools”
— Napoleon Bonaparte
Abstract

The present work investigates the effect of corrosion exposure on the mechanical properties of electron beam welded (EBWed) joints of aeronautical aluminum alloy 2024. The alloy sheets were delivered in T3-condition and then subjected to artificial ageing heat treatment at 170°C prior to electron beam welding process in order to investigate the effect of artificial ageing on the mechanical properties as well as on the joining efficiency of the welded specimens.

Three different artificial ageing times were selected in order to simulate the under-ageing (UA), the peak-ageing (PA) and over-ageing (OA) conditions, based on a previous experimental research of (Alexopoulos et al., 2016b). Tensile, fatigue and fracture toughness mechanical tests were performed according to the international standard specifications.

It has been proved that the joining efficiency of the non-corroded EBWed specimens in T3 condition is approximately 70 %. Regarding the corrosion effect on the EBWed joints in T3-condition, no essential decrease of the mechanical properties was noticed up to 4 hours where the slight surface pitting corrosion is the dominant degradation mechanism. The artificial ageing before the welding process essentially affect the conventional yiel stress due to the elimination of the artificial ageing induced hardening precipitates from the welding process. However, an essential increase of the elongation at fracture was noticed in the (OA) condition where it takes its maximum value. Fracture of the welded joints always started from the root of the weld for all the artificial ageing conditions. This mechanism seems to alter with increasing exfoliation corrosion time for the T3 condition where the fracture occurred within the fusion zone.
Ξεκίνηση Εισαγωγής

Το κράμα 2024 αποτελεί ένα κράμα αλουμινίου - χαλκού και είναι το ευρύτερα χρησιμοποιούμενο κράμα αλουμινίου σε αεροναυπηγικές εφαρμογές. Με γνώμονα την συνεχή βελτίωση της αεροναυπηγικής βιομηχανίας, η ανάγκη για μικρότερο βάρος και μικρότερο κόστος στην κατασκευή των αεροσκαφών οδήγησε στο να ληφθούν υπόψη για εφαρμογή τεχνικές συγκόλλησης. Αυτές εξετάζονται προκειμένου να αντικαταστήσουν τις παραδοσιακές διαφορετικές συνδέσεις με ήλους, οι οποίες αυξάνουν σημαντικά το βάρος της κατασκευής, υποβαθμίζουν τις μηχανικές ιδιότητες του υλικού (π.χ. σε κόπωση).


Για το λόγο αυτό, η παρούσα Διπλωματική εργασία θα εξετάσει αρχικά την μηχανική συμπεριφορά των συγκολλημένων με δέσμη ηλεκτρονίων (electron beam) ελασμάτων από αεροναυπηγικό κράμα 2024. Στη συνέχεια θα εξεταστεί η επίδραση της τεχνητής γήρανσης πριν τη συγκόλληση και της διάβρωσης σε ήδη τεχνητά γηρασμένα ελάσματα που συγκολλήθηκαν με δέσμη ηλεκτρονίων.

Μεθοδολογία

Το κράμα αλουμινίου 2024 παραλήφθηκε σε θερμική κατάσταση Τ3 με ονομαστικό πάχος ελάσματος 3.2 mm. Το εν λόγω κράμα αλουμινίου είναι θερμικά κατεργασιμό, δηλαδή οι μηχανικές του ιδιότητες μεταβάλλονται ανάλογα με την θερμική κατασκευή τεχνητής γήρανσης που έχει υποστεί. Για το λόγο αυτό επίπεδα ελάσματα από κράμα 2024 υπεβλήθησαν σε τεχνητή γήρανση για τρεις διαφορετικούς χρόνους προκειμένου να εξεταστεί η επίδραση της πρότερης μικροδομής (θερμικής κατασκευής) των ελασμάτων στην ικανότητα συγκόλλησής τους. Οι συγκολλήσεις με δέσμη ηλεκτρονίων στα διαφορετικά θερμικά κατασκευασμένα ελάσματα πραγματοποιηθηκαν στις εγκαταστάσεις της Ελληνικής Αεροπορικής Βιομηχανίας στην Τανάγρα Βοιωτίας, προκειμένου να εξεταστεί η επίδραση της διάβρωσης στις μηχανικές ιδιότητες των συγκολλημένων δοκιμίων.

Διπλωματική εργασία χωρίστηκε σε τέσσερα κεφάλαια. Το πρώτο κεφάλαιο περιλαμβάνει την βιβλιογραφική ανασκόπηση σχετικά με το κράμα αλουμινίου 2024, τις συγκολλήσεις που έχουν πραγματοποιηθεί στο εν λόγω κράμα καθώς και την επίδραση της διάβρωσης σε συγκολλημένα ή όχι δοκίμα. Το δεύτερο κεφάλαιο αποτελείται από την περιγραφή των πειραματικών διατάξεων που χρησιμοποιήθηκαν, τη διεξαγωγή των πειραματικών δοκιμών και τη μεθοδολογία.
που ακολουθήθηκε για την αποτίμηση των μηχανικών ιδιοτήτων. Το τρίτο κεφάλαιο παρα-
θέτει όλα τα αποτελέσματα των πειραματικών δοκιμών που διεξήχθησαν και το τέταρτο
κεφάλαιο περιλαμβάνει την ανάλυση των πειραματικών αποτελεσμάτων και σύγκριση με τα
αντίστοιχα αποτελέσματα της βιβλιογραφίας.

Πειραματικά Αποτελέσματα

Τα πειραματικά αποτελέσματα που προέκυψαν από τις μηχανικές δοκιμές εφελκυσμού,
κόπωσης και δυσθραυστότητας, ομαδοποιήθηκαν σε τέσσερις κατηγορίες με σκοπό την
ανάλυση των παρακάτω επιδράσεων στις μηχανικές ιδιότητες των συγκολλήσεων:

• η κατεργασία της συγκόλλησης με δέσμη ηλεκτρονίων στο χράμα αλουμινίου 2024-
T3
• η διάβρωση στα συγκολλημένα με δέσμη ηλεκτρονίων δοκίμια 2024-T3
• η θερμική κατεργασία τεχνητής γήρανσης πριν από τη διεργασία της συγκόλλησης
• η διάβρωση στα θερμικά κατεργασμένα και στη συνέχεια συγκολλημένα δοκίμια

Αρχικά εκτιμήθηκε ότι η επίδραση της συγκόλλησης με δέσμη ηλεκτρονίων στις μηχανικές
ιδιότητες του AA2024 σε κατάσταση T3, μειώνει κατά 40 % το συμβατικό όριο διαρροής
σε σύγκριση με το μη συγκολλημένο χράμα. Το όριο εφελκυστικής αντοχής μειώθηκε κατά 30 %, γεγονός που αδυνατίζει στο συμπέρασμα ότι η απόδοση της συγκόλλησης είναι
περίπου 70 %. Η παραμόρφωση θραύσης διαφέρει κατά περίπου 85 % καθώς η θερ-
μικά επηρεασμένη ζώνη σε οποιοδήποτε κατάσταση μεγαλώνει κατά 40 %. Η συγ-
κόλληση μείωσε σημαντικά (κατά 43 %) το όριο διαρροής αντοχής σε κόπωση σε σύγκριση
με τα αντίστοιχα αποτελέσματα κόπωσης σε μη συγκολλημένα δοκίμια σε κατάσταση T3
όπως φαίνεται και στο Διάγραμμα 1. Τέλος, ο χρόνος συντελεστής έντασης τάσεων Κtt
μειώθηκε αισθητά κατά 18 % λόγω της συγκόλλησης.

Figure 1: Καμπύλη κόπωσης συγκολλημένου χράματος αλουμινίου 2024-T3 σε σύγκριση με το μη συγκολλημένο.
Σε δεύτερο επίπεδο, διεξήχθησαν πειραματικές δοκιμές για την διερεύνηση της διάβρωσης στα συγκολλημένα με δέσμη ηλεκτρονίων κράματα 2024-Τ3. Αποδείχθηκε ότι το συμβατικό όριο διαρροής δεν μειώνεται σημαντικά μέχρι τις 4 ώρες διάβρωσης, όπου ο κύριος μηχανισμός υποβάθμισης λόγω διάβρωσης είναι ο σχηματισμός επιφανειακών κοιλοτήτων. Ωστόσο, σημαντική μείωση της παραμόρφωσης θραύσης παρατηρήθηκε ήδη από τις 2 ώρες διάβρωσης. Για μεγαλύτερες ώρες έκθεσης σε περιβάλλον διάβρωσης (π.χ. 24 και 48 ώρες) το συμβατικό όριο διαρροής των συγκολλημένων δοκιμίων μειώθηκε κατά περίπου 40% και η παραμόρφωση θραύσης κατά 69%, όπως φαίνεται και στο Διάγραμμα 2. Το γεγονός αυτό που μπορεί να αποδοθεί στην εμφάνιση διάβρωσης αποφλοίωσης και τον σχηματισμό μικρο-ρωγμών στην διαβρωμένη επιφάνεια, γεγονός που μειώνει τη διατομή των δοκιμίων και ειδικότερα στην περιοχή της θερμικά επηρεασμένης ζώνης.

Η τεχνητή γήρανση πριν από τη συγκόλληση δεν επηρεάζει ουσιαστικά το συμβατικό όριο διαρροής, γεγονός που οφείλεται στην τήξη και επαναστεροποίηση του υλικού στην ζώνη τήξης και επομένως διαλυτοποιήθηκαν οι κατακρημνίσεις που είχαν δημιουργηθεί λόγω της προγενέστερης τεχνητής γήρανσης. Παρατηρήθηκε ωστόσο, αυξήση της εφελκυστικής ολκιμότητας στην κατάσταση της υπερ-γήρανσης, γεγονός που αποδύθηκε στην κατάσταση της περιοχής κοντά στη διεπιφάνεια ζώνης τήξης και θερμικά επηρεασμένης ζώνης, με τη δημιουργούμενη μικροδομή των κατακρημνίσεων να παραμορφώνεται πλαστικά λόγω της δημιουργούμενης μικροδομής των κατακρημνίσεων. Η μικροσκοπική θραύση όλων των συγκολλημένων δοκιμίων ξεκινούσε από τη βία της συγκάλλησης σε ολός τον αιτημένο χώρο της συγκάλλησης, γεγονός που συνδέεται με την επιφάνεια καταπλάκωσης της συγκάλλησης που παίζει σημαντικό ρόλο στη διαμόρφωση της συγκάλλησης.

Τέλος, διεξήχθησαν πειραματικές δοκιμές για την διερεύνηση της διάβρωσης στα θερμικά κατεργασμένα και στη συνέχεια συγκολλημένα δοκίμα αλουμινίου. Ο χρόνος διάβρωσης που επιλέχθηκε ήταν οι 2 ώρες έκθεσης, καθώς παρατηρήθηκε ότι όταν η διάβρωση είχε διαρροής σε αντίθεση με την ολικότητα η οποία μειώθηκε αισθητά εξαιτίας της φακελοποίησης λόγω
διάχυσης υδρογόνου. Αξίζει να σημειωθεί ότι το συμβατικό όριο διαρροής δεν επηρεάζεται αισθητά μετά από 2 ώρες έκθεσης σε διάβρωση στα θερμικά κατεργασμένα και συγκολλημένα δοχεία αλουμινίου, με την μεγαλύτερη μείωση (11%) να παρατηρείται για την κατάσταση T3 όπως φαίνεται και στο Διάγραμμα 3. Η παραμόρφωση θραύσης δεν εμφανίστηκε μεγάλη μείωση έπειτα από 2 ώρες διάβρωσης, με τη μέγιστη μείωση (-17%) να παρατηρείται στην κατάσταση της υπερ-γύρανσης.

FigURE 3: Πειραματικά αποτελέσματα του συμβατικού ορίου διαρροής για το μη διαβρωμένο συγκολλημένο κράμα αλουμινίου σε σύγκριση με το διαβρωμένο για 2 ώρες συγκολλημένο κράμα.
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I would like to express my gratitude to my supervisor Dr. Nikolaos D. Alexopoulos from the University of the Aegean for giving me the opportunity to work with him and his team. His guidance and useful comments during these last five years of my Bachelor Degree and especially over the last year, taught me that Science is not a cloud of specific subjects; or a series of causatic manipulations but the method of approaching any subject in life.

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Last but not least, I would like to thank my family and friends for their immense support during my undergraduate studies. Special thanks to my sister Sofia-Danai for her valuable inputs, opinions, and help over these five years and my old best friends George, Christine and Maria for their unconditional support and respect in every step of mine.

I would like to dedicate this thesis to my old friend Georgia who is barely connected with my childhood and left from this world early this year. Her passion and dedication for daily improvement in every aspect of life will always be remembered.
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<td>Al</td>
<td>Aluminum</td>
</tr>
<tr>
<td>AA</td>
<td>Aluminum Alloy</td>
</tr>
<tr>
<td>EBW</td>
<td>Electron Beam Welding</td>
</tr>
<tr>
<td>EBWed</td>
<td>Electron Beam Welded</td>
</tr>
<tr>
<td>ExCo</td>
<td>Exfoliation Corrosion</td>
</tr>
<tr>
<td>MPa</td>
<td>Megapascal</td>
</tr>
<tr>
<td>GPa</td>
<td>Gigapascal</td>
</tr>
<tr>
<td>kN</td>
<td>Kilonewton</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>BM</td>
<td>Base Metal</td>
</tr>
<tr>
<td>HAZ</td>
<td>Heat Affected Zone</td>
</tr>
<tr>
<td>FZ</td>
<td>Fusion Zone</td>
</tr>
<tr>
<td>UA</td>
<td>Under Ageing</td>
</tr>
<tr>
<td>PA</td>
<td>Peak Ageing</td>
</tr>
<tr>
<td>OA</td>
<td>Over Ageing</td>
</tr>
<tr>
<td>FSW</td>
<td>Friction Stir Welding</td>
</tr>
<tr>
<td>TIG</td>
<td>Tungsten Inert Gas</td>
</tr>
<tr>
<td>MIG</td>
<td>Metal Inert Gas</td>
</tr>
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List of Symbols

\begin{align*}
L&\&T & \text{cutting direction} \\
F & \text{applied force} & \text{kN} \\
E & \text{modulus of elasticity} & \text{GPa} \\
R_p & \text{yield stress} & \text{MPa} \\
R_{p0.2\%} & \text{conventional yield stress} & \text{MPa} \\
R_m & \text{ultimate yield strength} & \text{MPa} \\
A_f & \text{elongation at fracture} & \% \\
R & \text{ultimate yield stress} & \text{MPa} \\
K & \text{stress curve coefficient} & - \\
P & \text{applied axial load} & \text{N} \\
K_{cr} & \text{critical stress intensity factor} & \text{MPa} \sqrt{m} \\
V & \text{center-opening displacement at center hole} & \text{mm} \\
B & \text{total specimen width} & \text{mm} \\
Y & \text{half span of gage} & - \\
r_y & \text{plastic zone adjustment} & - \\
P_{max} & \text{max amplitude of C(T) specimen} & - \\
\alpha & \text{the physical dimension plus plastic-zone adjustment} & - \\
\sigma_m & \text{constant stress} & \text{MPa} \\
\sigma_a & \text{changing stress} & \text{MPa} \\
\Delta \sigma & \text{range of stress} & \text{MPa}
\end{align*}
I would like to dedicate this work to my sister Sofia-Danai who has always supported me and pushed me not to limit the challenge but to challenge my limits.
Overview
The organization of the thesis is as it follows. Chapter 1 outlines the context and the background of the research work. The project aims and objectives are described. Chapter 2 provides a detailed description of the materials used in this study, as well as the experimental methods used to characterize the electron beam welds. In the sequel, Chapter 3, discuss the results that occur from the three mechanical tests. In Chapter 4 the analysis of the experimental results are presented. Finally the last Chapter 5 summarizes the conclusions and provides suggestions and recommendations for future work.
Chapter 1

Introduction

This chapter starts with an in-depth literature review about the basic characteristics of aluminum alloys and welds. The basic information about the main problems of aviation industry are provided. The state of the art as well as the motivation for this Thesis are also analyzed.

1.1 Aluminum alloys

Aluminum constitutes a unique metal. The superior combination of properties that are provided by aluminum makes it applicable in a wide range, from an ordinary spoon to the most modern aircraft.

According to (Davis, 1993), aluminum has a density of only 2.7 g/cm$^3$, approximately one-third as much as steel (7.83 g/cm$^3$). The light weight as well as the high strength of some aluminum alloys, permits design and construction of strong, lightweight structures that have a great deal of advantages especially for space vehicles and aircraft as well as all types of land and water-borne vehicles.

What is more, it is noted that aluminum resists the kind of progressive oxidization that causes steel to rust away. The exposed surface of aluminum combines with oxygen to form an inert aluminum oxide film only a few ten-millionths of an inch thick, which blocks further oxidation. The aluminum oxide film does not flake off to expose a fresh surface to further oxidation, like iron rust. Should the protective layer of aluminum is scratched, it will reseal itself at once. The thin oxide layer itself clings tightly to the metal and is colorless and transparent invisible to the naked eye. The discoloration and flaking of iron and steel rust do not occur on aluminum. Appropriately alloyed and treated, aluminum can resist corrosion by water, salt, and other environmental factors, and by a wide range of other chemical and physical agents.

In the sequel, aluminum surfaces can be highly reflective. Radiant energy, visible light, radiant heat, and electromagnetic waves are efficiently reflected, while anodized and dark anodized surfaces can be reflective or absorbent. The reflectance of polished aluminum, over a broad range of wave lengths, leads to its selection for a variety of decorative and functional uses.

In addition, aluminum typically displays excellent electrical and thermal conductivity, but specific alloys have been developed with high degrees of electrical resistivity. These alloys are useful, for example, in high-torque electric motors. Aluminum is often selected for its electrical conductivity, which is nearly twice that of copper on an equivalent weight basis. The requirements of high conductivity and mechanical strength can be met by use of long-line, high-voltage, aluminum steel-cored reinforced transmission cable. The thermal conductivity of aluminum alloys, about 50 to 60 % that of copper, is advantageous in heat exchangers, evaporators, electrically heated appliances and utensils, and automotive cylinder heads and radiators.
Chapter 1. Introduction

The ease with which aluminum may be fabricated into any form is one of its most important assets. Often it can compete successfully with cheaper materials having a lower degree of workability. The metal can be cast by any method. It can be rolled to any desired thickness down to foil thinner than paper. Aluminum sheet can be stamped, drawn, spun, or roll formed. The metal also may be hammered or forged. Aluminum wire, drawn from rolled rod, may be stranded into cable of any desired size and type. There is almost no limit to the different profiles (shapes) in which the metal can be extruded (Davis, 1993).

1.2 Aluminum history

The existence of aluminum (Al) according to (Mathers, 2002) was postulated by Sir Humphrey Davy in the first decade of the nineteenth century and the metal was isolated in 1825 by Hans Christian Oersted. For more than 30 years it has been remained a laboratory curiosity. Some limited commercial production began after 1886 and the extraction of aluminum from its ore, bauxite, became a truly viable industrial process. The method of extraction was invented simultaneously by Paul Heroult, in France, and Charles M. Hall, in the USA, and this basic process is still in use today.

It is noted that the reactive nature of aluminum makes it difficult to be found in a metallic state in nature but it is present in the earth’s crust in the form of different compounds, of which there are several hundreds. One of the first alloys to be produced was aluminum—copper. It was around 1910, that the phenomenon of age or precipitation hardening in this family of alloys was discovered, with many of these early age-hardening alloys finding a ready use in the aeronautical industry.

It is also described that a major impetus to the development of aluminum alloys was provided by the two World Wars, particularly the Second World War when aluminum became the metal in aircraft structural members and skins. It was also in this period that a major advance in the fabrication of aluminum and its alloys came about with the development of the inert gas shielded welding processes of MIG (metal inert gas) and TIG (tungsten inert gas). This enabled high-strength welds to be made by arc welding processes without the need for aggressive fluxes.

The end of the Second World War follows an existed industry that had gross over-capacity and that was searching for fresh markets into which its products could be sold. There was a need for cheap, affordable housing, resulting in the production of the "prefab" aluminum bungalow made from the reprocessed remains of military aircraft. Domestic utensils, road vehicles, ships and structural components were all incorporating aluminum alloys in increasing amounts.

Nowadays, western Europe produces over 3 million tonnes of primary aluminum (from ore) and almost 2 million tonnes of secondary or recycled aluminum per year. It also imports around 2 million tonnes of aluminum annually, resulting in a per capita consumption of approximately 17 kg per year. Aluminum now accounts for around 80% of the weight of a typical civilian aircraft and 40% of the weight of certain private cars. It is used extensively in bulk carrier and container ship superstructures and for both hulls and superstructures in smaller craft. The new class of high-speed ferries utilizes aluminum alloys for both the super-structure and the hull. What is more, it is found in railway rolling stock, roadside furniture, pipelines and pressure vessels, buildings, civil and military bridging and in the packaging industry where over 400 000 tonnes are annually used as foil (Mathers, 2002).
Aluminum alloys are divided into two categories according to how they are produced: wrought alloys and cast alloys. The wrought category is well known, as aluminum alloys may be shaped by almost every available process, including rolling, extruding, drawing, forging, and a number of other, more specialized processes. Cast alloys are those that are poured molten into sand (sand casting) or high-strength steel molds, and are allowed to solidify to produce the desired shape. The compositions of wrought and cast alloys are quite different. For instance, wrought alloys must be ductile for fabrication, while cast alloys must be fluid for castability.

The designation system for wrought and cast aluminum alloys that classifies the alloys by major alloying additions. This system is now recognized worldwide under the International Accord for Aluminum Alloy Designations, administered by the Aluminum Association, and is published as American Standards Institute (ANSI) Standard H35.1.

In accordance with the Association system, each wrought or cast aluminum alloy is designated by a number to distinguish it as a wrought or cast alloy and to categorize the alloy.

A wrought alloy is given a four-digit number. The first digit classifies the alloy by alloy series, or principal alloying element. The second digit, if different than O, denotes a modification in the basic alloy. The third and fourth digits form an arbitrary number which identifies the specific alloy in the series. A cast alloy is assigned a three-digit number followed by a decimal. The first digit signifies the alloy series or principal addition; the second and third digits identify the specific alloy; the decimal indicates whether the alloy composition is for the final casting (0.0) or for ingot (0.1 or 0.2). The designation systems for wrought and cast aluminum alloys are shown in Table 1.1 and Table 1.2, respectively.

Specification of an aluminum alloy is not complete without designating the metallurgical condition, or temper, of the alloy. A temper designation system, unique for aluminum alloys, was developed by the Aluminum Association and is used for all wrought and cast alloys. The temper designation follows the alloy designation, the two being separated by a hyphen. Basic temper designations consist of letters; subdivisions, where required, are indicated by one or more digits following the letter. The basic tempers are:

- F-As-Fabricated. Applies to the products of shaping processes in which no special control over thermal conditions or strain hardening is employed. For wrought products, there are no mechanical property limits.
Chapter 1. Introduction

### Cast alloys

<table>
<thead>
<tr>
<th>Cast alloys</th>
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<tbody>
<tr>
<td>1xx.x</td>
<td>Pure aluminum</td>
</tr>
<tr>
<td>2xx.x</td>
<td>Al-Cu</td>
</tr>
<tr>
<td>3xx.x</td>
<td>Al-Mn+Cu and/or Mg</td>
</tr>
<tr>
<td>4xx.x</td>
<td>Al-Si</td>
</tr>
<tr>
<td>5xx.x</td>
<td>Al-Mg</td>
</tr>
<tr>
<td>6xx.x</td>
<td>Unused</td>
</tr>
<tr>
<td>7xx.x</td>
<td>Al-Zn</td>
</tr>
<tr>
<td>8xx.x</td>
<td>Alloys of Al-Zn with other elements</td>
</tr>
<tr>
<td>9xx.x</td>
<td>Alloys of Al with other elements</td>
</tr>
</tbody>
</table>

**Table 1.2:** Classification of casting aluminum alloys.

- **O-Annealed.** Applies to wrought products that are annealed to obtain the lowest strength temper, and to cast products that are annealed to improve ductility and dimensional stability. The O may be followed by a digit other than zero.

- **H- Strain-Hardened (Wrought Products Only).** Applies to products that have their strength increased by strain hardening, with or without supplementary thermal treatments to produce some reduction in strength. The H is always followed by two or more digits. (Table 1.3)

- **W-Solution Heat Treated.** An unstable temper applicable only to alloys that spontaneously age at room temperature after solution heat treatment. This designation is specific only when the period of natural aging is indicated; for example: W /2 hr.

- **T-Thermally Treated to Produce Stable Tempers Other than F, O, or H.** Applies to products that are thermally treated, with or without supplementary strain hardening, to produce stable tempers. The T is always followed by one or more digits. (Table 1.3) (Epstein, Kaufman, and Pollak, 1994)

#### 1.3.1 Aluminum alloys series 2xxx

Aluminum alloys in which copper is the principal alloying element, in percent of 2.6 - 6.3%, although other elements, notably magnesium may be specified, are those of 2xxx- series alloys. The alloys of this series are widely used in aircraft where their high strength (yield strengths as high as 455 MPa) is valued (Davis, 1993).

The series 2xxx can be heat treated and mixes in some situations high strength and ductility and in some cases good weld ability. Exhibit increased sensitivity to atmospheric corrosion. The most resistant alloys of 2xxx series are 2024 and 2014, which are widely used in aircraft and automobile (Epstein, Kaufman, and Pollak, 1994).

#### 1.3.2 Aluminum alloy 2024-T3

According to (Davis, 1993) aluminum alloy 2024 has a general use for truck wheels, many structural aircraft applications, gears for machinery, screw machine products, automotive parts, cylinders and pistons, fasteners, machine parts, ordnance, recreation equipment, screws and rivets.

(Ilman, 2014) mention that aluminum alloy 2024-T3 is widely used in aircraft as structural material for components such as fuselage skin, fuselage bulkhead and
1.3. Aluminum designation systems

First digit indicates specific sequence of treatments:

| T1   | Cooled from elevated-temperature shaping process and naturally aged to a substantially stable condition |
| T2   | Cooled from elevated-temperature shaping process, cold worked, and naturally aged to a substantially stable condition |
| T3   | Solution heat-treated, cold worked, and naturally aged to a substantially stable condition |
| T4   | Solution heat-treated, and naturally aged to a substantially stable condition |
| T5   | Cooled from elevated-temperature shaping process and then artificially aged |
| T6   | Solution heat-treated, and then artificially aged |
| T7   | Solution heat-treated and then overaged/stabilized |
| T8   | Solution heat-treated, cold worked, and then artificially aged |
| T9   | Solution heat-treated, artificially aged and then cold worked |
| T10  | Cooled from an elevated-temperature shaping process, cold worked and then artificially aged |

Table 1.3: Subdivisions of T Temper. (Epstein, Kaufman, and Pollak, 1994)

lower wing skins due to its high strength to weight ratio and good corrosion resistance.

It is mentioned that AA 2024-T3 is an Al−Cu alloy with the copper content in the range of 3.8 – 4.9% whereas T3 represents solution heat treated and naturally aged to achieve significant hardening and strength (Staley and Lege, 1993) whereas good corrosion resistance of AA 2024-T3 is resulted from native protective oxide film that forms on its surface (Chen et al., 2011). Aluminum alloy 2024-T3 which is used for aircraft structure is often exposed to aggressive environment such as water vapour and aqueous chloride solution and combined effects of atomic hydrogen produced by chemical or electrochemical reaction in a corrosive environment and dynamic stress can cause environmentally assisted fatigue crack propagation (EAFCP) damage. (Ilman, 2014)

The chemical composition of aluminum alloy 2024 can be seen in Table 1.4. Additionally, the mechanical properties of aluminum alloy 2024 as it have been presented in (Alexopoulos et al., 2016b) can be seen in Table 1.5.

<table>
<thead>
<tr>
<th>Element (% wt.)</th>
<th>Cu</th>
<th>Mg</th>
<th>Mn</th>
<th>Fe</th>
<th>Si</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>4.30%</td>
<td>1.50%</td>
<td>0.64%</td>
<td>0.50%</td>
<td>0.50%</td>
<td>0.10%</td>
<td>0.25%</td>
<td>0.15%</td>
<td>rem</td>
</tr>
</tbody>
</table>

Table 1.4: Chemical composition of AA2024 (wt.%).

<table>
<thead>
<tr>
<th>Yield stress (MPa)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Modulus of elasticity (GPa)</th>
<th>Elongation to fracture(%)</th>
<th>Critical stress intensity factor (MPa * √m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>345</td>
<td>485</td>
<td>70</td>
<td>18</td>
<td>83</td>
</tr>
</tbody>
</table>

Table 1.5: Mechanical properties of AA2024-T3 (Alexopoulos et al., 2016b).
1.3.3 Corrosion and corrosion products

Corrosion of metals is described to be the degradation of metals by chemical surface reactions with aggressive components of the environment. The environment consists of the entire surrounding in contact with the material. The primary factors to describe the environment are the physical state gas, liquid, or solid, the chemical composition, constituents and concentrations, as well as the temperature. In some specific cases other factors which can be important are the relative velocity of a solution and the mechanical loads on the material, including residual stress within the material.

The majority of materials experience some type of interaction with a large number of diverse environments, which has an impact on the material’s mechanical properties. To be more specific, the mechanical properties such as the ductility and the strength of material or other physical properties, even though its appearance deteriorate with corrosion; which sometimes can be extremely severe, when the result is cracking. The metals, which are in use in real life, may be structural materials such as steel reinforcements in concrete structures, or steel cables of suspension bridges; or they may be functional materials such as dental alloys, or copper leads for printed circuits. One of the most important missions of engineers is to identify the corrosion behavior of a metal and prevent the material’s failure.

Another topic of a great consideration, is that of hydrogen embrittlement in metals. Sometimes the very slight corrosion involving hydrogen uptake from the surface might have an deleterious effect and possibly cause severe damage on the material, which may result in cracking. For the majority of metals, such as iron and steels, or aluminum and its alloys, or titanium and its alloys, etc., the chemical reaction with atmospheric oxygen is spontaneous, i.e. involving a net gain in entropy of the metal/environment system together with its surroundings. (Kaesche, 2012)

The corrosion process which often the metallic materials present is normally electrochemical. To be more specific, electrochemical process is a chemical reaction in which there is transfer of electrons from one chemical species to another. Characteristically, metal atoms lose or give up electrons, which is called as an oxidation reaction.

For instance, the hypothetical metal M that has a valence of n (or n valence electrons) may experience oxidation according to the reaction in equation 2.3:

\[ M \rightarrow M^{n+} + ne^- \]  

(1.1)

in which M becomes an n positively charged ion and in the process loses its n valence electrons; e is used to symbolize an electron.

Two characteristic examples in which metals oxidize are those which are described in equations 1.2 and 2.5.

\[ Fe \rightarrow Fe^{2+} + 2e^- \]  

(1.2)

\[ Al \rightarrow Al^{3+} + 3e^- \]  

(1.3)

The site at which oxidation takes place is called the anode. It is usual that oxidation sometimes is called an anodic reaction.

As a reduction reaction is termed the reaction, where the electrons generated from each metal atom that is oxidized must be transferred to and become a part of another chemical species. A characteristic example is described in equation 2.6. Some metals undergo corrosion in acid solutions, which have a high concentration
of hydrogen (H) ions and the H ions are reduced as follows in the equation and as a result hydrogen gas \((H_2)\) is evolved.

\[
2H^+ + 2e^- \rightarrow H_2 \tag{1.4}
\]

The nature of the solution to which the metal might be exposed make it possible for other reduction reactions to be noticed. For instance, an acid solution having dissolved oxygen, reduction can be seen in equation 2.7.

\[
O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{1.5}
\]

It is noteworthy that cathode is the location at which reduction occurs. It is possible for two or more of the reduction reactions above to occur simultaneously. A complete electrochemical reaction must consist of at least one oxidation and one reduction reaction, and will be the aggregation of them. There must be an equal analogy between the oxidation and the reduction, otherwise all electrons generated through oxidation must be consumed by reduction. (Callister and Rethwisch, 1991)

Some of the most usually appeared, in the nature, forms of metallic corrosion can be classified into six forms: uniform, galvanic, crevice, pitting, intergranular and exfoliation corrosion. The causes and means of prevention of each of these forms are discussed briefly in the next subsections.

**Uniform corrosion**

![Figure 1.1: Uniform corrosion](Nace-International, 2018)

Uniform or general corrosion (Figure 1.1), can be described as a fairly uniform penetration (or thinning) over the entire exposed metal surface. The general attack results from local corrosion cell action where multiple anodes and cathodes are operating on the metal surface at any given time. The location of the anodic and cathodic areas continues to move about on the surface, resulting in uniform corrosion.

Uniform corrosion represents the greatest destruction of metal on a tonnage basis. What is more, uniform corrosion often results from atmospheric exposure, such as most of the time polluted industrial environments, which are exposure in fresh, brackish, and salt waters or in soils and chemicals. (Davis, 2000)

**Galvanic corrosion**

Galvanic corrosion (Figure 1.2) occurs when a metal or alloy is electrically coupled to another metal or conducting nonmetal in the same electrolyte. The three essential components are the following:
• materials possessing different surface potential
• a common electrolyte
• a common electrical path

![Figure 1.2: Galvanic corrosion (Wikipediaia, 2018)](image)

A mixed metal system in a common electrolyte that is electrically coupled will not experience galvanic corrosion, regardless of the proximity of the metals or their relative potential or size.

During galvanic coupling, corrosion of the less corrosion-resistant metal increases, and the surface becomes anodic, while corrosion of the more corrosion-resistant metal decreases, and the surface becomes cathodic. The driving force for corrosion or current flow is the potential developed between the dissimilar metals. The factors which affect the extent of accelerated corrosion resulting from galvanic coupling can be described as it follows:

• the potential difference between the metals or alloys
• the nature of the environment
• the polarization behavior of the metals or alloys
• the geometric relationship of the component metals or alloys

The differences in potential between dissimilar metals or alloys cause electron flow between them when they are electrically coupled in a conductive solution. The direction of flow and, therefore, the galvanic behavior depend on which metal or alloy is more active. Thus, the more active metal or alloy becomes anodic, and the more noble metal or alloy becomes cathodic in the couple. The driving force for galvanic corrosion is the difference in potential between the component metals or alloys. (Davis, 2000, Callister and Rethwisch, 1991)

**Crevice corrosion**

Electrochemical corrosion may also occur as a consequence of concentration differences of ions or dissolved gases in the electrolyte solution. Crevice corrosion (Figure 1.3) is a form of localized attack that occurs at narrow openings or spaces (gaps) between metal to metal or non-metal to metal components.

The results of this type of attack is that oxygen is more plentiful, where the concentration cell formed between the electrolyte within the crevice, which is oxygen starved, and the electrolyte outside the crevice. In this case, the material within the crevice acts as the anode, and the exterior material becomes the cathode (Figure 1.4). Some of the reason that might produce are the design, which might occur at gaskets,
1.3. Aluminum designation systems

washers, bolt holes, rolled tube ends, threaded joints, riveted seams, overlapping screen wires, lap joints, beneath coatings (filiform corrosion) or insulation (poultice corrosion).

Figure 1.3: Crevice corrosion (Cox-Engineering, 2018)

Crevice corrosion resistance may differ from one alloy-environment system to another. However, the effect of crevice corrosion may be in the active as well as the passive metals. It must be noted that the attack is more severe for passive alloys, especially those in the stainless steel group. A rapid metal loss and penetration of the metal in that area may be the result of a breakdown in the passive film within a restricted geometry. A great deal of interrelated metallurgical, geometrical, and environmental factors, as well as electrochemical reactions, affect both crevice initiation and propagation. (Davis, 2000, Callister and Rethwisch, 1991)

Pitting corrosion

Pitting corrosion (Figure 1.6) can be described as a highly localized form of corrosion that produces sharply defined holes. These holes may differ in diameter, but most usually are very small. Pits may be isolated from each other on the surface or so close together that they resemble a roughened surface. The differences in the cross-sectional shape of pits are shown in Figure 1.5. It is worth to be mention that the majority of engineering metal or alloy is susceptible to pitting.

Figure 1.4: Schematic illustration of the mechanism of crevice corrosion between two riveted sheets (Callister and Rethwisch, 1991)
The mechanism for pitting resembles the crevice corrosion in that oxidation takes place within the pit itself, with complementary reduction at the surface. Pitting may appear when one area of a metal becomes anodic with respect to the rest of the surface or when highly localized changes in the corroded in contact with the metal, as in crevices, cause accelerated localized attack. (Davis, 2000, Callister and Rethwisch, 1991)

**Intergranular corrosion**

Intergranular corrosion (Figure 1.7) is defined as the selective dissolution of grain boundaries, or closely adjacent regions, without appreciable attack of the grains
1.3. Aluminum designation systems

themselves. This dissolution is caused by potential differences between the grain-boundary region and any precipitates, intermetallic phases, or impurities that form at the grain boundaries. The actual mechanism differs with each alloy system. (Davis, 2000)

Precipitates that form as a result of the exposure of metals at elevated temperatures (for example, during production, fabrication, and welding) often nucleate and grow preferentially at grain boundaries. If these precipitates are rich in alloying elements that are essential for corrosion resistance, the regions adjacent to the grain boundary are depleted of these elements. The metal is thus sensitized and is susceptible to inter-granular attack in a corrosive environment.

These chromium-rich precipitates are surrounded by metal that is depleted in chromium; therefore, they are more rapidly attacked at these zones than on undepleted metal surfaces. Impurities that segregate at grain boundaries may promote galvanic action in a corrosive environment by serving as anodic or cathodic sites. Therefore, this would affect the rate of the dissolution of the alloy matrix in the vicinity of the grain boundary. (Davis, 2000)

Exfoliation corrosion

Exfoliation corrosion (Figure 1.8) characterize the form of localized corrosion that initially affects aluminum alloys in industrial or marine environments. The mechanism of this corrosion proceeds laterally from initiation sites on the surface and generally proceeds intergranularly along planes parallel to the surface. The result of this corrosion products is the layered or flake like appearance which is cased by the attack in the grain boundaries that force metal away from the underlying base material.

In the heat treatable aluminum-copper-magnesium (2xxx) and aluminum-zinc-magnesium-copper (7xxx) alloys, exfoliation corrosion has usually been confined to relatively thin sections of highly worked products with an elongated grain structure. In extrusions, the surface is often quite resistant to exfoliation because of its recrystallized grain structure. Subsurface grains are uncrystallized, elongate, and vulnerable to exfoliation. In aluminum-copper-magnesium (2xxx) alloys, artificial aging to the T6 or T8 condition provides improved resistance. (Davis, 2000)
1.4 Corrosion of aluminum alloy 2024

Aluminum alloy 2024-T3 is one of the most widely used aluminum alloys in the aircraft. Consequently, a vast number of mechanical tests have been conducted, over the years, in order to assess the degree of corrosion damage on the structural integrity of aluminum alloy 2024. More precisely, several articles have tried to depict the impact of corrosion and fatigue on the structural integrity of aluminum alloy 2024-T3 as well as the resulting of micro-cracking on the fatigue behavior of the pre-corroded specimens.

(Alexopoulos and Papanikos, 2008) researched the corrosion exposure time effect, on the mechanical properties degradation of AA2024-T3 (3.2 mm nominal thickness). For this investigation, pre–corroded specimens exposed for different periods of time in exfoliation corrosion solution (ExCo). Subsequently, tensile and fracture toughness tests have been undertaken in order to conclude about the effect of corrosion. It has been proved that the “effective thickness”, which is the cross-sectional area of specimens which supposed to be unaffected by micro-cracks, decreases exponentially with increasing exposure time to the ExCo solution, as it described by Figure 1.9. Due to the propagation mechanism of micro–cracks. Characteristically, it has been noticed that the thickness of the test piece, after 96 hours of exposure to the solution, was reduced by 0.74 mm, as the actual reaming thickness was 2.46 mm (3.2-0.74 = 2.46 mm). As a result of the effective thickness degradation, the mechanical properties reduced. In detail, the modulus of elasticity decreases proportionally to the decrease in the effective thickness of specimens. What is more, It has been noticed that the yield strength, of aluminum alloy 2024-T3, has also been affected by the corrosion exposure due to cross-section decrease at higher exposure times as well as on ductility due to the combination of hydrogen embrittlement and cross-section degradation.

(Petroyiannis et al., 2005) have tried to provide evidence of corrosion induced hydrogen embrittlement of the aircraft aluminum alloy 2024. For this experimental procedure, tensile mechanical tests have firstly been conducted in 2024 aluminum alloys specimens of 3.0 mm nominal thickness, cut in longitudinal-tranverse (LT) direction, after being exposed, for 0.3 to 96 hours, to EXfoliation CORrosion solution.
1.5. Precipitation Heat Treating

As a result, the yield and ultimate tensile stress as well as the tensile ductility deteriorate after exfoliation corrosion exposure. The second part of their investigation has been followed the artificial ageing of the corroded specimens, in order to assess in which degree the mechanical properties can rehabilitate. It has proved that with the mechanical removal of the corroded layers, the yield and ultimate stress can be restored almost to their initial values. For the tensile ductility, it has been noticed that it can be restored to the level of the non-corroded material only after the heat treatment at 495°C where the trapped hydrogen is released.

Preliminary works in the literature (Jones et al., 2008, Van Der Walde and Hillberry, 2007) that are trying to quantify the damage in the properties of the aluminum alloy 2024 material from corrosion have been focused on the microstructure of specimens as well as the initiation mechanism, the propagation and the shape of microcracks. It has been researched the initiation and shape development of corrosion-nucleated fatigue cracking. It has been suggested that crack nucleation, most probably take place along the perimeter of a pit where the multiple stress amplification effects are particularly pronounced. Furthermore, it has been noticed that there are no microstructural continuities, or where the grain orientation is predisposed for the ensuing growth along crystallographic slip planes.

(Alexopoulos, 2009) estimated the effect of different artificial ageing conditions of the aluminum alloy 2024-T3 on the mechanical properties degradation due to corrosion exposure. The experiments which have been undertaken, for the different artificial aging conditions, were tensile and fracture toughness mechanical test. The specimens have been subsequently exposed to exfoliation corrosion environment after the heat treatment. The article describe that the microstructure analysis showed that for the reference (T3) and peak-ageing condition the corrosion-induced surface pits were followed by formation of a microcrack network. For the over-ageing condition large surface pits were noticed. In addition the tensile test results showed that the higher the over-ageing condition is, the lower degradation due to corrosion exposure the alloy has present. The fracture toughness $K_{cr}$ which have been calculated, confirms that the decrease due to corrosion is lower for the specimens of over-ageing conditions. It is important to note that the $K_{cr}$ values calculated, showed that the degree of decrease due to corrosion damage is negligible for the over-ageing condition.

1.5 Precipitation Heat Treating

The heat treating, which refers to any of the heating and cooling operations of a metal product may change the mechanical properties, the metallurgical structure, or the residual stress state of it. The strength and hardness of the precipitation hardenable wrought and cast aluminum alloys, can increase with the heat treating application. Both types of aluminum alloys with heating may present a strength degradation and an increase of ductility (annealing). In addition, the metallurgical reactions may vary with type of alloy and with degree of softening desired. (Wolfgang and Gunther, 1968)

In some metal alloys, which include aluminum –copper, copper – beryllium, copper – tin, and magnesium - aluminum, in which strength and hardness be enhanced by the formation of extremely small uniformly dispersed particles of a second phase within the original phase matrix. More precisely, this must be accomplished by phase transformations that are induced by appropriate heat treatments. The procedure is designated as precipitation hardening or “Artificial Ageing” because the
small particles of the new phase are termed “precipitates”. Even though the heat
treatment procedures are similar for the precipitation hardening and the treating
of steel to form tempered martensite; there are two different phenomena which
should not be confused. The difference lies in the mechanisms by which hardening
and strengthening are achieved. These should become apparent as precipitation
hardening is explained. (Callister and Rethwisch, 1991)

The explanation of the heat treatment procedure is facilitated by use of a phase
diagram. It must be noted that in practice, many precipitation-hardenable alloys
contain two or more alloying elements.

Figure 1.10 is a hypothetical phase diagram that describes the appreciable max-
imum solubility of one component in the other and the order of several percent;
as well as the solubility limit that rapidly decreases in concentration of the major
component with temperature reduction. It must be noted that the maximum solu-
bility corresponds to the composition at point M. The solubility limit boundary be-
tween the $\alpha$ and $\alpha + \beta$ phase fields diminishes from this maximum concentration
to a very low B content in A at point N. In addition, the composition of a precipitation-
hardenable alloy must be less than the maximum solubility. These conditions are
necessary but not sufficient for precipitation hardening to occur in an alloy system.
Precipitation hardening is accomplished by two different heat treatments, the solu-
tion heat treatment and the precipitation heat treating.

### Solution heat treating

Concerning the solution heat treatment, all solute atoms are dissolved to form a sin-
gle-phase solid solution. For an alloy of composition $C_0$ in Fig. 1.10, the treat-
ment consists of heating the alloy to a temperature within the phase field—say, $T_0$ and
waiting until all the $\beta$ phase, that may have been present, is completely dissolved.

In this stage, the alloy consists only of an $\alpha$ phase of composition $C_0$. In the
sequel, a rapid cooling or quenching to temperature $T_1$, which for many alloys is
room temperature, is applied to the extent that any diffusion and the accompanying
formation of any of the $\beta$ phase are prevented. In this way, a non-equilibrium situ-
atation exists in which only the $\alpha$-phase solid solution supersaturated with B atoms is
present at $T_1$. It must be noted that in this state the alloy is relatively soft and weak.
In addition, for most alloys diffusion rates at $T_1$ are extremely slow, such that the
single phase is retained at this temperature for relatively long periods.

As it described by Fig. 1.11, the precipitation heat treatment, the supersaturated
solid solution is ordinarily heated to an intermediate temperature $T_2$ within the $\alpha$+b
two-phase region, at which temperature diffusion rates become appreciable.

### Precipitation heat treating

The precipitation heat treatment stage includes the heat of the supersaturated $\alpha$ solid
solution to an intermediate temperature $T_2$ in Fig. 1.10. In this part the $\alpha+\beta$ two-
phase region, the temperature diffusion rates become appreciable. The $\beta$ precipitate
phase begins to form as finely dispersed particles of composition $C_\beta$, which process
is sometimes termed “ageing”. After the appropriate ageing time at $T_2$, the alloy
is cooled to room temperature; normally, this cooling rate is not an important con-
sideration. Both solution and precipitation heat treatments are represented on the
temperature-versus-time plot, in Fig. 1.11. The character of these particles, and sub-
sequently the strength and hardness of the alloy, depend on both the precipitation
Precipitation hardening is commonly employed with high-strength aluminum alloys. Although a large number of these alloys have different proportions and combinations of alloying elements, the mechanism of hardening has perhaps been studied most extensively for the aluminum−copper alloys.

The \( \alpha \) phase is a substitutional solid solution of copper in aluminum, whereas the intermetallic compound \( \text{CuAl}_2 \) is designated the \( \theta \) phase. For an aluminum−copper alloy of composition 96 wt% Al 4 wt% Cu, in the development of this equilibrium \( \theta \) phase during the precipitation heat treatment, several transition phases are first formed in a specific sequence. The mechanical properties are influenced by the character of the particles of these transition phases. During the initial hardening stage, copper atoms cluster together in very small and thin discs that are only one or two atoms thick and approximately 25 atoms in diameter; these form at countless positions within the \( \alpha \) phase. The clusters, sometimes called GP zones, are so small that they are really not regarded as distinct precipitate particles. However, with time and the subsequent diffusion of copper atoms, GP zones become particles as they increase in size. These precipitate particles then pass through two transition
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phases (denoted as $\theta'$ and $\theta''$), before the formation of the equilibrium $\theta$ phase as it shown in Fig.1.12. (Callister and Rethwisch, 1991)

![Figure 1.12: Schematic depiction of several stages in the formation of the equilibrium precipitate ($\theta$) phase. (a) A supersaturated $\alpha$ solid solution. (b) A transition, ($\theta''$), precipitate phase. (c) The equilibrium $\theta$ phase, within the $\alpha$ -matrix phase. (Callister and Rethwisch, 1991) ]

(Alexopoulos et al., 2017) have extensively investigated the effect of artificial ageing conditions on precipitation kinetics and tensile mechanical behavior of aluminum alloy 2024. Figure 1.13a summarizes the conventional yield stress $R_{p0.2\%}$ results and Figure 1.13b the elongation at fracture $A_t$ results. It has been proved that for the case of 170°C, the conventional yield stress $R_{p0.2\%}$ increase with the semi-log scale of ageing time up to 15 h where the under-ageing regime is evident. In the sequel, an increase in yield stress is evident from this point on for all investigated temperatures up till a maximum value. The peak-ageing for 170°C value was evaluated to be 487 MPa for 48 hours of artificial ageing, where a plateau of the conventional yield stress is evident that is a characteristic of the PA region. The over-ageing condition is noticed up to 98 h, where the conventional yield stress was noticed to essentially decrease. It must be underlined that this essential conventional yield stress increase in the peak-ageing condition is followed by an elongation at fracture decrease for 170°C. It must be underlined that according to the same investigation, the increase of approximate 100 MPa in conventional yield stress $R_{p0.2\%}$ (more than 26 % increase) is redeemed with an essential decrease in elongation at fracture $A_t$ (from 18.2 % to 8.1 %, i.e. more than 55 % decrease).

1.6 Aluminum Welding

Welding is described by (Mathers, 2002), as the joining of two components by a coalescence of the surfaces in contact with each other. There are two ways in which this coalescence can be achieved. One can be by melting the two parts together, "fusion welding". The other way is by bringing the two parts together under pressure, perhaps with the application of heat, in order to create a metallic bond across the interface, the so called solid phase joining.

The solid phase joining represent one of the oldest joining techniques. For instance, blacksmith’s hammer welding having been used for iron implement manufacture for 3500 years. The brazing welding constitute an ancient welding process. In detail, involves a braze metal which melts at a temperature above 450°C but below the melting temperature of the components to be joined so that there is no melting of the parent metals.
1.6. Aluminum Welding

![Figure 1.13: (a) Conventional yield stress $R_{p0.2\%}$ values for the different artificial ageing conditions of AA2024. (b) Elongation at fracture $A_f$ values for the different artificial ageing conditions of AA2024. (Alexopoulos et al., 2017)](image)

Nowadays, the modern solid phase techniques are typified by friction welding. It must be noted that there are two ways of achieving a fusion welding. On the one hand, there the weldings that involve the melting and fusion of the parent metals, which are known as autogenous welding. On the other hand, many welding processes involve the addition of a filler metal which is introduced in the form of a wire or rod and melted into the joint. In this occasion the melted parent metal with the filler metal form the the weld metal.

In the best possible way, the weldment, more specifically the complete joint, which include the weld metal, heat affected zones (HAZ) and the adjacent parent metal, should have the same mechanical properties as the parent metal.

However, there are a great deal of problems, that are related with the welding of aluminum. Consequently, the ideal achievement of the same mechanical properties, between the parent metal and the weldment, is impossible. Some of the traits that make a contribution on the loss of properties, in real life, are presented above (Mathers, 2002):

- gas porosity
- oxide inclusions and oxide filming
- solidification (hot) cracking or hot tearing
- reduced strength in the weld and HAZ
- lack of fusion
- reduced corrosion resistance
- reduced electrical resistance

1.6.1 Aluminum alloys 2xxx weldability

The composition of aluminium alloy 2xxx, which includes a solid solution of copper (Cu), result in high strength, due to the formation of a precipitate of copper aluminide CuAl$_2$. In addition, copper (Cu) permits precipitation hardening as well as it reduces corrosion resistance, ductility and weldability. This precipitate might have a
great deal of benefits. In order to utilize the maximum of it, this precipitate must be
present as an equal and finely divided submicroscopic precipitate within the grains.
This might be possible by solution treatment followed by a mindful controlled age-
ing heat treatment. At the condition of annealing, a coarse precipitate is composed
along the grain boundaries. Moreover in the overaged condition the submicroscopic
precipitates become rough. The strength of the alloy is less than that of the correctly
aged condition, in both of the above cases.

The aluminum alloys of 2xxx series, for many years were supposed to be un-
weldable. In the premature aluminum–copper alloys the copper proportion was some
2–4%. Consequently, the alloys were extremely sensitive to hot shortness. Since the
analogy of copper was increased to 6% or more, the weldability was essentially im-
proved due to the large amounts of eutectic available to back-fill hot cracks which
have been composed. It must be mentioned that, at 548°C, in the aluminum the limit
of copper of solid solubility of copper is 5.8%. The form of copper at ambient is a satu-
rated solid solution with particles of the hardening phase copper aluminate, \( \text{CuAl}_2 \),
within the grains as a fine or coarse precipitate or at the grain boundaries.

It must be noted that the welding on the age-hardened structure, redissolve the
precipitates and affect the ultimate tensile strength up to 50% in a T6 condition alloy.
For instance, the weldable alloy 2219 (AlCu6) can recover some of this strength loss
by artificial ageing but this is usually accompanied by a reduction in ductility. The
best results in this alloy are obtained by a full solution treatment and ageing after
welding, which is not often achievable in an overall fabricated structure. For the
aluminum alloy 2014 (AlZnMgCu), which is supposed to be one of the less weldable,
is mentioned that the heat-treatment might help to recover some tensile strength but
the improvement may cause a further reduction in ductility. Finally, it is noteworthy
that filler metals of similar composition, as for example Al alloy 2319 (AlCu6) exist
and weld metal strengths can suit with the properties in the HAZ. (Mathers, 2002)

1.6.2 Welding Techniques

The principal processes used for the joining of aluminium are separated in five big
categories.

The first category includes the fusion welding processes, where multiple weld-
ing techniques have been developed. The Tungsten inert gas welding and the Metal-
lic arc inert gas shielded are two of those. Both of them can achieve high-quality and
may also be manual, mechanized or fully automated. The first welding process uti-
lizes a non-consumable electrode and can be used with or without the addition of
wire additions. The Metallic arc inert gas shielded utilizes a continuously fed wire
and can be high deposition rate with twin wire additions. What is more, Manual
metal arc and Oxy-gas constitutes two more fusion welding process with limited
application as there are obsolescent methods. The first uses a flux-coated consum-
able electrode for non or lightly stressed joints and the latter offer low weld metal
quality as well as unstressed joints. In addition, Electron beam welding and Laser
welding are two precision welding processes that are used especially in aerospace
and defense industries. These methods require high capital cost Moreover, Electro-
gas is the last fusion welding process with limited applications. It is especially used
in large bus bars and cause porosity problems.

The second category, consist of the Welding with fusion and pressure processes.
Magnetically impelled arc butt welding is the only method in this category which is
fully automated and require capital equipment but has lower cost than flash butt.
The third category, consist of the Resistance and flash welding processes. To begin with Spot, projection spot seam welding is used especially for lap joints in sheet metal work, automotive, hollowware and aerospace industry. It needs high capital cost as well as high productivity. The Weld bonding process is a combination of spot welding through an adhesively bonded lap joint. It is usually used in automotive industry and can achieve very good fatigue strength. Furthermore, the High-frequency induction seam is a high capital costly method with high production rates. Finally, the Flash butt welding consist an expensive as well method that is used for dissimilar metal joints, in line and miter butt joints in sheet.

The fourth welding category, consist of the Stud welding processes. The Condenser, capacitor discharge method use a stud of 6mm max diameters. It is used especially in insulating pins, pan handles, automotive trim and electrical contacts. The second process is the Drawn arc that use a stud of 5–12mm diameters.

The last welding category, is the Solid phase bonding. Friction welding process is frequently used nowadays for joining dissimilar metals. It requires capital equipment and it is used for butt joints in round, rectangular bar and hollow sections. This process use flat plate and achieve rolled section butt welds (friction stir). Also, the Explosive welding is used for dissimilar metal joints and create field pipeline joints. What is more, the Ultrasonic welding and Cold pressure welding processes utilize lap joints in foil and are used for thin to thick sections. Finally, the Hot pressure welding create roll bonded lap joints and it used for edge to edge butt joints. (Mathers, 2002)

1.6.3 Electron beam welding (EBW) process

The application of electron beam welding (EBW) was started in the late fifties as an industrial welding process. The initial use was in the aircraft and aerospace industries as well as in the nuclear due to the high quality and reliability of the joints that offers. In the sequel, electron beam welding has been applied successfully in the medium—thickness welding in workshops and the welding of high—precision parts (Sun and Karppi, 1996). Electron beam welding in accordance with (Mathers, 2002) resemble laser welding process. It is a power beam process preferably fitted in the welding of close square joints in a single pass. It is noteworthy that the process of the electron beam welding process utilizes a vacuum chamber, where a high energy density beam of electrons of the order of 0.25 – 2.5 mm in diameter is generated.

A heating a tungsten filament to a high temperature is used in order for the beam to be generated. As a consequence, a stream of electrons is formed, that are accelerated and focused magnetically to create a beam that gives up its energy when it impacts the target – the weld line. A deep penetration is achieved in this way, with a keyhole penetration mode at fast travel speeds, as it is described in Figure 1.14, providing low overall heat input.

The most important parameters for the electron beam welding (EBW) process are the following:

- the accelerating voltage, a 150 kV unit being capable of penetrating 400 mm of aluminum
- the current applied to the electron gun filament, generally measured in milliamperes
- the travel speed
During the welding process, the item to be welded is generally mounted on an NC manipulator and the gun being held stationary. Most of the time, non-welded joint parts need to be closely fitting and are usually machined. The addition of a filler metal, is not usual, but in case there is a filler which gaps, leads to the creation of a concave at the weld face.

The electron beam welding (EBW) process may provide excellent results in a cost-effective manner, especially for batch type adjustments where a number of items can be loaded into the chamber as well as for high-precision welding, perhaps of finished machined items where minimal distortion is required.

However, the process deals with a great deal of disadvantages. For instance the electron beam welding (EBW) process requires the welding to be conducted in a vacuum chamber. Consequently, this render at the use of expensive diffusion pumps for the process as well as a sealed chamber, large enough to accommodate the item to be welded. What is more, it is required a costly equipment as well as a precision at engined of the components, so as to give an accurate fit-up. In addition to these the time taken to pump the chamber down, leads to make the process non-competitive with more conventional fusion welding processes.

A specific issue which is presented in the welding of aluminum alloys, with the electron beam process, is metal vapour from the weld pool causing arcing inside the electron beam gun. In detail, for those alloys which contain low boiling point alloys, for example magnesium and zinc this is a particular problem. More precisely, cavities are formed in the weld as the arcing inside the gun interrupts the beam A way to avoid this issue may be by trapping the vapour, or by changing the beam path with a magnetic field, or by shutting off the beam as soon as arcing is detected and reestablishing the beam immediately the vapour has dispersed. Should this can be done extremely quick, the weld pool remains molten and cavity formation is avoided. The main drawback of this is that it is generally insufficient to cause a loss of strength.

Regarding the non-heat-treatable alloys, the weld can be performed without the addition of filler wire. However, hot cracking problems may be encountered in the more sensitive grades and in the heat-treatable alloys. Additionally, heat affected zones (HAZ) are small and strength losses are less than would be experienced in a similar thickness arc welded joint (Mathers, 2002).
1.7 State of the art

Many researchers have investigated multiple welding techniques of aluminum alloy 2024. To be more specific, the already existing works in the literature have explicitly focus on fusion welding techniques as well as solid phase techniques on aluminum alloy 2024.

Regarding the fusion welding techniques, it has been noticed that aluminum alloys show high strength, good formability and weight savings but are difficult to be joined, because of their poor dentritic solidification microstructure and the development of porosity after welding (Li et al., 2018).

Concerning friction stir welding process (FSW), which is a solid phase process, it has been described from (Genevois et al., 2005) that allows the elimination of the solidification defects and is well suited for joining aluminum alloys, especially the non-weldable such as 2000 Al alloys. In this study, it has been characterized the 2024-T351 and 2024-T6 weld microstructures with the use of a combination of experimental techniques. What is more, the precipitate distribution has been determined quantitatively in order to understand the variation of the local mechanical properties. An additional work on friction stir welding AA 2024 from (Lockwood, Tomaz, and Reynolds, 2002) examined the global and local mechanical response of the weld experimentally and numerically. Concerning the tensile properties it is described that FSW AA 2024-T351 exhibits a conventional yield stress ($R_{p0.2\%}$) of 272 MPa, an ultimate tensile strength ($R_m$) of 426 MPa and the elongation at fracture ($A_f$) was 8.6 %. This lead to a 72 % joint efficiency regarding the $R_{p0.2\%}$ for the FSW process.

In another study which investigated the macroscopic grain structures of Al alloy TIG welds (Norman, Drazhner, and Prangnell, 1999), were presented the results of commercial aluminum alloy AA2024 which has been autogenously TIG welded using a range of processing conditions. In this investigation, the welds microstructure quality have been proved that is affected by the processing conditions. For instance at high welding speeds and low power densities, it is possible to promote the formation of an equiaxed-dendritic microstructure in the center of autogenous welds due to the development of an under cooled liquid ahead of the moving solid-liquid interface, which provides the correct thermal conditions for the nucleation and growth of new grains. What is more, (Owen et al., 2003) in a research conducted to provide non-destructive information about the residual stress field in TIG-welded 2024 Al alloy, proved that the maximum tensile stresses are approximately 60 % of the original yield stress for the plate.

What is more, a further work of (Alfieri et al., 2012) on laser welding of AA 2024 of 3.2 mm nominal thickness using a Yb:YAG disc laser, investigated the importance of adequate joint preparation to improve weld quality and also examined the effect of heat input and beam defocusing on the weld quality in terms of macro porosity content. It was proved that the tensile strength of welded joints was measured to be greater than 2/3 of the BM and therefore, gave ground for industrial application.

Concerning the electron beam welding (EBW) process on aluminum alloy 2024 little has been explicitly documented in the literature. (Wanjara and Brochu, 2010) on a previous work, about aluminum alloy 2024 in T3 condition, have tried to determine the influence of parametric conditions on the characteristics of the electron beam welding in the joining process. In detail, this investigation has been focused on the weld geometry, the micro-structure and mechanical properties as a function of the process conditions, for optimizing the parametric conditions, on the examination of the joints. An additional work on EBWed AA2024 (Çam et al., 1999) has indicated that the joint efficiencies are between 90 and 70 % in terms of the yield and
ultimate tensile strengths, respectively. That was attributed to strain concentration in the fusion zone and significant losses in the ductility. It is worth to mention that elongation at fracture efficiency was considered to be very low, almost 6.3 % owing to the significant undermatching in the weld zones.

However, there are previous works on electron beam welding on various aluminum alloys, such as the super aluminum 7075, which can not be successfully welded with conventional fusion welded methods according to (Arata, Ohsumi, and Hayakawa, 1976). In this report, an effort has been made in order to characterized the EB welding technique, which has been considered as a worth trying application on these material. More precisely, it has been reported that the partial penetration phenomenon of EB welded aluminum alloys is considerably affected by vaporizing alloying elements, such as Zn and Mg which are in high contain. What is more, for the same aluminum the tensile strength has been considered to reach as high as yield strength of the base metal if proper welding condition is employed. Nevertheless, it is worth to be mention that fracture toughness of electron beam welded zone of 7075 exceeds that of base metal, providing superior weld toughness.

1.8 Motivation

Many researchers have investigated multiple welding processes on aluminum alloy 2024. Nevertheless, It is evident that very little progress has been made on the electron beam welding process of AA 2024. To this end, the present investigation of this Thesis about the electron beam welded aluminum alloy 2024 is important. This research not only is it focused on multiple artificial ageing conditions for the electron beam welded 2024 aluminum alloy, but it also investigates the deleterious effect of corrosion on these conditions. The three mechanical tests, which have been undertaken, will contribute to export a complete analysis about the perform of the electron beam welded 2024 aluminum alloy.
Chapter 2

Experimental Procedure

This section introduces the methodological approach that was followed in order to evaluate the mechanical properties of electron beam welded 2024 aluminum alloy as well as the corrosion problem effect on the welded specimens. In detail, this chapter aims to provide information for the experimental procedure, the materials used for the research as well as the methodology used for the analysis of the experimental tests.

2.1 Methodology procedure

The methodology that was followed for the current investigation for the effect of corrosion exposure on the mechanical properties of electron beam welded AA 2024 specimens is schematically shown in the flow chart in Fig. 2.1.

Initially, rectangular sheets (35 cm x 50 cm) of AA 2024 were exposed to artificial ageing heat-treatment at 170°C for different ageing times in order to simulate the different ageing conditions, namely Under-Ageing (UA), Peak-Ageing (PA) and Over-Ageing (OA). Afterwards, the electron beam welding (EBW) process was performed by the Hellenic Aerospace Industry. Tensile, fatigue and fracture toughness C(T) specimens were machined from the electron beam welded sheets according to the (ASTM-E8, 2011), (ASTM-E466, 2002) and (ASTM-E561, 1988) specifications, respectively.
Chapter 2. Experimental Procedure

The experimental procedure was divided into two categories. In the first category, the electron beam welded (EBWed) tensile, fatigue and fracture toughness specimens were exposed to mechanical testing in order to evaluate the mechanical properties degradation due to the welding process.

In the second category, all the specimens were pre-exposed to laboratory exfoliation corrosion solution (ExCo), according to (ASTM-G34, 2001) specification, for different times up to 48 h. Prior to corrosive solution exposure, the specimens were ground up to 1200 grit and cleaned with alcohol according to (ASTM-G-1, 2011) specification. Subsequently, the pre-corroded tensile and fracture toughness specimens were subjected to mechanical testing for the evaluation of the effect of corrosion on the mechanical properties degradation of EBWed AA2024 specimens.

2.2 Material and specimens

The material used for the present investigation was a wrought aluminum alloy 2024 – T3 in sheet form of 3.2 mm nominal thickness. The chemical composition (wt.%) of the alloy used is shown in the following Table 2.1. The T3 condition included solution heat-treatment to 495°C, cold worked and naturally aged at room temperature (25°C) to a substantially stable condition.

<table>
<thead>
<tr>
<th>Element (% wt.)</th>
<th>Cu</th>
<th>Mg</th>
<th>Mn</th>
<th>Fe</th>
<th>Si</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>4.30%</td>
<td>1.50%</td>
<td>0.64%</td>
<td>0.50%</td>
<td>0.50%</td>
<td>0.10%</td>
<td>0.25%</td>
<td>0.15%</td>
<td>rem</td>
</tr>
</tbody>
</table>

**Table 2.1: Chemical composition of AA2024 (wt..%).**

The tensile, fatigue and fracture toughness C(T) specimens were cut parallel to the L rolling direction and according to (ASTM-E8, 2011), (ASTM-E466, 2002) and (ASTM-E561, 1988) specifications, respectively.

The waterjet machining technology was used for the cutting of the specimens, due to the fact that this method is one of the most recent developed and advanced in the industry of material processing. According to (Mathers, 2002), one of the most important advantages of water jet cutting is that it the laser or plasma-arc is that no heat is used in the process. As a result, there are no heat affected zones and no thermal distortion. It is worth to be mention that parts can be cut very accurately and cut part tolerances are very small, simplifying the task of fitting up for welding.

The plates which have been received for the mechanical testing are shown in the Fig. 2.2 and Fig. 2.3. The plates on Fig. 2.2 include the tensile and C(T) fracture toughness specimens. In addition, Fig. 2.2 includes the fatigue specimens.

**Figure 2.2: Electron beam welded tensile and fracture toughness C(T) specimens of the aluminum alloy 2024.**

The geometry of the tensile specimens, that were used for this Thesis, is depicted in the Fig. 2.4 with dimensions of 60 mm length and 12.5 mm width. For the fracture toughness specimens in Fig. 2.6, the width was 12.5 mm; and the crack length of the plastic band measured from the loading line (a) was 1.7 mm and the specific
2.2. Material and specimens

In order to examine only the mechanical behavior in the welding area and receive representative results about the effect of the welding process in the mechanical properties degradation, the welding area was chosen to be in the center of the specimens.
For the experimental procedure of this thesis there have been cut 63 EBWed specimens. The total number of specimens that were used for the mechanical tests can be seen in the following Table 2.2. In detail, 32 electron beam welded tensile specimens, 16 fracture toughness and 15 fatigue specimens have been tested.

<table>
<thead>
<tr>
<th>Different Ageing Condition</th>
<th>Tensile</th>
<th>Fracture Toughness</th>
<th>Fatigue</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 h</td>
<td>8</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>9 h</td>
<td>8</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>48 h</td>
<td>8</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>96 h</td>
<td>8</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>32</td>
<td>16</td>
<td>15</td>
</tr>
</tbody>
</table>

**Table 2.2:** Total number of electron beam welded aluminum alloys specimens.

The experimental procedure has been divided in two parts, as it was previously described. The first part includes the mechanical testing of the specimens right after the water-jet machining cutting and the second part includes the mechanical testing of the specimens after the exfoliation corrosion exposure.

### 2.3 Welding Process analysis

The welding of the aluminium alloy 2024 specimens was carried out with the electron beam welding (EBW) method. The welding process has been conducted by the Hellenic Aerospace Industry with the use of TINIUS machine which was employed to perform the necessary welds.

The welding machine used by the Hellenic Aerospace Industry is shown in the following Figure 2.7. It is worth to mention that the material which can be welded with this machine are stainless steels, nickel alloys, cobalt alloys as well as titanium alloys. The main characteristics of the machine are power of 30 KW, the cabin size is ‘68 m x 68 m x 84 m and the size of axons is 42 m Long Straight, 28 m Vertical. The computing program which is used is the W2000 and the allowed accuracy is ±1%.

**Figure 2.7:** Electron beam welding machine of Hellenic Aerospace Industry. Model Sciaky VX.3-68x68x84.
The welding procedure started with the correct clean of the all the specimens with a light alkaline solution (TURCO 415 NC-LT) and then there were placed in a retaining tool so as to avoid deformations upon welding. There was no gap between the specimens which have been welded. Afterwards, the retaining tool with the specimens have been placed in the welding chamber and vacuum followed. The welding was performed automatically by executing a program after the internal camera alignment was confirmed. The welding line have been targeted at 0.025 mm which has been succeed with the use of camera during the process.

The welding parameters were as follows:

- Accelerating Voltage (AV): 50 kV
- Beam Current (BC): 95 mA
- Focus coil current (Beam Focus, BF): 6.90 A
- Travel speed: 1650 mm /min
- Bumper beam distance from welding piece: 150 mm
- Empty chamber: 1x10-4 mbar

2.3.1 Light optical microscopy photos

An Olympus BX 41 M optical microscope was used to observe the size as well as the morphology of the grains in the different regions of the weld. The process which has been followed in order to assess the different regions that the electron beam welding joint technique creates is described above. The process start by etching a mirror-polished sample in Keller’s reagent for 1 min at 25°C. The Keller’s reagent is a mixture of nitric acid, hydrochloric acid, and hydrofluoric acid, used to etch aluminum alloys to reveal their grain boundaries and orientations. In the sequel, after the reveal of the formation of the electron beam welded aluminum alloy, the photos were taken.

2.4 Simulation of atmospheric corrosion

It is noteworthy that there are multiple tests in the industry, which can simulate the possible conditions under which an aircraft corrodes. More precisely, the phenomenon of corrosion in aircraft aging can be accelerated with various laboratory corrosion tests. Some of the most famous laboratory accelerated corrosion methods are summarized below:

- exfoliation corrosion tests
- salt spray tests
- alternate immersion tests
- cyclic acidified salt fog tests
- intergranular corrosion tests
Chapter 2. Experimental Procedure

The most widely method of laboratory corrosion used in alloy series 2xxx and 7xxx, is the exfoliation corrosion as it simulates better the exfoliation corrosion. In accordance with (Sprowls, Walsh, and Shumaker, 1972), the 24 hours accelerated corrosion exposure time is equivalent to about six years of exposure to natural environmental conditions regarding mass loss for alloy 2024-T4.

The exfoliation corrosion method causes to aluminum alloy pitting corrosion, intergranular corrosion and embrittlement due to hydrogen diffusion and trapping. In this Thesis, the EXfoliation COrrosion test, has been applied according with (ASTM-G34, 2001).

2.5 Accelerated Corrosion

The natural corrosion conditions in the “aging” aircraft have an impact on the structural integrity of them. In this thesis, the laboratory simulation of this corrosive environment exposure in short time was performed with the exfoliation corrosion test.

Exfoliation corrosion (ExCo) methodology has been chosen, as it is a methodology that simulates accordingly in the laboratory, the natural corrosion of aluminum alloys. For instance, the characteristics of corrosion damage that exist in real outdoor service, especially in marine and industrial environments. In particular, 48 specimens were placed in a corrosive environment prior to mechanical testing, as it can be seen in figure 2.8 and 2.9, for different exfoliation corrosion times, namely 2 hours, 4 hours, 8 hours, 12 hours, 24 hours, 48 hours. The Tables 2.3 and 2.4 above describe the total number of specimens and the different exposure times of ExCo exposure.

Exfoliation corrosion was performed in accordance with (ASTM-G34, 2001) specification, excluding unusual chemicals not likely to be encountered in natural environments. All the specimens have been firstly cleaned, with alcohol according to (ASTM-E8, 2011) specification.

The procedure of exfoliation corrosion starts with the geometrical dimensions measurement of each specimen. In the sequel, masking followed with insulating material so as to corrode only the cross section region. Afterwards, the specimens were immersed in the corrosive solution and exposed for various times. At the end
of the selected period of time in the solution, the specimens were removed carefully from specially arranged containers immersion (PVC cans), washed away with water and left to dry.

The solution which is used contains reagent grade sodium chloride (NaCl), potassium nitrate (KNO₃), nitric acid (HNO₃) as well as distilled or deionized water. The solution has been placed into specially arranged containers (PVC cans) or plastic bottles. For each specimen, the composition in proportion has been performed in accordance with the next Table 2.5. The solution contains in 1L 234 g of NaCl, 50 g of KNO₃ in water, and add 6.3 mL of concentrated HNO₃ (70 weight %). The temperature in which the solution shall be maintained is 25 ± 3°C.

Table 2.3: Number of tensile specimens exposed to different times of exfoliation corrosion (EXCO)

<table>
<thead>
<tr>
<th>Different Ageing Conditions of AA2024</th>
<th>Exposure times to EXCO solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2h</td>
</tr>
<tr>
<td>0 h</td>
<td>3</td>
</tr>
<tr>
<td>9 h</td>
<td>3</td>
</tr>
<tr>
<td>48 h</td>
<td>3</td>
</tr>
<tr>
<td>96 h</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2.4: Number of C(T) fracture toughness specimens exposed to different times of exfoliation corrosion.
Table 2.5: Composition in proportion for the ExCo solution.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>(0.4M)</td>
</tr>
<tr>
<td>KN03</td>
<td>(0.5M)</td>
</tr>
<tr>
<td>HNO3</td>
<td>(0.1M)</td>
</tr>
</tbody>
</table>

2.6 Mechanical Tests

The mechanical tests took place in the Laboratory of Mechanics of National Technical University of Athens, School of Applied Mathematical and Physical Sciences.

The machine which has been used to perform the experimental tests was the Instron 8801 which is shown in Figure 2.10. The main advantage of using this machine is that materials can be characterized under fatigue conditions and for mechanical breakage studies, both under static and dynamic stress conditions. The specific servo-hydraulic machine has a maximum static and dynamic load of ±100KN, while it provides the ability to control the system and monitor - analyze the results of specific tests via specific software (Wavematrix - BlueHill Software).

![Instron 8801 testing machine and its geometrical dimensions (mm) from Instron Reference-Manual.](image)

The procedure for conducting a mechanical test follows the procedure above. Firstly, the specimen is placed in the special slots of the machine (grippers) and then aligned, so that the force is applied axially and does not suffer any plastic deformation effects due to bending. The deformation changes are recording by two extensometers one of 50 mm which gives information about the mechanical behavior of the material of aluminum alloy and one of 12.50 mm which provides information about the mechanical behavior of the weld. Both of them are placed on each specimen, during the mechanical testing.

The data process is succeed by recording and storing the time, force, displacement of the machine grabber and the deformation of the two extensometers on the
The conversion of force into stress (which is defined as the quotient of force $F$ to the initial surface $A$ of the samples and measured in MPa) was made to facilitate the evaluation of the experimental results.

### 2.6.1 Tensile mechanical test

According to (Davis, 2004), should the tensile testing results are to be used to predict how a metal will behave under other forms of loading, it is desirable to plot the data in terms of true stress and true strain. True stress, $\sigma$, is defined as it is described by the equation \( 2.1 \), where $A$ is the cross-sectional area at the time that the applied force is $F$.

There are two types of materials. The ductile materials, which are considered as those that fail after extensive deformation and can be deformed plastically and save large values of elastic strain energy per unit volume to their breakage.

\[
\sigma = \frac{F}{A} \tag{2.1}
\]

In the other side there are the brittle materials which fail in very small deformations, i.e. when escapes from the linear region of the Hooke’s equation, equation \( 2.2 \).

\[
\sigma = E \times \epsilon \tag{2.2}
\]

The procedure followed for conducting the tensile test is as follows. To start with, the two machine grippers have been aligned so that the specimen is not twisted. In the sequel, the tensile specimen has been placed on the gripper and then aligned so that the force was applied axially. The purpose of this procedure, was to avoid any subjection of the specimen to parasitic bending loads due to bending. The recording of deformation changes has been succeed with the use of the two extensometers which were placed on the specimen. The ability to process all data is ensured by recording and storing all time data, load, displacement of machine grabbers and the deformation of the two extensometers on the computer. The initial length of the first extensometer was exactly 50 mm and of the second 12.5 mm. The conversion of force into stress $\sigma$ (which is defined as the quotient of force $F$ to the initial surface $A$ of the samples and converted to MPa) was made to facilitate the evaluation of the experimental results.

The evaluation of tensile mechanical properties is based on a curve of axial nominal stresses / axial nominal strain. The typical form of this curve is shown in the following diagram. The evaluation of the results which came from the experimental procedure of tensile tests, is based on this curve (figure 2.11). Hence, the tensile mechanical behavior of the specimens is determined thus the curve of axial nominal stresses / axial nominal strain.

The mechanical properties which are used to describe the tensile mechanical behavior are the following:

- **Modulus of elasticity, $E$**: The Modulus of elasticity is defined as the slope of the line that is tangent to the curve of nominal stress - nominal strain in the linear elastic area. The modulus of elasticity is measured in GPa.

- **Yield Strength, $R_p$**: The yield Strength is defined as that point at which appear irreversible deformities for the first time. That is, plastic deformations which are generated do not reset by removing the applied load. The yield strength is measured in MPa.
Chapter 2. Experimental Procedure

For this thesis, evaluated the $R_{p0.2\%}$. It is assessed by carrying the slope of the line from which the elastic modulus is calculated at 0.2% of the nominal strain of the specimen.

- **Ultimate Tensile Strength, $R_m$:** The Ultimate Tensile Strength is the maximum nominal stress that applied in the material before its failure. Is calculated by dividing the maximum tensile load $P_{max}$ to the initial cross section $A_0$ of the material and its measurement unit is MPa.

- **Elongation at fracture, $A_f$:** The elongation at fracture is a modulus for assessing the ductility of the material. Calculated by dividing the change in length of the specimen’s measuring area to the initial length $l_0$. As can be seen at Fig. 2.11, it is calculated by bringing a parallel line to the elastic area (linear) from the point of fracture of the material, then the point that will intersect the straight axis of nominal strain is the elongation at fracture ($A_f$). The elongation at fracture is dimensionless (length to length ratio), and is usually expressed as percent strain [%].

### 2.6.2 Fracture toughness mechanical test

(Kaufman, 2001) mentioned that fracture toughness as a general term describing the resistance of a material to unstable crack propagation at elastic stresses or to low ductility or brittle fracture of any kind. As used in this book, it does not involve resistance to crack initiation but only to the unstable propagation of a crack already present. The term fracture toughness is sometimes used to denote especially the critical strain energy release rate, but this is not the literal definition.

The fracture toughness tests for this Thesis have been conducted with the Instron 8801 machine of a 100 kN maximum static load test, in the Laboratory of Mechanics of National Technical University of Athens, School of Applied Mathematical and Physical Sciences.
2.6. Mechanical Tests

In addition, an anti-buckling device was constructed to ensure the correct performance and validity of the results. The test was carried out according to (ASTM-E561, 1988) and has been divided in two parts. These two parts are described accordingly the first part is the Fatigue stage and the second is the Quasi-static test.

For the fracture toughness mechanical test it have been used compact tension C(T) specimens which is shown in the following Fig. 2.12.

![Figure 2.12: Fracture toughness compact specimen C(T)](image)

Initially, the two machine grippers have been aligned so that the specimen is not twisted. The specimen connected to the relative anti-buckling device is placed on the grippers and then aligned so that the force is applied axially and the bend is not subjected to bending.

**Fatigue Stage**

The first part of the mechanical test includes the subjection of each test specimen to constant fatigue. This step was carried out with load control and the imposed fatigue load was from 0.6 kN to 0.9 kN always tensile (stress ratio R = 0.1). The repeated imposed stress to the specimen (fatigue) was designed to create a natural fatigue crack at the tip of the specimen’s artificial groove and avoid any plastic deformation.

The main purpose was to create a natural crack due to fatigue with a length between 1.3 mm and 2 mm according to (ASTM-E561, 1988). To calculate the length of the crack due to fatigue, a suitable optical device (microscope) was used during this test step.

The test is complete as soon as this natural crack reaches the desired length and then the specimen is ready to be tested in tensile test. It is noteworthy that high fatigue loading cannot be accepted due to the fact that it generates large plastic deformations at the edge of the crack. In case the crack is not between the accepted length the results will be invalid of the experimental test.

**Quasi-static stage**

The second stage of the fracture toughness mechanical test includes the subjection of the specimen in tensile stress with a very low displacement rate of 0.01 mm / min of the machine grippers, according to (ASTM-E561, 1988).
To begin with the test, a Crack Mouth Opening Displacement (CMOD) device has been fitted in the compact tension specimen, in order to store the data of the extension of the elongation-meter in connection with the load displacement of the crack—lips.

The data of the experimental load-displacement curve of the crack lips, it is possible to construct the $K_R$ resistance curve of the material using the compliance method.

In the sequel, are calculated the stress curves $K_R$ of the material for different external loads $P$. The critical external load is that for which the calculated stress curve coefficient $K$ is tangent to the $K_R$ rupture resistance curve of the material. At this point an unstable crack propagation occurs, whereby the critical $K_{cr}$ stress intensity factor for the specific thickness of the material is evaluated.

The evaluation of this Mechanical Test is conducted according to the specification (ASTM-E561, 1988) in order to construct the $K_R$ resistance curve of electron beam welded 2024. Firstly, It is calculated the quotient of $V$, which is the opening of the crack mouth lips, to $P$ which is the axial load imposed to the specimen, according to the equation 2.3.

$$C = \frac{V}{P} \quad (2.3)$$

Secondly, it is calculated the EBC according to equation 2.4, which is the product of $E$, the modulus of elasticity of the material, which calculated from the tensile test of specimens with the same artificial aging; $B$ is the thickness of the specimens (in this case the nominal thickness was constant at 3.2 mm).

$$EBC = E \times B \times C \quad (2.4)$$

The equation $U$ is calculated according to the formula 2.5.

$$U = \frac{1}{1 + \sqrt{E \times B \times C}} \quad (2.5)$$

The calculation of $U$ and the $c_0$ and $c_5$ for the compact specimen C(T), is followed by the calculation of the apparent crack length to $a/w$ length of the specimen.
The following equation 2.6 calculates the factor \( a/w \), in which \( a \) is the crack length of the plastic band measured from the loading line and \( w \) is the specific charging length of the test piece measured from the loading line and finally \( c_0 = 1.0010, c_1 = -4.6695, c_2 = 18.460, c_3 = -236.82, c_4 = 1214.9, c_5 = -2143.6 \) for the particular charge / measurement selected.

\[
a/w = c_0 + c_1(U) + c_2(U^2) + c_3(U^3) + c_4(U^4) + c_5(U^5) \tag{2.6}
\]

In the sequel, it must be calculated the polynomial of the crack length with specific length which is given by the equation 2.7.

\[
f(a/w) = \frac{2 + a/w}{\left(1 - a/w\right)^{3/2}} \times \left[0.886 + 4.64 \times (a/w)^2 + 14.72 \times (a/w)^3 - 5.6 \times (a/w)^4\right] \tag{2.7}
\]

Using the \( f(a/w) \) which have been calculated, the \( K_R \) function of the tension intensity factor for different lengths of active cracks is given by equation 2.8.

\[
K_R = \left[\frac{P}{B \times \sqrt{W}}\right] \times f(a/w) \tag{2.8}
\]

The length of the plastic zone \( r_y \) as a function of \( R_p \) is calculated as it is shown in equation 2.9.

\[
r_y = \frac{1}{2\pi} \times \left(\frac{K_R}{R_p}\right)^2 \tag{2.9}
\]

Finally, using the above equation 2.10, the effective crack length is calculated as a function of the original crack length of the apparent crack growth rate corrected by the length of the plastic zone in front of the edge of the crack, as it is shown in equation 2.10.

\[
\alpha_{eff} = a_0 + f(a/w) + r_y \tag{2.10}
\]

Given the \( K_R \) and \( \alpha_{eff} \) pairs is constructed the resistance curve. The theoretical solution of stress intensity factor for the specific crack length and for various axial loads is calculated. Then, having the maximum axial load value imposed on the \( P_{\text{max}} \) specimen and gradually decreasing its value in the formula, is calculated the curve adjacent to the experimental curve. The specification states that at this point of intersection the unstable crack propagation takes place, from which the critical coefficient of stress \( K_{cr} \) for the specific material and the specific geometric dimensions of the specimen is also evaluated. This is a graphical method of calculating the crucial stress factor \( K_{cr} \) of the material.

### 2.6.3 Fatigue mechanical test

According to (Klesnil, Lukas, and Lukáš, 1992) a complete fracture may occur to a metal with no obvious damage being observed throughout the majority of the loading cycles, when a machine part or a whole structure is loaded by cyclic external forces. In addition to that the size of the external forces may be that small so their single application does not create any detectable damage at all. The final fatigue fracture is preceded by complex submicroscopical and microscopical changes in the structure of metal, which are of a cumulative and irreversible type.

It is worth to be mention that chronically the initial occurrence of fatigue fractures has been attached with the development of structures containing structural elements subjected to cyclic external forces. The first systematic experiments were performed in the years 1852-1870 by August Wohler.
Chapter 2. Experimental Procedure

The basic metal-fatigue characteristics has been the Wohler’s curve, that is used until now, also called the S/N curve, which represents the dependence of the stress amplitude $\sigma_a$ (for a given value of mean stress) on the number of loading cycles to complete fracture $N_f$. The stress amplitude at which fracture still does not occur even after a very high number of loading cycles (of the order of $10^7$) has since Wohler’s time been called fatigue endurance limit.

(Lemaitre and Desmorat, 2005) There are two types of fatigue, that connected with the situation of metallic material. The fatigue category in non-cracked material and category fatigue on already cracked material. The fatigue on already cracked material, that is the fatigue which will be presented in this Thesis, is has two subcategories according to the time of failure of the material, which directly relates to the stresses imposed in the material. The polycyclic fatigue and the low cycle fatigue.

In detail, in polycyclic fatigue stresses imposed cannot exceed the yield point $R_p$ of the material, while the lifetime of the material ranges from $10^4$ to approximately $10^6$ charging cycles to failure of the material. Polycyclic fatigue paradigms are all systems that rotate or vibrate, such as wheels, axles. What is more, at the low cycle fatigue material subject to loads with high stress values, which are higher than $R_p$ yield stress of the material and therefore considerable plastic deformations are expected. The lifetime of the material is short, and in no case exceeds $10^4$ load cycles to failure of the material. Examples of low cycle fatigue data is subject to overload, e.g. earthquake.

The mechanical fatigue tests applied to characterize the mechanical behavior of the material or the manufacturing (specimen) or the structure itself (full scale). A dynamic load can be considered to consist of two components, an average or constant stress $\sigma_m$ and a changing stress $\sigma_a$. Also, in the analysis of dynamic stress should be considered and the range of stress $\Delta \sigma$. In most tests at laboratory the imposed stresses change sinusoidally with time, as can be seen at the Fig.2.14. The characteristic variables of fatigue are given from the equations above.

- The maximum $\sigma_{max}$ and minimum $\sigma_{min}$ stress.
- The stress $\sigma_a$:

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$ (2.11)

![Figure 2.14: Nomenclature of periodical charges. Dowling, 2012](image.png)
• The stress $\sigma_m$:

$$\sigma_m = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2}$$  \hfill (2.12)

• The range of stress $\Delta \sigma$:

$$\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}} = 2 \times \sigma_a$$  \hfill (2.13)

The mechanical fatigue tests were carried out in the Laboratory of Mechanics of National Technical University of Athens, School of Applied Mathematical and Physical Sciences. The standard practice for force controlled constant amplitude axial fatigue tests of the electron beam welded aluminum alloy 2024 specimens has been conducted in accordance with (ASTM-E466, 2002) specification. More precisely, as it is described from the specification, the axial force fatigue test is used to determine the effect of variations in material, geometry, surface condition, stress, and so forth, on the fatigue resistance of metallic materials subjected to direct stress for relatively large numbers of cycles.

This practice covers the procedure for the performance of axial force controlled fatigue tests to obtain the fatigue strength of metallic materials in the fatigue regime where the strains are predominately elastic, both upon initial loading and throughout the test. This practice is limited to the fatigue testing of axial unnotched and notched specimens subjected to a constant amplitude, periodic forcing function in air at room temperature. This practice is not intended for application in axial fatigue tests of components or parts (ASTM-E466, 2002).

The Instron 8801 machine was used to conduct the mechanical tests, the maximum static load cell was 100 kN and it was imposed a static charge and at the same time a fixed amplitude. and fixed frequency sinusoidal load. The range of frequency that has been selected was 20 Hz.

The condition of the test specimen in order to get successful results has been prepared and cleaned with alcohol in accordance with (ASTM-G-1, 2011) specification. Then the specimen was placed on and aligned on the machine grippers. The alignment of the specimen is necessary so that the force applied is axial along the axis of the specimen in order to avoid parasitic effects due to bending.
\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \]  

(2.14)

In the sequel, the applied static forces for each specimen separately \( F_{\text{mean}} \), \( F_{\text{amplitude}} \) have been calculated.

The calculated forces, as well as the charge frequency, are placed in the computer program to conduct the experiment. During the experiments, all the time, force, displacement data of the machine grippers and stress cycles were recorded and stored to the computer program used.

The evaluation of the experiments have been performed with the use of the program Origin 2017 (OriginLab, 2017). The force effects were converted to an axial nominal stress, which is defined as the quotient of force \( F \) to the initial surface \( A \) of the specimens and is measured in MPa.
Chapter 3

Results

This chapter provides all the results from the mechanical tests that were in detail described in Chapter 2. The effect of the welding process on the aluminum alloy 2024 will be analyzed first and in the sequel the effect of corrosion on the electron beam welded AA 2024 joints. The effect of artificial ageing before the welding process will be also discussed and the corrosion effect on the above artificially aged welded aluminum alloy joints will be drawn. The results will be analyzed extensively in Chapter 4.

3.1 Effect of welding

One of the main purposes of this Thesis is to assess the effect of electron beam welding process on the mechanical properties of AA 2024 in T3-condition, in order the quality of the weld to be understood as well as the effect on the mechanical properties of the above artificially aged welded joints.

3.1.1 Light optical microscopy results

Figure 3.1 shows a typical cross-section of an EBWed joint of AA2024-T3. The photos have been taken in order to correlate the structural characteristics of the weldments. In all welded joints the district areas, namely the fusion zone (FZ) (Fig. 3.1a), the heat affected zone (HAZ) (Fig. 3.1b) and the base material (BM) can be seen. The solidified grains within the fusion zone can be also recognized in Fig. 3.1c.

It can be seen that the microstructure of FZ (Fig. 3.1a) consists of the equiaxed grains. In Fig. 3.1c these solidified grains within the fusion zone are more clear. This can attributed to the intensive thermo-mechanical effects at elevated temperatures in this region. Regarding the base material, it can be noticed that the microstructure consisted of grains elongated in the rolling direction. For the heat affected zone (HAZ) (Fig. 3.1b), a narrow region boundary between the base metal (left side) and the fusion zone (FZ) (right side) is evident. It can be noted that in HAZ the plastic deformation is absent and only heat input plays a role, coarsened grains are observed.
Chapter 3. Results

3.1.2 Typical tensile flow curves

Figure 3.2 shows a typical tensile flow curve from the welded joints of AA 2024 (red curve) in T3-condition. In addition, a typical tensile curve of a non-welded specimen (black curve) was also added to the Figure for comparison purposes (Alexopoulos et al., 2016b). It is important to underline the differences between the mechanical properties of the non-welded and the electron beam welded specimens.

More precisely, the yield stress of the non-welded specimen is approximate at 385 MPa. According to (Callister and Rethwisch, 1991) this is sometimes called the proportional limit, and that point of yielding may be determined as the initial departure from linearity of the stress–strain curve. With increasing axial deformation, axial nominal stress continues to increase up to the maximum point of 490 MPa until fracture.

On the other hand, the curve of the electron beam welded specimen exhibits a different behavior. Axial nominal stress increases continuously with increasing axial strain up to 330 MPa that is the final fracture point. The specimen experience has not a designated yield stress point that like the non-welded specimen due to the contentiously increases stress-strain curve and therefore a conventional yield stress point $R_{p0.2\%}$ must be calculated according to (Callister and Rethwisch, 1991).
3.1. Effect of welding

FIGURE 3.2: Typical experimental tensile flow curves for an electron beam welded AA2024-T3 specimen in comparison with a non-welded specimen at the same temper.

3.1.3 Fatigue S-N curve

The experimental fatigue tests were exploited to construct the S-N fatigue curve of the EBWed specimens. The experimental data of the welded joints (red polygons) are presented in the Figure 3.3. The horizontal axis describes the fatigue cycles for fracture (logarithmic scale), while the vertical describes the maximum applied stress (linear scale). The above curve of the graph appears to be asymptotic to the horizontal axis as the applied stress decreases. This means that the test specimen exhibits an infinite lifetime of fatigue, no matter how small the applied stress is.

It is observed that the fatigue life (or the fatigue cycles to fracture) tends to increase with decreasing the maximum applied stress $\sigma$. The maximum fatigue stress for a stress ratio $R = 0.1$ is about 250 MPa while the minimum value of fatigue stress is 120 MPa. The experimental curve presents a mildly transition up to 220 MPa. Afterwards, an intense linear transition from 220 MPa to 140 MPa is observed.

This intense transition from the region of low cycle fatigue to that of high cycle fatigue behavior is typical for aluminum alloys. Generally, small changes in applied stresses lead to major changes in the fatigue life. After the 140 MPa the fatigue life seems to reach at a plateau.

The conventional fatigue endurance limit in the above graph was considered to be in $10^7$ stress cycles and represents a realistic, predetermined lifetime of fatigue. The fatigue endurance limit of the welded joints was estimated to be around 125 MPa, where an asymptotic curve fit was noticed with y-axis.
3.1.4 Typical fracture resistance curves

Typical fracture resistance curves ($R$-curve) have been constructed for the evaluation of the critical stress intensity factor $K_{cr}$. The $R$-curves utilize the values of the applied force and the corresponding crack mouth opening displacement (CMOD) of the notch for the testing specimens. Typical curves for the welded (red curve) and the non-welded (black curve) specimens which already exist in the literature (Alexopoulos et al., 2016a) can be seen in Figure 3.4.

Differences can be noticed between the two specimens mainly at their maximum load values. The non-welded specimen exhibit higher maximum load of approximate 6.4 kN, while only 5.8 kN was observed for the welded specimens. Hence, it can be assumed that the welded specimens exhibit lower mechanical properties related to fracture.
3.2 Effect of corrosion exposure on the welded joints

Another aim of this Thesis is to assess the effect of corrosion exposure on the mechanical properties of AA 2024 EBWed joints. A wide range of different exfoliation corrosion exposure times was used, in order to understand the corrosion–induced degradation of the mechanical properties of electron beam welded joints of aluminum alloy 2024 in T3-condition.

3.2.1 Typical tensile flow curves

The effect of exfoliation corrosion on the reference electron beam welded (EBWed) AA 2024 joints is summarized in the flow curves diagram of the Figure 3.5. The diagram presents some typical tensile flow curves of the welded and corroded specimens. More precisely, for the reference EBWed aluminum alloy 2024 joints it has been chosen a wide range of exposure times at ExCo solution starting from 2 hours and up to 48 hours.

It must be noted that for each different exposure time at least 3 tensile specimens have been tested to get reliable average data. Table 3.1 shows the average and standard deviation values of the evaluated tensile mechanical properties.

In the Figure 3.5 each curve which represents a different exposure time has a different color. More precisely, the red curve symbolizes the reference specimen in T3-condition without any corrosion. The 2 hours corrosion exposure time is shown with the green curve while the purple curve shows the 4 hours exposure and the brown curve symbolizes the 8 hours corrosion. The curve with the olive color describes the 12 hours exposure and for the extreme exposure times the orange curve represent the 24 hours while the yellow curve the 48 hours.

It is obvious that both axial stress and axial strain decrease with increasing exposure time to ExCo solution. It has been noticed that no essential stress drop is evident up to 2 hours of exposure to corrosion, but ductility decrease essentially from 3.83 % to 3.68 %. In addition, the specimens which have been subjected to 4 hours corrosion have an almost 5.6 % stress decrease as well as a 10 % decrease at
Chapter 3. Results

<table>
<thead>
<tr>
<th>ExCo Time</th>
<th>Rp0.2% (MPa) Average</th>
<th>Rp0.2% (MPa) St. dev.</th>
<th>Rm (MPa) Average</th>
<th>Rm (MPa) St. dev.</th>
<th>Af (%) Average</th>
<th>Af (%) St. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0h</td>
<td>232</td>
<td>5.3</td>
<td>330</td>
<td>6.1</td>
<td>3.83</td>
<td>0.6</td>
</tr>
<tr>
<td>2h</td>
<td>213</td>
<td>9.5</td>
<td>328</td>
<td>5.55</td>
<td>3.68</td>
<td>0.7</td>
</tr>
<tr>
<td>4h</td>
<td>186</td>
<td>2.3</td>
<td>312</td>
<td>7.97</td>
<td>3.45</td>
<td>0.27</td>
</tr>
<tr>
<td>8h</td>
<td>182</td>
<td>2.5</td>
<td>304</td>
<td>5.85</td>
<td>3.29</td>
<td>0.19</td>
</tr>
<tr>
<td>12h</td>
<td>178</td>
<td>2.7</td>
<td>311</td>
<td>2.9</td>
<td>3.21</td>
<td>0.31</td>
</tr>
<tr>
<td>24h</td>
<td>176</td>
<td>2.8</td>
<td>276</td>
<td>2.7</td>
<td>3.12</td>
<td>0.35</td>
</tr>
<tr>
<td>48h</td>
<td>162</td>
<td>3.5</td>
<td>262</td>
<td>3.4</td>
<td>3.05</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table 3.1: Average values of the tensile mechanical properties of the EBWed AA 2024-T3 joints after exposure to different exfoliation corrosion times.

Figure 3.5: Typical experimental tensile flow curves for electron beam welded AA2024-T3 specimens for different exposure times to exfoliation corrosion solution.

the elongation at fracture, from the reference joints. Furthermore, for 8 hours exposure to ExCo solution, stress continues to decrease to 182 MPa while ductility drop reach 15 %. For the 12 hours, the elongation at fracture slightly decrease to 3.21 % from 3.29 % of the 8 hours exposure and the stress decrease to 23 % from the initial property of T3-condition. For the extreme exposure times of 24 hours and 48 hours, it is noticeable from the graph that, the axial nominal stress decrease 25 % and 30 % respectively, while the ductility drop percentages reach 18 % and 20 %.

3.2.2 Light optical microscopy photos

Typical optical microscopy photos of the welding area of electron beam welded AA 2024 after being exposed, for different times, to ExCo solution, can be seen in Fig. 3.6. The deleterious effect of exfoliation corrosion is noticeable with the increasing exposure time.

Fig. 3.6a shows the typical fracture location of the non-corroded EBWed joint. It is evident that fracture occurs within the fusion zone. Actually small-corrosion induced pits can be noticed after only 2 hours exposure to the corrosive environment
3.3 Effect of artificial ageing before the welding process

(Fig. 3.6b). For the case of 4 hours exposure time (Fig. 3.6c), some pits were generated especially at heat affected zone (HAZ). After 8 and 12 hours (Fig. 3.6d, 3.6e), it is observed that surfaces seems to be heavily corroded at the heat affected zone (HAZ) as well as the base metal. Finally, uniform pitting is noticed after 24 and 48 hours of exposure (Fig. 3.6f, 3.6g).

![Typical fracture location of the EBWed joints for different corrosion exposure times](image)

**Figure 3.6**: Typical fracture location of the EBWed joints for different corrosion exposure times (a) 0 h, (b) 2 h, (c) 4 h, (d) 8 h, (e) 12 h, (f) 24 h, (g) 48 h, exposure at the exfoliation corrosion solution (3.2mm nominal thickness of the specimen).

3.3 Effect of artificial ageing before the welding process

Another aim of this Thesis is to assess the effect of artificial ageing on the mechanical properties of EBWed joints of aluminum alloy 2024. The hours have been selected according to Chapter 2, to address all ageing conditions namely the Under-ageing condition (UA), the Over-ageing condition (OA) as well as the Peak-ageing (PA) condition for AA 2024.
3.3.1 Typical tensile flow curves

Typical tensile flow curves for the aluminum alloy 2024 specimens which have been firstly artificially aged at 170°C and subsequently electron beam welded can be seen at Figure 3.7.

It must be underlined that for each different artificial ageing time 3 tensile specimens have been tested for more reliable results. The Table 3.2 shows the average values of the tensile mechanical properties of the tested specimens.

In Figure 3.7 each curve represent the average results of each different artificial ageing time and has different symbol and color. More precisely, the red curve represent the reference EBWed aluminum alloy 2024 joints, the 9 hours of artificial ageing are represented with the black curve, the 48 hours of artificially aged aluminum alloy 2024 specimens are indicated with the blue curve and the 96 hours of artificial ageing are marked with the green curve.

![Figure 3.7: Typical experimental tensile flow curves for AA 2024 specimens artificially aged at 170°C and subsequently electron beam welded.](image)

It is obvious from the graph that in all the conditions similar values of yield stress and ultimate tensile strength are represented. In addition to that for the before weld heat treatment specimens a significant ductility decrease for Under-ageing (9 hours) condition and Peak-ageing (48 hours) condition are noted with a total decrease of 40 % and 36 %, respectively. For the Over-ageing condition (OA), after 96 hours of artificial ageing, the yield stress and ductility seem to reach its’ maximum values.

3.3.2 Typical fracture resistance curves

Figure 3.8 describes the typical fracture resistance curves for AA 2024 specimens which have been first artificially aged at 170°C and subsequently electron beam welded. For each different artificial ageing time 2 fracture toughness tests have been performed in order to get more convenient results. The Table 3.3 shows the average values of the critical intensity factor values of the tested specimens.

The Fig. 3.8 presents the $K$-curves, which show the values of the maximum applied force and the corresponding crack mouth opening displacement (CMOD) for
3.3. Effect of artificial ageing before the welding process

<table>
<thead>
<tr>
<th>Artificial Ageing Time at 170°C</th>
<th>Rp0.2% (MPa) Average</th>
<th>Rp0.2% (MPa) St. dev.</th>
<th>Rm (MPa) Average</th>
<th>Rm (MPa) St. dev.</th>
<th>Af (%) Average</th>
<th>Af (%) St. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 h</td>
<td>232</td>
<td>5.4</td>
<td>330</td>
<td>1.3</td>
<td>3.83</td>
<td>0.66</td>
</tr>
<tr>
<td>9 h</td>
<td>220</td>
<td>2.9</td>
<td>294</td>
<td>3.1</td>
<td>2.19</td>
<td>0.3</td>
</tr>
<tr>
<td>48 h</td>
<td>228</td>
<td>1.5</td>
<td>322</td>
<td>1.9</td>
<td>2.43</td>
<td>0.21</td>
</tr>
<tr>
<td>96 h</td>
<td>210</td>
<td>9.5</td>
<td>358</td>
<td>2.7</td>
<td>5.52</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 3.2: Average values of tensile mechanical properties of the three tested specimens of the artificially aged and welded specimens.

<table>
<thead>
<tr>
<th>Artificial Ageing at 170°C Time</th>
<th>Kcr (MPa*√m) Average</th>
<th>Kcr (MPa*√m) St. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 h</td>
<td>68</td>
<td>1.68</td>
</tr>
<tr>
<td>9 h</td>
<td>58</td>
<td>0.85</td>
</tr>
<tr>
<td>48 h</td>
<td>63</td>
<td>1.39</td>
</tr>
<tr>
<td>96 h</td>
<td>60</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 3.3: Average values of critical intensity factor of the artificially aged and welded AA 2024 fracture toughness specimens.

The artificially aged and electron beam welded joints. Each different curve represent the average values of each artificial ageing time and has a different color. To be more specific, the T3 condition is marked with the red curve, the under-ageing condition (9 hours) is represented by the black curve, the peak-ageing condition (48 hours) is indicated with the blue curve and the over-ageing condition (96 hours) with the green curve.

Figure 3.8: Typical Resistance Curves for the artificially aged at 170°C and subsequently electron beam welded AA2024 specimens.

It can be noted from the graph that the reference specimen exhibit to 5.8 kN force, while after 9 hours of artificial ageing (UA) an increase of the maximum force and corresponding CMOD is observed. In addition to that, an essential increase of maximum force and respective CMOD at 48 hours (PA) can be noticed. What
Chapter 3. Results

is more, at over-ageing condition, after 96 hours of artificial ageing, both force and corresponding crack mouth opening displacement (CMOD) reach its minimum values.

3.4 Effect of corrosion exposure of the artificially aged joints

The final goal of this Thesis is to evaluate the effect of corrosion exposure on the mechanical properties of AA2024 welded joint. According to the findings in section 3.2.1, the 2 hours exposure time to exfoliation corrosion solution has an essential tensile ductility decrease while stress is not essentially change. Additionally, there is no noticeable pitting in the cross-section of the specimens as it has been proved from the light optical microscopy photos in section 3.2.2. As a result, the 2 hours exfoliation corrosion exposure have been selected to be performed in the artificially aged and welded joints for comparison purposes with the non-corroded artificially aged specimens.

3.4.1 Typical tensile flow curves

Figure 3.9 represent the typical tensile flow curves that compares the non-corroded artificially aged specimens, which have been accordingly presented in section 3.3.1, with the artificially aged welded joints that have been subjected to 2 hours exfoliation corrosion solution. The red curves in the following diagrams present the non-corroded specimens which have been artificially aged at 170°C, while the blue curves represent the 2 hours corroded welded specimens of each different artificial ageing condition.

It must be underlined that in order to get reliable results for each condition 3 specimens have been corroded and tensile tested. The Table 3.4 presents the average values of the tensile mechanical properties of corroded specimens which have been tested.

<table>
<thead>
<tr>
<th>Artificial Ageing Time at 170°C</th>
<th>Rp0.2% (MPa)</th>
<th>Rm (MPa)</th>
<th>Af (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>St. dev</td>
<td>Average</td>
</tr>
<tr>
<td>0</td>
<td>206</td>
<td>14</td>
<td>318</td>
</tr>
<tr>
<td>9</td>
<td>237</td>
<td>1</td>
<td>313</td>
</tr>
<tr>
<td>48</td>
<td>216</td>
<td>17</td>
<td>314</td>
</tr>
<tr>
<td>96</td>
<td>205</td>
<td>8</td>
<td>345</td>
</tr>
</tbody>
</table>

| Table 3.4: Average values of tensile mechanical properties of the artificially aged and welded AA 2024 specimens which have been subjected to 2 hours ExCo solution. |

Generally, in all the conditions an essential ductility drop is evident while yield stress decrease slightly. For the comparison of the non-corroded and corroded specimens in T3 condition, that is presented in Fig. 3.9a, elongation at fracture decrease up to 3.6 %. For the under-ageing condition in Fig. 3.9b, a 5.4 % ductility decrease in noticeable with the 2 hours corrosion. At the peak-ageing condition, Fig. 3.9c, elongation at fracture drop reach 6 %. At the over-ageing condition, Fig. 3.9d, ductility seems to decrease the most up to 17 %.
3.4. Effect of corrosion exposure of the artificially aged joints

3.4.2 Typical fracture resistance curves

The typical fracture resistance curves comparison between the non-corroded artificially aged specimens, which have been accordingly presented in section 3.3.2, with the artificially aged welded joints that have been subjected to 2 hours exfoliation corrosion solution are presented in Figure 3.10. The red curves in the following graphs present the non-corroded, while the blue curves represent the 2 hours corroded welded specimens of each different artificial ageing condition.

It must be underlined that in order to get reliable results for each condition 3 specimens have been corroded and tensile tested. The table 3.5 presents the average values of the critical intensity factor mechanical properties of corroded specimens which have been tested.

<table>
<thead>
<tr>
<th>Artificial Ageing at 170°C Time</th>
<th>Kcr (MPa*√m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>0</td>
<td>66</td>
</tr>
<tr>
<td>9</td>
<td>54</td>
</tr>
<tr>
<td>48</td>
<td>53</td>
</tr>
<tr>
<td>96</td>
<td>56</td>
</tr>
</tbody>
</table>

Table 3.5: Average values of critical intensity factor of the two tested specimens of the artificially aged and welded AA 2024 fracture toughness specimens which have been subjected to 2 hours ExCo solution
In general, the effect of corrosion is evident especially in T3, in the under-ageing as well as the peak-ageing conditions. For the comparison of the non-corroded and corroded specimens in T3 condition, that is presented in Fig. 3.10a as well as the comparison in the under-ageing condition in Fig. 3.10b, a 7% critical stress intensity factor decrease in noticeable with the 2 hours corrosion. At the peak-ageing condition, Fig. 3.10c, critical intensity factor drop reach 15%. At the over-ageing condition, in Fig. 3.10d, ductility seems to decrease the least up to 6%.

**Figure 3.10:** Typical fracture resistance curves comparison between the non-corroded (*) and 2 hours corroded (*), artificially aged AA 2024 welded specimens.
Chapter 4

Analysis of the results

In this chapter the experimental tests results are in depth analyzed. This section is divided into 4 sections: (a) the effect of welding on T3-condition and (b) the corrosion effect on already welded joints. The next sections are dealing with (c) the effect of artificial ageing before welding and (d) the corrosion effect on the already artificially aged welded joints.

4.1 Effect of welding on T3-condition

4.1.1 Tensile properties

In order to assess the effect of welding on the tensile mechanical properties, the reference properties of AA 2024–T3 have been retrieved from the literature (Alexopoulos et al., 2016b) and are shown in Table 4.1. Degradation of the mechanical properties have been estimated by having as reference values the non-welded properties. The degradation results due to welding can be seen in Fig. 4.1. It must be noted that all investigated tensile properties, namely the conventional yield stress ($R_{p0.2}$), the ultimate tensile strength ($R_m$) as well as the elongation at fracture ($A_f$), have been calculated.

<table>
<thead>
<tr>
<th>Yield stress (MPa)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Modulus of elasticity (GPa)</th>
<th>Elongation to fracture(%)</th>
<th>Critical stress intensity factor (MPa * $\sqrt{m}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>345</td>
<td>485</td>
<td>70</td>
<td>18</td>
<td>83</td>
</tr>
</tbody>
</table>

Table 4.1: Mechanical properties of AA 2024 - T3.

Regarding the conventional yield stress ($R_{p0.2}$), the non-welded specimens exhibited average values of approximately 391 MPa while the electron beam welded (EBWed) specimens around 231 MPa. This refers to approximately 40 % decrease. According to (Mathers (2002)), in order to achieve a fusion welding, the components have to be locally melted and re-solidified. The different zones which are formed due to fusion welding differ concerning the mechanical properties. As a result, there might be a substantial loss of strength, because of the width of the heat affected zone (HAZ) as a function of the high thermal conductivity of aluminum and the consequent size of the area.

Average value of the ultimate tensile strength ($R_m$) of the non-welded aluminum alloy 2024-T3 specimens is approximately 480 MPa, while the welded joints have an approximate average $R_m$ of 330 MPa. This decrease is almost 30 % and therefore a joining efficiency of more than 70 % can be achieved. To this end, it has to be noticed that Al-Cu alloys are considered to be non-weldable because of their tendency to solidification cracking and inferior mechanical properties of the welded joints. The
70% joining efficiency is considered to be extremely high for fusion welding of such aluminum alloys.

Concerning the elongation at fracture ($A_f$) of the non-welded aluminum alloy 2024-T3 the average value exhibit 24.5%, while the welded joints have an approximate average $A_f$ of 3.82%. This decrease is almost 85%, which was expected as the HAZ is probably in the peak-ageing condition that according to the literature exhibits the minimum elongation at fracture. Therefore the capability of HAZ to plastically deform is extremely limited. This explains the lower $A_f$ of the welded joint.

![Percentage decrease of the mechanical properties of the electron beam welded joints from the non-welded specimens.](image1)

**Figure 4.1:** Percentage decrease of the mechanical properties of the electron beam welded joints from the non-welded specimens.

### 4.1.2 Fracture toughness properties

Fig. 4.1 shows also the representative results for fracture toughness tests of the non-welded aluminum alloy 2024, from the literature (Alexopoulos et al., 2016a) against the electron beam welded AA 2024 joints. It must be noted that the critical stress intensity factor ($K_{cr}$) has been calculated based on the nominal thickness $t=3.2$mm of the alloy and in accordance with the (ASTM-E561, 1988) standard that has been extensively described in section 2.6.2. In (Alexopoulos et al., 2016a) the average $K_{cr}$ value of the reference AA 2024-T3 specimens of the same thickness was calculated to be $83 \pm 2$ MPa$\sqrt{m}$. On the other hand, the $K_{cr}$ value of the welded specimens was calculated to be at $68 \pm 2$ MPa$\sqrt{m}$. This corresponds to almost 18% decrease that was found to be lower from the mechanical properties investigated. This degradation can be explained from Fig. 4.2, that shows the welded area of the fracture toughness specimen. To be more specific, it is obvious from the Figure 4.2 that the

![Crack path of fracture toughness C(T) welded specimen.](image2)

**Figure 4.2:** Crack path of fracture toughness C(T) welded specimen.
4.1. Effect of welding on T3-condition

4.1.3 Fatigue life

Figure 4.3 shows the experimental S–N curve of the electron beam welded (EBWed) aluminum alloy 2024 specimen against the respective non-welded (Alexopoulos et al., 2013). It must me noted that the reference curve has been constructed for the same thickness of the material ($t=3.2\ \text{mm}$) as well as the same loading ratio ($R=0.1$). The three different areas of fatigue life, namely the low cycle fatigue regime, the high cycle fatigue regime as well as the fatigue endurance limit, can be noticed, based on the results of the non-welded specimens.

It can be observed from the graph that the fatigue life (or the fatigue cycles to fracture) tends to increase with decreasing the maximum applied stress $\sigma$. The experimental curve of reference non-welded specimens (blue curve) that was constructed from (Alexopoulos et al., 2013), presents a mildly transition up to 300 MPa. In the sequel, an intense linear transition from 300 MPa to 220 MPa is observed. This intense transition from the region of low cycle fatigue to that of high cycle fatigue behavior is typical for aluminum alloys. It must be underlined that in general, small changes in applied stresses lead to major changes in the fatigue life. The non-welded AA 2024 seems to exhibit fatigue endurance limit at the magnitude of 210 MPa with constant amplitude fatigue loading.

![Fatigue Life Graph]

**Figure 4.3:** Comparison between the fatigue properties of the non-welded (*) AA2024 and the electron beam welded AA2024 (*).

As far as the electron beam welded aluminum alloy (red curve) is concerned, it is obvious from the graph that the S-N curve present qualitatively similar behavior with the non-welded aluminum alloy. It must be noted that for the lower applied stresses the fatigue cycles to fracture there is no considerable difference against the non-welded AA 2024.

In general, the calculated slope for the non-welded specimen of AA 2024 is $-64.5 \pm 7$ while for the welded specimens the calculated slope is $-27.53 \pm 3$. To this end, for the non-welded specimens with the increasing applied force there is a lower
degradation of fatigue life, while for the welded specimens with a small increase of the applied force, very big changes of the fatigue life can be noticed. As a result it must noted that the fatigue endurance limit was decreased by 40% after the welding.

4.2 Effect of corrosion on the welded joints at T3 condition

4.2.1 Conventional yield stress

Figure 4.4 present the normalized experimental results for the conventional yield stress of the corroded welded joints against the respective non-welded corroded specimens of aluminum alloy 2024. It has been mentioned in Chapter 3, that different exposure times to exfoliation corrosion have been performed on the welded specimens. The red line has been constructed for the six different exposure times in exfoliation corrosion environment, for the reference EBWed AA 2024 based on the nominal cross-section of the specimens and the blue line for the non-welded specimens of AA2024, that exist in the literature (Alexopoulos et al., 2016b), for 0.5 hour to 48 hours exposure to corrosion.

It is worth to mention that, for the non-welded specimens the $R_{p0.2\%}$ seems to decrease exponentially with increasing EXCO time. Furthermore, for short exposure times of exposure to the corroded environment, from 0.5 hour up to 8 hours, a marginal $R_{p0.2\%}$ decrease can be noticed. Concerning the welded aluminum alloy joints, it was calculated that the conventional yield stress exhibits 232 MPa without any corrosion. It must be underlined that after 2 hours of ExCo no significant decrease of the conventional yield stress was noticed (approximately 8%). This can be attributed to the slight pitting corrosion that is evident in the surfaces of the specimens. For higher exposure times ($\geq$ 4 hours) to corrosion solution where the exfoliation corrosion mechanism is dominant, an essential decrease of the conventional yield stress is noticed. What is more, for the highest exposure time of 48 hours the conventional yield stress has exhibited a 30% stress drop.

![Figure 4.4: Corrosion-induced decrease of the normalized conventional yield stress for welded (*) and non-welded (*) specimens for different exposure times to exfoliation corrosion environment.](image-url)
4.2. Effect of corrosion on the welded joints at T3 condition

4.2.2 Elongation at Fracture

The elongation at fracture $A_f$ results for the pre-corroded welded joints of AA2024 against the non-welded specimens are presented in Figure 4.5. The figure presents the percentages of the remaining property from the initial values. A wide range of exposure times have been selected, from 0.5 up to 48 hours. The red line has been constructed for the six different exposure times of the reference EBWed specimens in exfoliation corrosion environment based on the nominal cross-section of the specimens and the blue line for the non-welded specimens directly retrieved from the literature (Alexopoulos et al., 2016b).

For the non-welded specimens of AA2024 a continuous decrease of the elongation at fracture, $A_f$, is evident due to corrosion exposure; this was not the case for the EBWed specimens where a considerable decrease was noticed up to 4 hours and then it seems to be stabilized. Even from the 2 hours corrosion exposure time an approximate 10% decrease was noticed for the non-welded specimens due to the hydrogen embrittlement phenomenon, while for the welded joints the respective decrease was only 4%.

After 48 hours of ExCo exposure the $A_f$ of the non-welded specimens was reduced by almost 69% from the initial property. Regarding the welded joints after the highest exposure time of 48 hours in this case, the respective decrease of the mechanical property is only 24%, that was attributed to the extreme exfoliation corrosion and micro-cracks formation mechanism.

![Figure 4.5: Corrosion-induced decrease of the ductility (elongation at fracture) for welded (*) and non-welded (*) specimens for different exposure times to exfoliation corrosion environment.](image)

4.2.3 Macroscopic evaluations of fracture specimens

Fig. 4.6 shows the tensile fracture location of electron beam welded joints. The cross-sections photos of the 2024–T3 specimens after being exposed to different times of ExCo have been examined by optical microscope.

It has been observed that the fracture mechanism seems to start from the root of the weld and continues within the fusion zone for the exposure times up to 12 h
on the ExCo solution. Fig. 4.6a, which represent the non–corroded condition and Fig. 4.6b that represent a middle time of exposure time to ExCo describe that phenomenon. On the other side, it is obvious from Fig. 4.6c (24 hours exposure) that for the extreme exposure times, (e.g. 24 and 48 h) the fracture location seems to change. It is observed that the mechanism is the interface between the fusion zone and the heat affected zone.

![Figure 4.6: Fracture location of electron beam welded joints of 2024-T3 aluminum alloy after the exposure to exfoliation corrosion environment for (a) 0 h, (b) 8 h and (c) 48 h.](image)

(Alexopoulos et al., 2016b) have been described that for the AA 2024 the exfoliation corrosion exposure affects the mechanical properties by means of hydrogen diffusion and subsequent local embrittlement. It is well-known that for higher exposure times to corrosion solution, corrosion–induced surface pits are formed and act as surface notches; that have a profound effect on the ductility degradation of the specimen.

More precisely, in the case of AA2024 some surface pits seems to be formed after 2 hours exposure and the pits seems not to grow deeply into the core of the material but parallel to the surface. After 4 hours of corrosion exposure, the outer surface seems to be heavily corroded and almost a 40 \(\mu\)m corroded layer is formed below the outer specimen surface layer that decreases the specimen thickness.

Concerning the electron beam welded joints, for the altering of fracture mechanism, for short exposure times up to 12 hours the pits which are generated not grow deeply into the weld area. As it have been described, after the 24 hours exposure to exfoliation corrosion (ExCo), the fracture location has been formed between the fusion zone and the heat affected zone. This conclude to the fact that the formed corrosion has been penetrated in the welding area with the result of changing the fracture mechanism.
4.3 Effect of artificial ageing before welding

4.3.1 Conventional yield stress

This section refers to the comparison between the conventional yield stress of the artificially aged and electron beam welded 2024 aluminum alloy specimens against the non-welded artificially aged AA2024 that already exist in the literature (Alexopoulos et al., 2016b). The Figure 4.7 shows the average values of the experimental results for the $R_{p0.2\%}$. The blue line describes the results for the non-welded specimens while the red line represents the values for the welded specimens which have been firstly artificially aged and then subjected to electron beam welding.

Concerning the results of the welded specimens, it is obvious from the graph that $R_{p0.2\%}$ presents qualitatively similar behavior with the non-welded aluminum alloy. However, the artificial ageing heat treatment does not essentially affect the conventional yield stress property of the EBWed joints. This may attributed to the fact that the welding has been performed after the artificial ageing and as a consequence the effect of artificial ageing (e.g increase on the $R_{p0.2\%}$) is eliminated. It must be also noted that a 53 % $R_{p0.2\%}$ degradation from the non-welded is evident in the peak-ageing (PA) condition.

![Figure 4.7: Conventional yield stress, ($R_{p0.2\%}$) comparison between the non-welded (*) artificially aged specimens against the welded (*) AA 2024 joints.](image)

4.3.2 Elongation at fracture

This section refers to the comparison between the elongation at fracture of the artificially aged at 170°C and electron beam welded 2024 aluminum alloy joints against the artificially aged, at the same temperature, non-welded AA 2024 that already exist in the literature (Alexopoulos et al., 2016b).

It is worth to mention that the essential yield stress increase in the peak-ageing condition is followed by a ductility decrease. Concerning the elongation at fracture for the welded joints, attempts a high decrease up to 85 % in the under-ageing (UA) condition, from the non-welded specimens. In detail, the ductility decreases with a
higher rate in the under-ageing (UA) regime for EBWed specimens. The minimum value of elongation at fracture is noticed after 48 hours of artificial ageing, corresponding to the peak-ageing (PA) condition, for the non-welded specimens while for the EBWed joints the minimum value is noticed in 9 hours of artificial ageing (UA).

Regarding the non-welded specimens in the over-ageing condition (after 96 hours artificial ageing) a partial recovery of ductility is attempted. On the contrary, the EB-Wed joints in the over-ageing (OA) condition presented an essential recovery of almost 40% from the peak-ageing (PA) condition, that is even higher of the respective value of the reference EBWed specimen.

![Graph showing ductility comparison between non-welded and EBWed joints](image)

**Figure 4.8:** Ductility, $A_f$, comparison between (a) the artificially aged at 170°C non-welded AA2024 (*) and (b) the artificially aged at 170°C and electron beam welded (*) joints.

### 4.3.3 Critical stress intensity factor

In this section the comparison between the critical stress intensity factor $K_{cr}$ of the artificially aged at 170°C and electron beam welded 2024 aluminum alloy joints against the artificially aged non-welded specimens, that already exist in the literature (Alexopoulos et al., 2016b), is described.

The Figure 4.9 shows the average values of the experimental results for the $K_{cr}$. The blue line describes the results for the non-welded specimens while the red line
represents the values for EBWed joints which have been artificially aged and subsequently subjected to electron beam welding process.

It must be underlined that the critical stress intensity factor degradation mechanism is different for the welded and non-welded specimens. Regarding the non-welded specimens the short artificial ageing times (up to 9 hours) does not essentially affect the $K_{cr}$ value. In contrast, the welded joints attempt a considerable decrease in under-ageing (UA) regime where the maximum difference in critical stress intensity factor between the two investigated specimens is evident, e.g. -28% (from the non-welded). This can be attributed to the welding induced microstructural changes that accelerate the ageing of the material with the formation of the HAZ.

As far as the peak-ageing (PA) regime is concerned, the difference in $K_{cr}$ values between the two investigated specimens is smaller than in the under-ageing (UA) condition (23%). However, the artificial ageing affect the critical stress intensity factor in a different way, where an increase up to the maximum values for the welded joints is evident, along with a significant decrease in the non-welded specimens. At the over-ageing (OA) condition the non-welded specimens exhibited a recovery of the $K_{cr}$ value, while for the EBWed joints a significant decrease was noticed.

Figure 4.9: Critical stress intensity factor, $K_{cr}$, comparison between the artificially aged at 170°C non-welded (*) AA2024 (Alexopoulos et al., 2016b) and the artificially aged at 170°C electron beam welded (*) aluminum alloy 2024.

4.4 Effect of corrosion on the mechanical properties of artificially aged welded specimens

4.4.1 Conventional yield stress

Figure 4.10 presents the experimental results for the conventional yield stress of the corroded welded joints against the respective non-corroded welded specimens of aluminum alloy 2024. The blue curve in Fig. 4.10 marks the non-corroded artificially aged and EBWed specimens while the red curve indicates the corroded artificially aged and EBWed specimens.
Chapter 4. Analysis of the results

It has been mentioned in Chapter 3, that 2 hours of exposure time to exfoliation corrosion solution have been performed on the welded specimens, as according to the findings in section 3.2.1 this exposure time leads to an essential tensile ductility decrease while stress is not essentially change.

In addition, in this section the comparison between the corroded and non-corroded results of the $R_{p0.2\%}$ for the non-welded artificially aged AA 2024 from (Alexopoulos et al., 2016b) are presented in Figure 4.11. The orange curve represents the non-corroded artificially aged non-welded specimens while the magenta curve the corroded ones.

![Figure 4.10: Conventional yield stress $R_{p0.2\%}$ comparison between the artificially aged at 170$^\circ$C and electron beam welded aluminum alloys 2024-T3 specimens (*) and the artificially aged and electron beam welded (EBWed) joints with 2 hours exposure to ExCo solution (*).](image)

It is obvious from the figures that the corrosion exposure leads to a decrease of the conventional yield stress. Concerning the effect of corrosion on the non-welded specimens, a slightly higher decrease on the conventional yield stress, with the increasing artificial ageing time is evident, with the highest decrease in the peak-ageing (PA) condition of approximately -8.6%. On the contrary, for the EBWed joints the corrosion induced degradation of $R_{p0.2\%}$ is lower with the increasing artificial ageing time with the maximum degradation approximately 11%, to be present in T3 condition. This decrease in the T3 condition where pitting formation is not essential can be attributed to the hydrogen embrittlement effect.
4.4. Effect of corrosion on the mechanical properties of artificially aged welded specimens

4.4.2 Elongation at fracture

This section presents the quantitative results of the elongation at fracture of the electron beam welded 2024 aluminum alloy when artificially aged and subsequently subjected to a laboratory corrosive environment. Figure 4.12 shows the average values of the experimental results of the $A_f$ for the welded specimens. The blue curve in Fig. 4.12 marks the non-corroded artificially aged and EBWed specimens while the red curve indicates the corroded artificially aged and EBWed specimens.

Additionally, in this section the comparison between the corroded and non-corroded results of the $A_f$ for the non-welded AA 2024 from (Alexopoulos et al., 2016b) are presented in Figure 4.13 where the orange curve has been constructed for the non-corroded artificially aged non-welded specimens while the magenta curve for the corroded artificially aged non-welded specimens.

As can be seen from the figures, corrosion exposure tends to decrease the $A_f$ in all the artificial ageing conditions. However, the degradation percentages is different for the non-welded specimens, in T3 as well as in the over-ageing (OA) condition the elongation at fracture exhibited the maximum decrease of 26 %. In contrast, no essential $A_f$ decrease was noticed for the EBWed joints in all the artificial ageing stages with the maximum degradation to be noticed in the over-ageing (OA) condition, e.g. -17 %.

A significant corrosion effect on the two graphs is evident, relative to the experimental curve corresponding to the aged tests. Regarding the effect of corrosion on the non-welded specimens, in T3 condition as well as in the over-ageing (OA) condition the elongation at fracture decrease the most up to almost 26 %. In contrast, the EBWed joints exhibited a slight effect of corrosion on $A_f$ and the maximum degradation was noticed in the over-ageing (OA) condition, e.g. -17 %.

As already discussed in a previous section, no major corrosion-induced surface pits were formed on the welded specimens that could act as stress raisers and therefore degrade their mechanical. Hence, this ductility decrease is mainly attributed to the hydrogen embrittlement effect.
Chapter 4. Analysis of the results

4.4.3 Critical stress intensity factor

In this section the quantitative determination of the corrosion induced degradation of the critical stress intensity factor of the artificially aged electron beam welded 2024 aluminum alloy are presented. Figure 4.14 shows the average values of the experimental results for the $K_{cr}$.

The blue line describes the results for the artificially aged at 170°C and subsequently electron beam welded specimens, while the red line represents the values for the pre-corroded for 2 hours artificially aged and EBWed specimens.

It can be noticed from the figure that the curve corresponding to the corroded welded specimens is qualitatively different from the curve of the non-corroded specimens. The $K_{cr}$ tend to decrease up to the peak-ageing condition for the corroded specimens where the maximum value for the non-corroded is evident. Further ageing time at the over-ageing condition led to a recovery of the $K_{cr}$ for the corroded welded specimens while a decrease is evident for the non-corroded. The maximum corrosion induced degradation of the $K_{cr}$ in the peak-ageing condition, e.g. -15.6%.

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**Figure 4.12**: Ductility (elongation at fracture) $A_f$ comparison between the artificially aged at 170°C and electron beam welded (EB-Wed) aluminum alloys 2024-T3 specimens(*) with 2 hours exposure to ExCo solution (*).
4.4. Effect of corrosion on the mechanical properties of artificially aged welded specimens

**Figure 4.13:** Ductility (elongation at fracture) $A_f$ degradation of artificially aged at $170^\circ$C for aluminum alloys 2024-T3 specimens with 2 hours exposure to ExCo solution.

**Figure 4.14:** Critical stress intensity factor $K_{cr}$ degradation of artificially aged at $170^\circ$C and electron beam welded (EBW) aluminum alloys 2024-T3 specimens with 2 hours exposure to EXCO solution.
Chapter 5

Conclusions

The experimental research for this Thesis has been conducted in order to analyze the mechanical behavior of electron beam welded (EBWed) aluminum alloy 2024. The conclusions that accrue from the three mechanical tests can be described as it follows.

- An essential decrease of ductility and yield stress of AA2024 EBWed joints was evident in comparison with the non-welded specimens.
- Fatigue endurance limit was decreased by 43% after welding.
- The welded specimens showed lower CMOD value for the maximum load value than the reference ones.

- The corrosion-induced degradation is inverse for yield stress (decreasing) and tensile ductility (increasing) with increasing ageing at the T3 condition.

- Artificial ageing heat treatment before welding does not essentially affect the conventional yield stress of the welded joint.

- A significant recovery in the elongation at fracture of the artificially aged and EBWed specimens was evident at the over-ageing condition.

- Critical stress intensity factor mechanism is essentially affected from the artificial ageing heat treatment and welding in a different way than the non-welded specimens.

- No significant decrease due to corrosion exposure for the conventional yield stress (up to 11%) and the elongation at fracture (up to 17%) of the artificially aged and EBWed specimens was evident.

- A decrease of approximately 15.6% in the critical stress intensity factor due to corrosion exposure was noticed up to the peak-ageing condition.
Chapter 6

Future Work

The experimental research that has been conducted provides a good starting point for discussion in order to validate the conclusions that were drawn. Future research might focus on:

- The examination of further artificial ageing heat treatment times on the mechanical properties of electron beam welded AA 2024.

- The simulation of the effect of 2 hours exfoliation corrosion on the fatigue S-N curve of the welded joints.

- The investigation of the tensile and fracture toughness behavior of the artificially aged and EBWed specimens on different exfoliation corrosion times.

- The performance of post-weld heat treatment of electron beam welded specimens.


Alexopoulos, Nikolaos D et al. (2016a). “Mechanical properties degradation of (Al–Cu–Li) 2198 alloy due to corrosion exposure”. In: Procedia Structural Integrity 2, pp. 597–603.


