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**Fatigue Assessment of Laser Beam and
Friction Stir Welded Joints Made of
Aluminium**

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NOMENCLATURE

AA	Aluminium Association alloy designation
LBW	Laser Beam Welding
FSW	Friction Stir Welding
HAZ	Heat Affected Zone
MPW	Magnetic Pulse Welding
NZ	Nugget Zone
TMAZ	Thermo-mechanically Affected Zone
FEM	Finite Elements Method
T_m	Melting Temperature
CAM	Computer Aided Manufacturing
EST	Effective Sheet Thickness

Introduction

This work focuses on the fatigue assessment of butt-welded and overlap-welded joints made of aluminium alloy. The fatigue life of two sets of overlap welded specimens was tested. The aluminium sheets were welded either with the Friction Stir Welding (FSW) or the Laser Beam Welding (LBW) techniques. The research is part of the German project "ALLEGRO".

Background

Aluminium alloys has a lower density when compared to the three times bigger one of the steel but it shows also lower mechanical properties and high material cost. To reach performance comparable with steel, higher volume are needed and this frustrates the weight advantage.

Therefore, aluminium has always been an important construction materials in aircraft manufacturing, that requires light structures with minor concern for the costs, instead it initially faced the scepticism of the automotive sector. The modern pursuit of lightweight vehicles made percentage of aluminium in cars rapidly increase.

Besides the well known need for reduction of fuel consumptions and most important of pollutant emission, the rapidly rising electric car market is demanding lighter structures to compensate the limited energy storage capacity of the batteries that affects car autonomy.

Figure 1: “ALLEGRO” logo.

This background led to the birth of project “ALLEGRO”, logo in Figure 1, in the Hessen region that is also funding the research. Main partners in this cooperations are TU Darmstadt, Kassel Universität and Fraunhofer Institute for Structural Durability and System Reliability LBF where the present work has been carried out.

The project focuses on high performance aluminium alloy with the aim to perfect the forming processes and develop the possibility of locally adjust the material characteristics in order to suit the component properties requirements.

INTRODUCTION

Correlations between forming processes parameters and material local properties are investigated to achieve the highest spatial properties resolution. Moreover, joinability of semifinished products is addressed with the purpose of master joining processes which could possibly not affect the gradient behaviour or rather could confer such properties to the components. FSW, LBW and magnetic pulse welding emerged as suitable processes that could improve the weldability of aluminium usually very hard to accomplish with the conventional method.

Also fatigue is addressed in the project, since where cyclic loads occur, service life needs to be assessed. Fatigue is also a main concern in welded workpiece given that the spot that underwent a joining process usually have lower performances than the base material resulting as a preferential place for crack nucleation to occur. Researches need to be carried out to further investigate the suitability of the actual fatigue recommendation possibly leading to better estimation of service life and security factors to be applied in design procedures.

Given this reason, Allegro fits also within the Fraunhofer LBF research aimed to the integration of manufacturing induced local material properties into the operational design and evaluation of cyclically stressed components and structures.

Thesis structure

This work is structured in seven chapter and three appendices. Chapter 1 will introduce the present state of the art. Therefore, some words will be spend about the aluminium alloy, the welding techniques used to joint the specimens studied in the thesis and about the basic concepts involving the fatigue assessments.

In Chapter 2 more detailed explanations about the fatigue phenomena and on the available concepts to carry out a fatigue assessment. Approaches that were used in developing the thesis are deeper explained so that it will be possible to refer to them in the continuation.

Chapter 3 introduces the reader to the specimens used, the material, their configuration and how the size and the macrospical dimensions of the section where obtained.

Chapter 4 introduce some of the results derived from the experiments on the available specimens as well as all the data that were gathered during an initial phase of research in the available literature

Chapter 5 describes how the finite elements analysis was carried out. The misalignment of the jointed sheets is addressed and in first approximation neglected. Some words are spent on element types and the applied load and constraints. All the decision that led to the finite elements models are explained. In the end, a convergence study and a parametric study on the model are described.

Chapter 6 present the experimental data that were used as test series and the results achieved from the development of a finite element analysis for each of them.

Chapter 7 contains a final outlook on the work and gives some path that could be followed in further developments that will take their first steps from this thesis.

Chapter 1

State of the Art

In this chapter material, welding techniques and the fatigue assessment are introduced. As part of the “Allegro” project investigations, only aluminium series 5000, 6000 and 7000 are taken into account, since these series have similar mechanical properties. Given the interest of the project in innovative welding techniques, only friction stir and laser beam welding techniques are addressed, thus they are briefly described.

1.1 Material

The focus in this work is on the aluminium alloys. In particular, alloys that belong to the Series 5000, 6000 and 7000. These are very different alloys whether for the chemical composition or for the chance of being heat treated.

Figure 1.1: Schematic representation in the plane temperature-time of the heat treatment process.

Only series 2000, 6000 and 7000 can be hardened with ageing heat treatment known as precipitation hardening. The process consist in keeping workpieces at elevated temperature for hours, this allows the nucleation of precipitates that obstruct the dislocations movement in the crystal's lattice. A schematic graph temperature-time of how the process is carried out is given in Figure 1.1. This results in increased Mechanical properties. Table 1.1 gives an overview of the

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main mechanical characteristics of the three series. Wide ranges in the values can give an idea of the hardening achieved with the heat treatments.

Table 1.1: Mechanical properties of series 5000, 6000 and 7000. [Mat18]

series	5000	6000	7000	
Mechanical Properties	Range	Range	Range	Unit
Ultimate Tensile Strength	110 - 590	89.6 - 560	70.0 - 750	MPa
Yield Tensile Strength	40.0 - 540	40.0 - 490	69.0 - 730	MPa
Elongation at Break	0.5 - 35.0	1.0 - 35.0	1.0 - 25.0	%
Modulus of Elasticity	68.9 - 73.0	67.0 - 140	67.0 - 73.0	GPa
Poissons Ratio	0.330	0.330	0.330	
Brinnell Hardness	28 - 185	40 - 95	59 - 150	

Series 5000

Aluminium alloys belonging to this series has magnesium as the second largest component. They are wrought aluminium which cannot be heat treated therefore mechanical properties are enhanced with cold rolling processes. The main characteristics are a good corrosion resistance even suitable for marine applications and a good weldability also with conventional arc processes. Usually the welding process does not produce remarkable loss of strength or hardness as happens for the series 6000 and 7000. [Smi18]

Series 6000

This series mainly contain relevant percentage of magnesium and Silicon. Alloys that belong to this family are easy to machine and to anodize. Moreover, they offer good corrosion resistance and formability especially in the O temper condition. They are commonly used as general purpose aluminium alloys and extensively used in welding fabrication. Among the three heat treatable series, series 6000 offers the lowest gain in terms of strength after the heat treatment. [Smi18]

Series 7000

Series 7000 aluminium alloys contain mainly aluminium, zinc and magnesium. They offer the highest performance in terms of mechanical properties among all the other series of aluminium alloys and moreover it is worth it mentioning excellent fatigue behaviour. When Copper is introduced in the chemical composition, often to improve corrosion resistance, welding is not easily achieved especially with conventional techniques. If corrosion is to avoid, they should be anodized, primed, painted or protected with some type of chemical film. These alloys were firstly developed for aerospace sector and found applications as structural components in aircraft. [Smi18]

EN AW-7075

EN-AW 7075 is the Aluminium Association designation for this material, EN AW-7075 in European standards. This particular alloy was first developed in Japan in

1943 and used for airframe production, but it gained its standard designation only in 1954. Table 1.2 shows permitted ranges under applicable standards. Components made of this material can be strengthened by a heat treatment which causes precipitation of $MgZn_2$ in the lattice. There are several temper conditions for the material which greatly influence the mechanical properties. In this work it has been used the T6 temper that corresponds to the artificial aged condition. It is achieved by operating a solution heat treatment and an artificially ageing process until the alloy meets standard mechanical property requirements. [Smi18]

Table 1.2: Chemical composition of a 7075 aluminium. % W = weight percentage; “res” = residuals. [Mat18]

	Al	Zn	Mg	Cu	Fe	Cr	Si	Mn	Ti	Res
Min % W	86.9	5.1	2.1	1.2	0	0.18	0	0	0	0
Max % W	91.4	6.1	2.9	2.0	0.5	0.28	0.4	0.4	0.2	0.15

1.2 Welding techniques

1.2.1 Laser Beam Welding LBW

The laser beam welding is a fusion welding process that over the last decades has rapidly grown in importance in automotive and aircraft industries. It has contributed improving efficiency and reducing costs. Laser beam welding is a common manufacturing method for a wide range of steel products. Actually, the process has only recently been approved for critical applications involving aluminium alloys. The properties of aluminium alloys influence the interaction between the beam and the material to a far greater extent than for steels.

This technique offers high quality joints with a HAZ that is narrower than the conventional MIG and MAG. The beam is focused on a very little spot, this entail high rate of heating and cooling and high power density of the order of 1 MW/cm^2 . The welding process is very efficient and can be fully automated by using robots, this fact allows a welding high rate that suits especially high volume applications.

Laser beam has also drawbacks. It requires a high cost for the equipments and its maintenance as well as high skilled labour. Moreover, even if the power density is very high, the efficiency in power transformation that very often it can be lower than 5%. The reason is in the working principle that is characterized by many losses, especially thermal losses [SM10].

Working Principle

When a high voltage is supplied to the flash lamps they start to emit light photons. As they are absorbed by the atoms of the ruby crystal, electrons get excited to higher energy level. When electrons go back to their ground energy level, photons are emitted and this is called spontaneous emission. The photons can either excite other atoms, absorption is happening again, or can cause the so called stimulated emission, when their passage agitates an already excited atom ending in a new photon emission. When the population inversion happen, photons start to move across the crystal being reflected by the mirrors. Finally, some of the

Figure 1.2: Scheme of the main parts of a ruby laser. [The18]

photons make it through the partially reflecting mirror and generate the laser beam [SM10]. In Figure 1.2 the laser main parts of a laser are illustrated.

Type of Laser

Solid state laser they includes the synthetic ruby laser, neodymium in glass (Nd:glass) and, the most commonly used, neodymium in doped yttrium aluminium garnet (Nd:YAG).

Gas laser this kind of lasers use mixtures of gas as a gain medium. The most famous are helium and nitrogen (He-Ne) lasers and CO₂ lasers.

Fiber laser the optical fiber is the laser medium itself so that it does not need any delivering system.

Weldability issues LBW

Porosity, solidification cracking, and poor weld bead geometry are the most frequently occurring problems. Porosity often occurs due to the rapid solidification rates and deep weld pools that do not allow for dissolved gases to escape. Remedies are often a use of appropriate filler materials, process gases as well as material preparation [SM10].

1.2.2 Friction Stir Welding FSW

Friction stir welding FSW is an innovative solid state welding first developed and patented in 1991 at The Welding Institute TWI. This technique offer many advantages when compared to the classic procedures such as MIG/MAG or TIG, resulting in lower distortion and higher joint strength. Nonetheless, it has better efficiency consuming less energy, produces no toxic fumes, does not require shielding gas or filler metal as the tool is considered non consumable. Actually, this kind of weld does not need neither any particular attention nor preparation to the metal surface conditions.

FSW seems to suit especially in the challenging task of aluminium welding. It was found out for FSW to be able to join all aluminium alloys including those like

series 2000 and 7000 that are considered as virtually not weldable with classical liquid state techniques, due to the decrease in strength after re-solidification.

In [ZHS13] when the weight of friction stir welded and staggered rivets overlap specimen is compared, a 20 g saving is discovered over a total weight of 292 g. Therefore, is meeting a rising interest in many fields

There are available articles, e.g., [Dil06], [Inf+16], [Rod+16], [Sci+08], which focus on welds between two different series of aluminium as well as between dissimilar material such as aluminium and Magnesium, copper, titanium. The most common joints are butt-welded joints, overlap-welded joints and with Tee-joints [MM05].

Figure 1.3: Friction stir working scheme. [Den+17]

Working principle

In FSW rotating speed and traverse speed of the tool are set. The tool is plunged into two clamped sheets and as heat generated and conducted in the pin proximity is sufficient to enhance material plastic behaviour, the rotating tool is propelled forward. The process requires for a load in the order of kN to be applied during its entire duration. A scheme is given in Figure 1.3.

The weld has some common features such as a hole left by the pin at withdrawn and a ring pattern visible in the top weld surface zone, originated by the the rubs between the tool shoulder and the material surface in its traversing motion.

Frictional heat is generated by the wear between the shoulder and metal surface. This heat along with that generated by the mechanical mixing process and the adiabatic heat within the material, cause the stirred materials to soften without melting. Temperature are estimated to reach values not bigger than 75 – 80% of the melting temperature T_m . Therefore, the process is explained with the stirring action exerted by the pin that mixes the material while generating a plasticized zone around itself.

When welding aluminium, the material in the weld nugget undergoes plastic deformation at elevated temperature, so fine recrystallized grains are generated, this entails lending to the weld remarkable mechanical properties. In the so called nugget zone estimated to be slightly wider than the pin diameter the dynamic recrystallization takes place while welding. One of the main drawback is the precipitates dissolution and coarsening [MM05].

Tool

As described in [MM05], the tool, in Figure 1.4, is characterized by three important dimensions. Pin height and diameter which affect the the material flow under the plastic behaviour. The shoulder diameter has a influence on the generated heat that is proportional to the third exponent of that dimension.

Figure 1.4: Schematic tool 3D drawing

Defect and issues in FSW

Defects are usually related to wrong parameters setting, so that excessive or poor heating of the material can occurs.

In [PJK15] case of too little heat generated welds could present inner channel or surface groove. In the opposite situation the shoulder could create excessive flash and a thinner section in correspondence of the weld seam.

Figure 1.5: Hook and cold lap defects in a friction stir welded joints [Bal+18].

Another common defect, e.g., found in [Bal+18] and [Inf+16], is known as hook defect and occurs in overlapped-joints. When the oxide layers on the surface of the sheets can not be melted by the heat generated leading to a significant effective sheet thickness reduction that affect the fatigue life. In Figure 1.5 the defect is indicated with an arrow.

1.3 Fatigue assessment

Determining the fatigue life is one of the major concern when designing a mechanical component. As shown in Figure 1.6, many approaches are available to evaluate the fatigue life of a workpiece. The concepts are suitable whether the component addressed is welded or not, however some further precautions needed to be taken in the former case.

The seeking of always more conservative results led to approaches that were increasing the depth of the investigation. It is not easy to give a sorted description of all the method since there is no global way to proceed. A subdivision into global and local concepts can be made at a macroscopic level. when going a little bit in depth, the former includes all the nominal approaches and the latter the structural and notch ones and the fracture mechanics. Moreover, some of the above mentioned local approaches can be further divided into stress based or strain based approach.

In the following section some words will be spent in summarizing the available

Figure 1.6: Available fatigue approaches. Figure from [BW15]

concepts for the assessment. Then, in Chapter 2 the approaches used to carry out this assessment will be explained more into detail. In [Bau17], [RSF06] and [RSF09] the reader will find a more accurate discussion on the topic.

1.3.1 Nominal stress approach

This approach is also known as “global approach” since the assessment is based on the overall loads applied to the addressed structure. Local stress concentration effects are roughly taken in account.

The method consists in deriving the nominal stress and comparing it to the designed S-N curve which represents the permissible stress for the addressed structural detail. In the IIW recommendations [HOB09] structure details are available in a table and for each of them a FAT class is provided based on the material.

FAT classes are usually designed with FAT and a number that represents the permissible stress range $\Delta\sigma$ at 2×10^6 cycles with a survival probability $P_s = 97.7\%$ for a stress ratio $R = 0.5$.

The fatigue life is a result of this comparison and the application of a damage accumulation hypothesis that is a modified and relative form of Miner’s rule.

In case no structural detail could suit the addressed element, e.g., the case of a complex structure detail or when the nominal stress cannot be determined, local concepts have to be used [Bau17; RSF09].

1.3.2 Structural stress approach

This approach belongs to the local concepts, it was first developed for the tubular welded joints and then successfully applied even in non tubular ones [RSF09]. This method addresses more in depth the structure under analysis the local effects in the notch ligament are not taken in account. Therefore, lowered S-N curves also known as structural S-N curves are derived only by considering macrostructural behaviour. Stress raising effects caused by the joint members are taken into considerations in the fatigue stress calculations except the effects from the weld itself.

Initially, it was used as a parameter for the assessment the strain at the weld toe derived by applying strain gauges in designed spot [Hai68]. Then, the finite element analysis allowed to rethink the approach in terms of stress leading to the so called hot spot stress method [RSF06].

In the above mentioned method the surface stress at the weld toe is linearly extrapolated from the surface stresses at designed points whose locations is recommended in [HOB09]. The stresses can be derived by a finite elements analysis as well as using strain gauges.

A significant difference in the two manners to measure the surface stresses is that only the procedure which involves the strain gauges intrinsically takes into account the structural distortion produced in the fabrication process [RSF09]. In the FEM environment an ideal distortion-free model is usually addressed and when no information regarding the misalignment and residual stresses are available, [HOB09] recommends factors to enhance the axial stress at the weld toe.

Recommendations concerning the design S-N curve are available in case of steel structure in [NFM06]. Moreover, a modified method for assessing thin walled components in the automotive is proposed in [FS01].

1.3.3 Notch stress approach

Notch methods go more in detail when analysing defects. Here the microgeometry is taken into account and whether stress- or strain- based approaches have been suggested.

A real radius $r \rightarrow 0$ in the crack tip leads to a singularity that entails $\sigma \rightarrow \infty$ and makes it hard to estimate an reasonable fatigue life. Thus, addressed weld toes and roots are fictitiously rounded with a reference radius r_{ref} whose dimension is chosen based on the workpiece thickness.

Moreover, it can be assumed for the material to have either linear elastic behaviour in case of an elastic approach or elastic-plastic material law in case of a strain based approach.

The maximum stress or stress and strain in the fictitiously rounded notch tip is derived and used to perform the assessment.

Elastic approach usually leads to the evaluation of an enhancing factor for the stress called notch factor, $K_t = \sigma_{max} / \sigma_N$, the milder the notch the lower the K_t . In the IIW recommendation [HOB09] specify a minimum value $K_t \geq \sigma_{max} / \sigma_N$ and specify for mild notches the need to address the parent material at the weld toe with a the structural stress approach to avoid the achieving of non conservative-results [Bau17; RSF09].

1.3.4 Crack propagation approach

This method is used once a crack is generated. Purpose is to describe the crack behaviour and growth until the final fracture. Here a brief explanation is given for the sake of completeness. Usually the crack propagation is studied using the Paris law 1.1

$$\frac{da}{dN} = C_0 \cdot \Delta K^m \quad for : \quad \Delta K \geq K_{th} \quad (1.1)$$

Where ΔK is the stress intensity factor and K_{th} is the threshold value under which propagation is assumed not to take place. The value of ΔK can be esti-

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mated either using parametric formulae or a FE analysis. Parameter C_0 and m are material dependent.

Chapter 2

Fatigue strength assessment of welded joints

Fatigue life of a component is affected by many factors, this contribute to make very complex facing the physic process that leads to the failure. Material, Environment, quality of the surface finishing, loading history and load amplitude as well as shape and size of the component affect its life or its permissible load. Nonetheless, when welded joints are assessed also weld defects as well as residual stresses and distortion play a relevant role.

Though residual tensile stresses can sometimes be also very severe at the notch edge being locally higher then the material yield stress and rapidly decrease in the area adjacent the notch. It is estimated that cyclic loading could reduce the residual stresses or altered them in a favourable way if the ductility of the material is adequately high and the cyclic load severe [RSF06].

In this chapter the approaches that were used in this work are introduced.

2.1 Fatigue

Figure 2.1: In (a) repeated fatigue, in (b) variable stress amplitude cyclic loading and in (c) oscillating fatigue

Service loads can have either constant amplitude as in Figure 2.1a or variable amplitude as in Figure 2.1b. As shown in Figure 2.1c a constant load can be described using parameter:

stress range

$$\Delta\sigma = \sigma_{max} - \sigma_{min} = 2\sigma_a \quad (2.1)$$

mean stress

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (2.2)$$

stress amplitude

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \quad (2.3)$$

stress ratio

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (2.4)$$

2.1.1 Wöhler S-N curve

Figure 2.2: Wöhler curve scheme with parameters indicated.

Experimental results are usually plotted in a bi-logarithmic plane as in Figure 2.2. Stress range or stress amplitude is plotted versus the number of cycles to failure. The data can be interpolated to obtain the so called Wöhler line which is usually expressed using the Basquin's equation 2.5. A and k are two constants respectively defining height of a fixed point, e.g., a FAT class and the inverse slope of the curve. Thus, a straight line is generally traced on the plot in addition to the experimental point.

FAT class, as defined in [HOB09], is the endurable stress range $\Delta\sigma$ [MPa] that occurs at number of cycles $N = 2.0 \times 10^6$ cycles with a survival probability of $P_s = 97.7\%$ and for a stress ratio $R = 0.5$. The knee point instead is usually collocated on the abscissa in correspondence of $N = 1.0 \times 10^7$ cycles.

When assessing fatigue life in the high cycles range it is common to have a second line that starts from the knee point. In this case a second inverse slope k^* is necessary. A often recommended value is $k^* = 22$.

$$\sigma = A \cdot N^{\frac{1}{k}} \quad (2.5)$$

2.2 Existing method for assessment

Early assessment methods consisted in testing the welded joints object of the study until the failure in order to obtain a Wöhler curve. The advantage was that a S-N curve for the welded joints could be achieved with drawbacks such as high costs to gather the experimental data and scarce chances of making the results suit an even slightly different joint configuration.

To overcome this some concepts arose around 1960 and 1970. Since at that time there were no possibility of integrate experimental results with finite element analysis as well as with computer calculation, many of the recommendations have been revised in the past years improving reliability and scatter.

In the following some of the available approaches are briefly explained. Purpose is always to derive a fatigue life given the nominal stress applied on the component geometry or the opposite when a desired life is giving and a component had to be designed to face some determined nominal stresses.

To derive a S-N curve an inverse slope k as well as a proper FAT class value are recommended depending on the material and on the welding, moreover in case of very high cycle fatigue life it is suggested a second inverse slope $k^* = 22$ to deal with number of cycles on the right of the the knee point, [HOB09].

The methods described in the following sections are only the ones that were used in thi work. To carry out this assessment it was decided to begin with elastic approaches both global and local. Among the reason to proceed in this manner, the fact that friction stir welds were developed recently and no actual recomandation are available.

Thus, more conventional recommendations such as the ones in [HOB09] and suggested FAT classes for the notch and the effective assement in [Stö+11] were addressed.

2.2.1 Nominal stress approach

This approach is used to estimate a fatigue life when is evaluated a nominal stress applied to a weld or, more general, on a structure. Then a designed S-N curve has to be defined.

Thus, it is assumed for the fatigue life to have the same S-N course as the Wöhler curve and as recommended in [HOB09], a knee point is located at $N = 1.0 \times 10^7$ cycles and a slope for the curve is chosen. FAT class as is defined in section 2.1.1 define the height of the curve and can be chosen following the IIW recommendation [HOB09]. These Endurable stresses are listed and organized based on different materials, structural details and other features in a table.

Two examples of the table in [HOB09] containing structural details and their corresponding FAT classes can be found in Figure 2.3a for the butt welded and in Figure 2.3b for the overlap welded ones. In this way the designed S-N curve is completely defined. In case of high cycle fatigue, a second linear section with a different shallower slope can be defined.

Finally, the nominal stress derived for the structure is compared with designed S-N curve and the assessment can be carried out.

No.	Structural Detail	Description (St.= steel; Al.= aluminium)	FAT St.	FAT Al.	Requirements and Remarks
214		Transverse butt weld, welded on non-fusible backing, root crack	80	28	Backing removed, root visually inspected. Misalignment <10% of plate thickness.
215		Transverse butt weld on permanent backing bar terminating >10 mm from plate edge, else ->	71 63	25 22	Misalignment <10% of plate thickness.
216		Transverse butt welds welded from one side without backing bar, full penetration root controlled by NDT no NDT	71 36	28 12	Misalignment <10% of plate thickness.

(a) Butt welded joints

614		Transverse loaded overlap joint with fillet welds. Stress in plate at weld toe (toe crack) Stress in weld throat (root crack)	63 36	22 12	Stresses to be calculated using a plate width equalling the weld length. For stress in plate, excentricity to be considered, as given in chapters 3.8.2 and 6.3. <i>Both failure modes have to be assessed separately.</i>

(b) Overlap welded joints

Figure 2.3: Extracts from the table in [HOB09] which contains the FAT classes recommendations.

2.2.2 Notch stress approach

The notch stress approach is usually performed deriving a notch factor K_t through a finite element analysis for the addressed defects. The factor mentioned above is then used to enhance the nominal stress and compare it to the designed S-N curve characterized by the FAT class proposed for the structural detail. FAT classes can be found in [Eib+03], [Son09] and [Stö+11]. When developing the geometry in the analysis, notches as well as weld toes and roots are fictitiously rounded with a fixed radius. Figure 2.4 gives some examples of possible location in which the method should be applied.

Figure 2.4: Notch stress method example [HOB09]

As specified in [Bau17] the first used radius was the so called fictitious radius $r_f = 1.0 \text{ mm}$ applied for fatigue assessment in welded thick sheets $t < 5 \text{ mm}$. This method is called “effective notch stress approach” and the derived stress can be directly used for an assessment.

When assessing welding thin sheets $t \leq 5$ mm one of the most used radius is $r_{\text{ref}} = 0.05$ mm. The reason is that a big radius such as the $r_f = 1.0$ mm affects the calculation by considerably reducing the effective sheet thickness therefore weakening the structure. Instead, for joints with a thickness $3 \text{ mm} \leq t \leq 10$ mm the last radii are either too big or too small so a radius $r_f = 0.3$ mm was proposed [SBB10]. These variations are called reference radius r_{ref} .

Each of the radii has his own recommended FAT values derived in dependence of where the failure occurs in combination with material and applied load. If the residual stress is not available it is possible to proceed in a conservative manner by assuming high residual tensile stress to be present. As a consequence of this, mean stress is considered not to affect the fatigue strength in the assessment [Bau17].

However, it was found out that assessments with the reference radii when used in combination with recommended FAT classes were leading to non conservative results in some cases. Thus, for these radii was suggested to use an averaged stress value which requires using the “effective stresses” method [Bau17].

2.2.3 Effective stresses

Figure 2.5: Effective stress and both critical and microstructural lengths [Bau17]

This method was originally conceived by Neuber [Neu01] and Peterson [Pet59]. The effective stresses requires to address the stress gradient in the notch ligament. A reference radius as well as a realistic radius can be used [Bau17]. This approach is included in the notch stress one, though they are different, because it requires the evaluation of the stress field in the notch neighbourhood.

In this concept a finite elements analysis has to be performed to address the stress gradients in the notches vicinity. Thus, notches in the model are rounded using the $r_{\text{ref}} = 0.05$ mm. In order to achieve an effective stress, its gradient resulting from the analysis must be evaluated on a straight line moving perpendicular to the notch edge and starting from its rounded tip. As shown in Figure 2.5, two different ways to proceed are available but both cases require either a microstructural length ρ^* or a critical length a , to determine an effective stress.

When available in some recommendation as [Stö+11], these lengths can be used as are specified. microstructural and critical lengths can also be derived when assessing a data pool trough successive numerical analysis, choosing the lengths entailing the smaller scatter in the resulting S-N curve.

In [Stö+11] and [Bau+15] recommendations concerning which FAT class and inverse slope to use are given. Thus, when a designed S-N curve is defined, the

assessment can be performed.

stress averaging approach [Neu01] the stress gradients is averaged over a microstructural length ρ^* to calculate an effective stress σ_{eff}

$$\sigma_{eff} = \frac{1}{\rho^*} \int_0^{\rho^*} \sigma(x) dx \quad (2.6)$$

critical distance approach [Pet59] the stress at a distance a from the surface is used as effective stress σ_{eff}

$$\sigma_{eff} = \sigma(x = a) \quad (2.7)$$

This parameters can be considered as influenced by the material and they can be derived empirically. Furthermore, they are related to each other [TH09], equation 2.8.

$$\rho^* = 4 \cdot a \quad (2.8)$$

2.3 Mean stress sensitivity

In certain circumstances a fatigue enhancement factor can be applied as suggested in [HOB09] and [Son09]. Reason is that comparing the designed S-N curve with $R = 0.5$ with experimental data obtained from test with lower load ratio, thus with lower mean stress, or from stress relieved components the estimated service life may result over conservative. Therefore a stress sensitivity factor could be introduced and the stresses are derived using the Haigh's diagram.

(a) [HOB09]

(b) [FKM12]

Figure 2.6: Plot of the factor $f(R)$ in (a) and Haigh's plot with from the FKM guidelines (b)

The IIW recommendations [HOB09] suggest an enhancement factor $f(R)$ that should be used to multiply the fatigue class. As shown in Figure 2.6a, three different cases are distinguished and it is highly discouraged to modify fatigue strength without reliable information on residual stress. Residual stress is defined as the sum of all the stresses that are not considered in the fatigue analysis but are affecting fatigue life. Category I is for unwelded base material, wrought products and stress relieved welded components, category II is meant for small-scale thin walled elements containing short welds and category III admits only $f(R)=1$. Category I $f(R)$ values and their stress ratio ranges of validity are given

in Equation 2.9. Moreover, in Equation 2.10 could be found a general formulation to transform the stress amplitude in range $-1 \leq R \leq 0.5$, into an equivalent stress amplitude for a target stress ratio included in the same range.

$$f(R) = \begin{cases} 1.3 & R < -1 \\ -0.4 \cdot R + 1.2 & -1 \leq R \leq 0.5 \\ 1 & R > 0.5 \end{cases} \quad (2.9)$$

$$\sigma_{a,R_{TARGET}} = \frac{1.2 - 0.4 \cdot R_{TARGET}}{1.2 - 0.4 \cdot \frac{\sigma_{m,R_{ACTUAL}} - \sigma_{a,R_{ACTUAL}}}{\sigma_{m,R_{ACTUAL}} + \sigma_{a,R_{ACTUAL}}}} \cdot \sigma_{a,R_{ACTUAL}} \quad (2.10)$$

Sonsino in [Son09] recommends a slightly different factor as in equation 2.11.

$$f(R) = \begin{cases} 1.32 & R < -1 \\ -0.22 \cdot R + 1.1 & -1 \leq R \leq 0 \\ -0.2 \cdot R + 1.1 & 0 < R \leq 0.5 \\ 1 & R > 0.5 \end{cases} \quad (2.11)$$

Approaches with an enhancing factor lead to a curve in the Haigh's diagram but usually it is approximated with two lines with an M values as a slope. Each of the M values are evaluated in the portions of the plane included in the range $R \in [-1; 0]$ and $R \in]0; 0.5]$. A relationship between the M value and the different stresses is defined for the two ranges, respectively 2.12 and 2.13. For the sake of completeness, a general equation is given in 2.10 but it must be specified that it is meant only for the methods proposed in the IIW recommendation.

$$M_1 = \frac{\sigma_{a,R=-1}}{\sigma_{m,R=0}} - 1 \quad (2.12)$$

$$M_2 = \frac{\sigma_{a,R=-1} - \sigma_{a,R>0}}{\sigma_{m,R>0} - \sigma_{m,R=0}} - 1 \quad (2.13)$$

FKM guidelines [FKM12] proposes three different M values for the slope of the line in the Haigh's diagram based on the residual stresses: low $M_\sigma = 0.3$, moderate $M_\sigma = 0.15$ and high $M_\sigma = 0$. The course of the line plotted is based on its slope M'_σ that is defined in equation 2.14. In Figure 2.6b can be found the Haigh's diagram available in [FKM12].

$$M'_\sigma = \begin{cases} 0 & R < -\infty \\ M_\sigma & -\infty \leq R \leq 0 \\ M_\sigma / 3 & 0 \leq R \leq 0.5 \\ 0 & R > 0.5 \end{cases} \quad (2.14)$$

Chapter 3

Experimental Fatigue Life Evaluation

This chapter focuses on the specimens that were tested at the Fraunhofer LBF. Only overlap welded specimens were available either friction stir or laser beam welded. Thus, the dimensions are given and the procedure used to address them is described. Finally, the experimental results are given and briefly discussed.

3.1 Specimens

The specimens were made of aluminium EN-AW 7075 in T6 temper. Sheets with a thickness $t = 1.5$ mm were jointed in the overlap welded using either the LBW or the FSW techniques that are described in Chapter 1. All the specimens $200\text{ mm} \times 50\text{ mm} \times 1.5\text{ mm}$ and Figure 3.1 gives an overview of the their geometry together with the main size. Moreover, in Figure 3.2 and Figure 3.3 some pictures of the specimens taken before the test stage are given.

Figure 3.1: Schematic representation of the specimens geometry

3.2 Process Parameters

All the welding processes were performed at the Kassel Universität and then the specimens were provided to the Fraunhofer Institute. For the laser welded specimens was used a fiber laser and the main process parameters can be found in Table 3.1.

Figure 3.2: Specimen LBW_LJ_AL1_1

Figure 3.3: Specimen FSW_LJ_1_1

Friction stir welding was carried out with a rotating speed of 800 rpm and a travelling speed 1200 mm/min. Two different pins were available as well as two main tool holders. The pins were M5 threaded pin whether with a cylindrical or conical shape and their height was respectively 5 mm and 4 mm. Concerning the tool holders, the smaller one had a shoulder diameter of 12 mm and the bigger one of 14 mm. Figure 3.4 shows a picture of the mounted cylindrical pin in the 14 mm shoulder tool holder.

Figure 3.4: FSW welding tool

Table 3.1: Laser parameters

Specimen	Power [kW]	Focal diameter [μm]	travelling speed [mm/min]	Filler material
LBW_LJ_AL1	4.2	600	75	AlSi12
LBW_LJ_AL2	4.2	600	75	AlSi12
LBW_LJ_AL3	4.2	600	75	AlSi12
LBW_LJ_AL4	4.2	600	75	AlSi12
LBW_LJ_AL5	4.2	600	75	AlSi12
LBW_LJ_AL7	4.2	600	75	-
LBW_LJ_AL8	4.2	600	75	-
LBW_LJ_AL11	5.2	600	100	-
LBW_LJ_AL12	5.2	600	100	-

3.3 Dimension acquisition

Designing FEM models of the actual specimens required a deeper investigation than mere observation of their overall size. Geometry of the cross section in the weld proximity needed to be addressed as well as potential misalignments of the jointed plates. Therefore, two types of measuring were carried out, using a stereo microscope to analyse the cross section and using a laser instrument to evaluate misalignment. Figure 3.5 show the two stages.

(a) Stereo Microscope

(b) Laser system

Figure 3.5: Stereo microscope and laser measurement

3.3.1 Cross-section picture

Cross section picture were taken using a stereo microscope Stemi SV 11 APO from Carl Zeiss. From the same jointed plates from which the specimens were cut also a sample of the weld cross section was taken. This was then prepared for the microscope by being etched with a reagent, included into a resin stub and the surface that was undergoing the observation was polished.

Through the microscope many pictures were taken this allowed to observe if there were any defects in the welding and for the overlapped joints how the notches were positioned in the section. Two examples of cross section pictures can be found in Figure 3.6.

After having taken cross section pictures, measures necessary to develop a FEM model were achieved using CorelDRAW X6®. Therefore, the pictures taken with the microscope were pasted in the software and after having modified the scale the measuring feature allowed to derive all the information needed. Figure 3.6b shows a cross section picture resulting from CorelDRAW with all the measures.

Figure 3.6: Cross section pictures taken with a stereo microscope

3.3.2 Laser measurement

Figure 3.7: Laser measurement, lines in grey were marked on the specimens so that measures could be taken in the same locations for each specimen

Laser measurements were conducted on the specimens in order to verify if there were significant misalignment between the jointed sheets. In Figure 3.7 a sketch is provided in which are drawn the lines, in grey, along which the laser instrument has taken the measure. Along the three lines the software handling the measure sampled the relative distance between specimen surface and laser source while storing the points in a “*.csv” file. Later the data were evaluated using MATLAB.

Initially, the plotted profiles were incident with the x-axis, this was due to a misalignment between the specimen surface and the rails on which the laser instrument was moving to record the points. Thus, the first step was to evaluate the slope using a linear interpolation and then using the obtained polynomial to eliminate the slope. The measured distance were shifted so that the initial part of the profile was laying on the x-axis.

Finally, all the points were plotted for each specimen and the misalignment between the jointed sheets was investigated. This time the profile of each of the two sheets making up a specimen was interpolated and this allowed to measure

Figure 3.8: Laser measurement, two of the resulting plots from Excel.

the angle between the two straight lines that had been derived. All the angle were collected and they are available in Appendix A in Table A.1. In Figure 3.8 the derived profile of a FSW and a LBW overlap joint are given.

3.4 Test campaign

The Overlap welded specimens made whether with the friction stir or the laser beam were tested until the complete failure. A reduction of the specimen stiffness to the 80 % of the starting value was set as an alternative condition leading to the arrest of the test rig.

Since the overlap joints are characterized by a very low endurable stresses together with the fact that the aim of this tests is to lay in the range 1×10^4 to 1×10^7 , the frequency for the tests was set in the range 30 Hz to 50 Hz. The frequency at which each test was carried out is specified in Table 3.2 and Table 3.3.

The experimental results for the FSW overlap welded specimen are plotted in Figure 3.9. The points are split in three sets that are identified whether by the color or the type of marker. A square marker was used to indicate a failure originated in the base metal otherwise a circle is used. Instead, the yellow color was chosen to highlight the two specimens whose flanks were grinded before they were tested. In Figure 3.11a and 3.11b two pictures of a specimen failed in the base material are given, in this case the failure does not involve the weld seam

Figure 3.9: FSW specimen experimental results.

resulting entirely originated and propagated in the overlapped area.

An attempt was made in this manner since it was observed that all the failures in the base metal originated from the surfaces on the specimen sides in the overlapped area. It was thought that the finish of those surfaces were to blame as initially the specimens were tested in the “as received” condition from the water jet cut. Thus, the flanks were polished in three steps using in the order 320, 600 and 1200 grit size sandpaper.

Based on the two yellow squares, the achieved fatigue life showed no remarkable improvement linked to the grinding process. Nonetheless, the failure occurred in both cases in base material. Therefore, it was concluded that even with a good finish the phenomena could not be stopped or that at least with a polishing process such as the one described was not possible to reach defects deriving from the cutting process and sited between the overlapped sheets.

In Figure 3.10 are plotted the LBW experimental results together with two S-N curves evaluated for the same data. Both of them, were derived using the maximum likelihood criteria. The difference is that in one case the curve was derived in a proper manner leaving to the script the task of evaluating the best inverse slope and location and stress for the knee point. In the other case the evaluation was carried out for a fixed knee point at 1×10^7 cycles as it was done for all the other experimental data. The purpose of proceeding in this manner was to have the chance later to compare this data with all the points collected from several papers as is explained in Chapter 4.

Figure 3.10: LBW specimen experimental results.

Figure 3.11: Side (a) and top (b) view of the crack in a base material failed FSW specimen.

Also in this plot two types of marker were chosen to identify the specimens welded using AlSi₁₂ as filler material. Different colors identify different welding conditions for the chosen power and travelling speed of the seam. No remarkable differences were observed between the three sets of data.

At a first comparison of the results, the friction stir welds showed a higher

CHAPTER 3. EXPERIMENTAL FATIGUE LIFE EVALUATION

fatigue life compared to the laser ones. The ratio between the endurable stresses evaluated at 2×10^6 cycles for the two S-N curve is circa 2.3. Therefore, based on this tests the friction stir welding technique seems to be a valid competitor of the laser ones. Nonetheless, such a low fatigue strength for the laser welded specimens was a bit unexpected but when compared with experimental results from [Son+97] it was observed for it to be in agreement with them.

Table 3.2: Results from the FSW specimens tested at the Fraunhofer LBF.

Specimen	F_a	$\sigma_{N,a}$	R_{global}	Cycles to failure	Freq
	[kN]	[MPa]			[Hz]
FSW_LJ_1_1	2	26.7	0.1	1626675	30
FSW_LJ_1_2	5.5	73.3	0.1	20572	30
FSW_LJ_1_3	1.5	20	0.1	2195612	30
FSW_LJ_1_4	2	26.7	0.1	640067	30
FSW_LJ_1_5	3	40	0.1	169439	30
FSW_LJ_2_1	2.5	33.3	0.1	259204	30
FSW_LJ_2_2	1.5	20	0.1	1897649	30
FSW_LJ_2_3	4.5	60	0.1	28815	30
FSW_LJ_2_4	3.5	46.7	0.1	68011	30
FSW_LJ_2_5	4.5	60	0.1	34496	30

Table 3.3: Results from the LBW specimens tested at the Fraunhofer LBF.

Specimen	F_a	$\sigma_{N,a}$	R_{global}	Cycles to failure	Freq
	[kN]	[MPa]			[Hz]
LBW_LJ_AL1_1	2.5	33.3	0.1	7201	40
LBW_LJ_AL1_2	1	13.3	0.1	144321	50
LBW_LJ_AL2_1	0.75	10	0.1	503972	50
LBW_LJ_AL3_1	2.5	33.3	0.1	7113	40
LBW_LJ_AL3_2	1.5	20	0.1	27277	50
LBW_LJ_AL4_1	0.75	10	0.1	940369	50
LBW_LJ_AL4_2	0.75	10	0.1	844144	50
LBW_LJ_AL5_1	1	13.3	0.1	167559	50
LBW_LJ_AL5_2	0.75	10	0.1	2400584	50
LBW_LJ_AL7_1	1	13.3	0.1	81489	50
LBW_LJ_AL7_2	2	26.7	0.1	7418	50
LBW_LJ_AL8_1	1.5	20	0.1	36519	50
LBW_LJ_AL11_1	1	13.3	0.1	114263	50
LBW_LJ_AL12_1	2	26.7	0.1	11693	50
LBW_LJ_AL12_2	1.5	20	0.1	29094	50

Chapter 4

Literature reasearch and parameters investigation

A literature research was carried out on the published researches focused on the fatigue life of friction stir welded joints, forty-three articles as well as other kinds of publication were rallied. Initially, all the experimental data and the informations about welding and testing conditions were collected in a database to create a data pool. Then, the material was addressed and only results from aluminium series 5000, 6000 and 7000 were taken in account. The experimental data were obtained at different stress ratio therefore came out to be necessary evaluating a mean stress sensitivity to compare them. Eventually, the data pool was sorted in many ways in order to obtain each time a cloud with a smaller scatter between the points, drawback was a decrease in the point considered.

4.1 Literature research

Experimental data available in the publications were taken in account with the purpose of creating a data pool to work with. Therefore, collected data were stored in a table using EXCEL.

Not only information regarding number of cycles until failure and the correspondent stress were taken in account because the the aim was of carrying out a deeper investigations. Therefore, in the database were stored informations concerning welding parameter, tool geometry and specimen size and geometry. Cross sections, when found, were collected because they allowed developing FEM models for specimens used in the articles.

Once everything was stored and sorted in the database, a plot containing all the experimental data was created so that it was possible to filter the table thus to compare only data with some similarity in the parameters. The above mentioned plot is shown in Figure 4.1. In the plot legend is provided because purpose of the plot is to give an overview of the data gathered and their high dispersion. However, in Table 4.1 all the papers that were addressed in the literature research are listed.

Figure 4.1: Original data pool containing all the data as they were collected

Table 4.1: Table containing the list of the paper addressed.

Legend			
[Bal+18]	[Bes+17]	[BKB12]	[BLP15]
[BTL05]	[CAV+09]	[Cir+06]	[Cos+12]
[Den+16]	[Den+17]	[Dic03]	[Dil06]
[EKK10]	[Eri03]	[Eri05]	[FP07]
[Gio+09]	[He+15]	[He+16]	[HGB14]
[HMR70]	[Inf+16]	[Kra14]	[Kra15]
[KŞK06]	[M R96]	[Mag+16]	[MFC07]
[MM05]	[Ner03]	[OGW15]	[Rao+17]
[Rei+14]	[Rod+16]	[Sci+08]	[SHS12]
[SS10]	[SS12]	[Sus+17]	[TOS12]
[Uem+09]	[Xu+12]	[ZHS13]	

4.2 Neglected data

Since some of the data were too scattered when compared to the others, they needed to be addressed. Stress values too low or too high were investigated and sometimes it was necessary to neglect them.

Causes that led to such unexpected behaviour were various, e.g. in [FP07] five experiments had been carried out applying an anti-bending device on the overlap welded specimens resulting in a higher fatigue life or in [Uem+09] the specimen surfaces were grinded resulting in enhanced fatigue life. All the data from [KŞK06] were not taken in account because some informations were missing and furthermore the stress values were considered to be excessively lower than encountered stresses for similar alloys and similar number of cycles to fracture.

Figure 4.4 shows the new plot without the neglected data and with all the stress ratio transformed to $R=0$ as it is explain in Section refsec:factormeanstress. In the plot the amount of data is clearly reduced and the scatter slightly decreased.

4.3 Derivation of a mean stress sensitivity factor

Figure 4.2: Haigh's diagram containing the evaluated endurable stresses at 2×10^6 cycles for each set of data

Though some data were neglected, the cloud of collected points remained very scattered. Moreover the different stress ratio used in different articles were contributing in making very hard to compare data of different researches. Thus, it was necessary to estimate a mean stress sensitivity that could allow comparison between test series characterized by different R by transforming all of them to a same stress ratio.

CHAPTER 4. LITERATURE REASEARCH AND PARAMETERS INVESTIGATION

Although in guidelines [HOB09; FKM12] are available recommendations on how to evaluate a mean stress sensitivity factor, most of them are meant and validated for the case of arc welds. Therefore, it was decided to derive for each set of data the correspondent S-N curve with a 50 % survival probability using the maximum likelihood criteria while imposing a common position to the knee point at 1.0×10^7 cycles. This was done in accordance to the IIW guideline [HOB09]. Later, all the endurable stresses occurring at 2.0×10^6 cycles, same value used to define FAT classes, were collected in a database which allowed also the filtering of the data and eventually they were plotted in a Haigh's diagram.

Figure 4.2 shows the achieved graph. It must be specified that in the diagram some dots are connected to each other with a line, this was the case of specimen belonging to a same series and tested with different stress ratios. Otherwise, every data points are represented by the point itself. At the same time, it can be noticed that no articles which tested a same batch of specimens with more than two stress ratios were available. No way to connect more points with only one straight line seemed possible.

As a consequence, it was not possible to define a rigorous value for the mean stress sensitivity, and certainly not a sole value for it throughout the plane. The first quarter of the Haigh's diagram was split in two parts in which a not null slope was derived, one included in the range $-1 \leq R < 0$ and the other in $0 < R \leq 0.5$. In each sector were available two lines linking points that belonged to the same test sets as previously explained. There, the couple of lines available in each sector were averaged as an initial approximation. It was decided to proceed in this manner because no set of data led to a sole line to link the points nonetheless no actual recommendation for the FSW can be found in the guidelines. In equation 4.1 the derived value for M and its interval are given and in Figure 4.3 the plot in the Haigh's diagram of the line with these slopes is shown.

$$M = \begin{cases} 0, & R < -1 \\ 0.71, & -1 \leq R < 0 \\ 0.25, & 0 < R \leq 0.5 \\ 0, & R > 0 \end{cases} \quad (4.1)$$

It seems to be reasonable the fact that the M value in the first interval is approximately three times the other one, this is in accordance with what is stated in the FKM guidelines [FKM12]. However, what stated above is far from representing a definitive as well as rigorous way to define a proper mean stress sensitivity. Further experiments aimed to define some recommendations to evaluate properly a mean stress sensitivity should be carried out.

For the sake of completeness, in Appendix C are available Figure C.1, Figure C.2 together with Table C.1 and Table C.2 which provide a better overview of the available data for the evaluation of a mean stress sensitivity factor.

Eventually, with the derived factor all the data were transformed to the stress ratio $R = 0$ and plotted again, this can be seen in Figure 4.4. At this point, it was possible to proceed with an investigation of the parameters effects on the fatigue life.

Figure 4.3: Haigh's diagram and the line evaluated for the mean stress sensitivity

Figure 4.4: Plot containing only the filtered data transformed to a stress ratio $R=0$

4.4 Survey on the effect of welding parameter on fatigue life

The data pool was filtered using several criteria with the purpose of observing which among the welding parameters affect the fatigue life of welds. Only the friction stir weld were addressed because its use is quite recent and requires further

(a) Graph with FSW overlap welded Joints

(b) Graph with FSW butt welded Joints

Figure 4.5: Plots with data pool split based on the different types of joint and sets clustering the same aluminium series

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investigations.

The S-N curves were evaluated using the maximum likelihood criteria on the considered group of points. Based on the global cloud achieved as the experimental values were all collected, it was not possible to clearly estimate the location of a knee point so its position was fixed at 1.0×10^7 cycles. Thus, every time it was necessary to evaluate only the inverse slope k , and the stress value in correspondence of the knee point.

Due to the big data dispersion, a difference in the global fatigue strength of the types of joint could be foreseen but it was not easy to clearly separate their trends. The considered cloud is the one obtained after having transformed all the stress ratios, Figure 4.4. Initially, it was decided to split the data in two different clouds based on the weld type, butt welded and overlap welded joint. Three aluminium series were taken into account series 5000, 6000 and 7000. The two clouds were plotted in different graphs, the three series were highlighted and an S-N curve each was evaluated just to make a rough comparison between them and to see if there were any influences exerted by the material of the joints. The results are shown in Figure 4.5a and Figure 4.5b that represent respectively butt welded and overlap welded joints.

From the graphs can be already stated that butt welded joints are showing a higher fatigue life especially when compared with the one offered by the other type of joint. This trend is not related to the alloy composition but it can be explained with the geometry configuration of the welds. In many article addressing the overlap configuration, e.g., [Eri05], [Inf+16], [Kra14], it was observed for the crack to originate always from the crack-like roots between the interfacing surfaces of the sheets. This defect is generally associated with a reduction of the effective sheet thickness thus a weaker cross section.

For the overlap welds in Figure 4.5a can be said that aluminium alloy form series 5000 have the highest endurable stress at 2×10^6 cycles and the shallower slope for the S-N curve. This series seems to be the best among the ones considered and the 7000 came out as the worst to choose. However, the considered results for the 5000 lay very close to the high cycle fatigue life instead the ones for the 7000 are closer to low cycle fatigue life. Thus, their S-N curves are based on incomplete informations. This must be taken in account when making some conclusions from the graph.

The results of the experiments carried out at the Fraunhofer Institute LBF are plotted as black dots in Figure 4.5a. As mentioned in Section 3.1 friction stir overlap welded joints made of EN-AW 7075 in T6 temper were tested. They show a generalized higher fatigue life even compared to results obtained using the same aluminium series. Only the slope seems to be similar in the two cases. This could be ascribed to the different welding condition that influenced the cross section of the specimens. This trend was not unexpected since based on what was found out in the parametrical study section 5.8, for same nominal load lower maximum local stresses were encountered in the asymmetric geometry.

For what concerns the butt welds in Figure 4.5b, the aluminium series 7000 has the highest fatigue life with a value for the k not so far from the one proper of the series 6000. The endurable stress for 2×10^6 cycles its very similar in the aluminium 5000 and 6000, 38 MPa. To the serie 7000 has a circa 1.7 bigger stress at the same number of cycles, 64 MPa.

In each of the following sections the results achieved through the investigation on how and which parameters are affecting the fatigue life of the welded joints

are described.

4.4.1 Effect of the shoulder

Figure 4.6: Plot highlighting the effects of the shoulder Geometry

Table 4.2: Parameters referred to the elements in the legend of Figure 4.6. All the three sets were welded using the same parameters therefore only one line is given in the table. For the headers: Al, aluminium alloy; t, thickness; d_s, shoulder diameter; ν, travelling speed; ω, revolution speed; ν/ω, revolutionary pitch.

Label	Al	t [mm]	d _s [mm]	ν [$\frac{\text{mm}}{\text{min}}$]	ω [rpm]	ν/ω [$\frac{\text{mm}}{\text{rev}}$]
[Gio+09]	6082	1.5	6.0	450.0	1810.0	0.25

In [Gio+09] the author focused on evaluating the effects of the shoulder geometry. All the welding parameters were kept constant as can be observed in Table 4.2 and three different types of shoulder were used, they can be seen in the sketches in the plot. It came out that the scroll geometry for the shoulder was leading to worse fatigue life. This was explained with a smaller tool surface dragging with the processed material resulting in smaller heat generated. Thus, the amount of heat generated is very important to ensure the success of the joining process. Furthermore, [Tan+98; FGM01] believed that heat generated by the shoulder friction on the metal surface is the main part of the total amount.

4.4.2 Effect of the pin

Figure 4.7

Table 4.3: Parameters referred to the elements in the legend of Figure 4.7. For the headers: Al, aluminium alloy; t, thickness; d_s, shoulder diameter; ν, travelling speed; ω, revolution speed; ν/ω, revolutionary pitch.

Label	Al	t [mm]	d _s [mm]	ν [$\frac{\text{mm}}{\text{min}}$]	ω [rpm]	ν/ω [$\frac{\text{mm}}{\text{rev}}$]
[Eri05] Sh15ConvexPin	6082	4.0	15.0	300.0	1500.0	0.2
[Eri05] Sh15ConcavePin	6082	4.0	15.0	300.0	1500.0	0.2
[Eri05] Sh18ConvexPin	6082	4.0	18.0	300.0	1500.0	0.2
[Eri05] Sh18ConcavePin	6082	4.0	18.0	300.0	1500.0	0.2

In [Eri05] the author addressed how different geometry of the pin bottom face were influencing the strength. It is believed for the pin to influence the metal flow around itself so in [Bal+18; KSK06; Eri05] investigations have been carried out in order to find out how the geometry of the pin was influencing the success of a welding process. Nonetheless, in [Kra14] is investigated overlap welded joints fatigue life to state if a specifically designed pin geometry could lead to better results than a smooth pin. In Table 4.3 the welding parameters used are given and a sketch of the pin ends can be found in the top left corner of the plot. Two diameter were available for the tool shoulder and whether a concave or a convex

end for the pin, they were used in all the four possible combination.

From Figure 4.7 can be observed that the concave end leads in general to a slightly better fatigue life than the convex one. This could be explained probably with a better metal flow right under the pin ends during the welding process [Eri05]. Even an influence of the shoulder can be noticed since the specimens joined with the bigger 18mm diameter of the shoulder resulted in a little bit higher endurable stresses.

This said, it can be recommended the use of a concave pin when welding and of a bigger shoulder diameter. However, precautions must be taken so that a too big shoulder will not cause excessive flashes on the toe surface of the weld as well as too high temperature in the section.

4.4.3 Alloy influence

From Figure 4.8 emerges that the mechanical properties that are proper of each alloys are obviously affecting the fatigue strength. In the graph were plotted only aluminium alloys from the 6000 and 7000 series with similar welding condition that are given in Table 4.4. The first focus was put on this two series since they are the same whose mechanical properties and of formability are addressed in the project “Allegro”.

It is possible to affirm that the different mechanical properties of the base material as has been described in section 1.1 have an effect on the fatigue strength of the joints. Thus, alloys from the aluminium series 7000 seem to have an endurable stress evaluated at 2×10^6 cycles bigger than the one of the series 6000 of a factor that is approximately 1.3.

As reported in the text boxes in the plot, the value of the inverse slope are similar so the 6000 aluminium present a slightly smaller fatigue life in the range of interest for this work, 1×10^4 to 1×10^7 cycles.

However, in [Uem+09] alloys from the series 5000, 6000, 7000 are addressed and the first of the tree should be the alloy with a closest fatigue strength to the one of the base metal. It emerged that a typical behaviour for heat treatable alloys is to present a hardness decrease in the TMAZ due to the coarsen of the precipitates, this phenomena cannot happen in the 5000 alloys that from a hardness measurement showed a small increment, [Uem+09]. This said, among the collected data there were no experimental set with any 5000 alloys that suited the filtering criterion so a direct comparison in this graph was not possible.

In Figure 4.9 alloys from the series 5000 and 6000 were plotted. It was possible to isolate the data in a very tight range for the speed and for the thickness and all the welds were achieved using the diameter for the tool shoulder. The actual values are available in Table 4.5.

However, it can be said that the fatigue life of the two aluminium alloys are quite similar even though they belong to different series and their mechanical properties are achieved thanks to different phenomena.

Thus, as it happens in case of a static strength comparison, the aluminium 7000 results in having better mechanical properties since it seems to be capable of bearing longer cyclic loadings.

Figure 4.8: Comparison between alloys 6000 and 7000

Table 4.4: Parameters referred to the elements in the legend of Figure 4.8. For the headers: Al, aluminium alloy; t, thickness; d_s, shoulder diameter; ν , travelling speed; ω , revolution speed; ν/ω , revolutionary pitch.

Label	Al	t [mm]	d _s [mm]	ν [$\frac{\text{mm}}{\text{min}}$]	ω [rpm]	ν/ω [$\frac{\text{mm}}{\text{rev}}$]
[Cir+06] 0.14	6082	3.0	nan	100.0	715.0	0.14
[Cir+06] 0.2	6082	3.0	nan	143.0	715.0	0.2
[Cir+06] 0.29	6082	3.0	nan	143.0	490.0	0.29
[Cir+06] 0.3	6082	3.0	nan	215.0	715.0	0.3
[He+15]	7075	8.0	25.0	150.0	300.0	0.5
[Den+17]	7050	3.0	nan	120.0	800.0	0.15

Figure 4.9: Comparison between alloys 5000 and 6000

Table 4.5: Parameters referred to the elements in the legend of Figure 4.9. For the headers: Al, aluminium alloy; t, thickness; d_s , shoulder diameter; ν , travelling speed; ω , revolution speed; ν/ω , revolutionary pitch.

Label	Al	t [mm]	d_s [mm]	ν [$\frac{\text{mm}}{\text{min}}$]	ω [rpm]	ν/ω [$\frac{\text{mm}}{\text{rev}}$]
[Eri05] Sh15ConvexPin	6082	4.0	15.0	300.0	1500.0	0.2
[Eri05] Sh15ConcavePin	6082	4.0	15.0	300.0	1500.0	0.2
[Ner03] OverlapWelded	5754	3.0	15.0	548.0	1542.0	0.36

4.4.4 AA 6082 T6

Figure 4.10: Cloud of data of joints made only of aluminium AA6082 T6

Table 4.6: Parameters referred to the elements in the legend of Figure 4.10. For the headers: Al, aluminium alloy; t, thickness; d_s, shoulder diameter; ν, travelling speed; ω, revolution speed; ν/ω, revolutionary pitch.

Label	Al	t [mm]	d _s [mm]	ν [$\frac{\text{mm}}{\text{min}}$]	ω [rpm]	ν/ω [$\frac{\text{mm}}{\text{rev}}$]
[Cir+06] 0.1	6082	3.0	nan	143.0	1500.0	0.1
[Cir+06] 0.14	6082	3.0	nan	100.0	715.0	0.14
[Cir+06] 0.2	6082	3.0	nan	143.0	715.0	0.2
[Cir+06] 0.29	6082	3.0	nan	143.0	490.0	0.29
[Cir+06] 0.3	6082	3.0	nan	215.0	715.0	0.3
[Cos+12]	6082	4.0	16.0	300.0	1500.0	0.2
[Eri05] T6buttWelded	6082	5.8	nan	350.0	1000.0	0.35
[Eri03] 0.32	6082	4.0	14.0	700.0	2200.0	0.32
[Eri03] 0.56	6082	4.0	14.0	1400.0	2500.0	0.56
[Gio+09] flatShoulder	6082	1.5	6.0	450.0	1810.0	0.25
[Gio+09] scrollShoulder	6082	1.5	6.0	450.0	1810.0	0.25
[Gio+09] shallowShoulder	6082	1.5	6.0	450.0	1810.0	0.25
[MFC07] 6082	6082	3.0	15.0	800.0	1500.0	0.53
[Sci+08]	6082	0.8	6.0	720.0	2085.0	0.35

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In this section the point were filtered by rallying together as more papers as possible that addressed the aluminium alloy 6082 in the temper T6. No limits were imposed neither on the specimen thickness nor on the welding parameters. The result is shown in Figure 4.10. As done before, in Table 4.6 the information about the experiment condition are given. For the sake of clarity, “nan” is reported in the table instead of a number in case of a lack of information in the correspondent paper.

The cloud of point plotted is very scattered and no clear trend can be highlighted. A S-N curve is plotted in the background it was evaluated with the maximum likelihood method. Precaution where taken in distinguishing data point from different sets so that firstly an inverse slope was evaluated for each set, then a mean of the results was calculated and finally it was used to derive the S-N curve for the cloud. Although the speed parameters and their ratio are believed to influence the joint strength, it is not possible to observe in this graph a clear trend for their influence.

The only conclusion that can be achieved is that many parameters are affecting in a remarkable way the fatigue life of friction stir welds. Since all the collected experimental data belong to test campaign that used too wide ranges of all the parameters that affects the fatigue life, it is not easy to isolate single trends at this stage. Therefore, further experiments should be carried out focusing on the influence of the tool geometry as well as on the rotating and travelling speeds. Possibly, this should be done while taking care of producing sets of data that could match with experiments of other authors already available in order to increase the accuracy of the survey while taking advantage of a bigger data pool.

Chapter 5

Finite Element Analysis

Finite elements analysis was carried out, some test series were isolated from the database resulting from the literature research in Chapter 4. Thus, four kind of geometries were designed: two for the FSW overlap welded joints, one for the LBW overlap welded joints and one for the LBW butt welded joints. Based on the finite elements analysis results, it was possible to address the local stress gradient in the notch ligament under the hypothesis of material linear elastic behaviour. The aim of the analysis was whether to derive the notch factor for each specimen to perform the notch stress assessment (Section 2.2.2) or to obtain the effective stress as described in Section 2.1.1. Abaqus® 6.14 and its scripting feature with Python were used to derive the data concerning the stress in the specimens. Thus, the stress gradient in the notch proximity was addressed by creating paths perpendicular to the defect edge and collecting all the stress values in a database. Finally, the extrapolated data were opened in Spyder where the maximum notch stress and averaged stress were sought.

5.1 Test series

Some test series were isolated by picking all the papers which were providing the cross section of the specimens tested in addition to their experimental results. Thus, the selected papers are listed in Table 5.1. [Bal+18; Kra14; Son+97] had more than one set of data so a model was designed for each set.

5.2 Material

The notch stress and the effective stress approaches are only elastic assessments. Thus, in accordance with the theory of elasticity a generalized Hooke's law, equation 5.1, is used to define the connection between stress σ and strain ε of a solid body.

Due to its nature of linear approximation, no plastic strain is admitted at any level of stress therefore as material elastic limit is exceeded, remarkable difference in predicted and real behaviour of the material are noticed.

$$\sigma = E \cdot \varepsilon \quad (5.1)$$

This approximation simplifies both the analysis and the material parameter setting. Thus, the material Young's modulus E and the Poisson's ratio ν are

Table 5.1: Selected test series for which FEM models were designed.

Ref	“Allegro”	“Allegro”	[Bal+18]	[Inf+16]
Aluminium	AA 7075	AA 7075	AA 7075	AA 6082
Temper	T6	T6	T6	T6
Technique	FSW	LBW	FSW	FSW
Joint type	Overlap	Overlap	Overlap	Overlap
No of set	1	1	4	1
Ref	[Kra14]	[Son+97]	[Son+97]	
Aluminium	AA 6082	EN AW-6005A	EN AW-6005A	
Temper	T6	-	-	
Technique	FSW	LBW	LBW	
Joint type	Overlap	Butt	Overlap	
No of set	2	5	2	

Table 5.2: Parameters necessary to characterize the linear elastic behaviour.

Aluminium Alloy	Young’s Modulus, E [GPa]	Poisson’s ratio, ν
EN-AW 6005	70	0.33
EN-AW 6082	70	0.33
EN-AW 7075	72	0.33

sufficient to carry out the simulation. In Table 5.2 the above mentioned parameter are given for all the aluminium alloys encountered in Table 5.1.

5.3 Geometry

Figure 5.1: Model overview snap (a) and model cross section samples (b),(c),(d),(e)

The notch tips and the other weld toes and roots were rounded with a reference radius. Since the thickness of the sheets was $t=1.5$ mm, a radius $r_{\text{ref}} = 0.05$ mm was chosen according to the notch stress approach (see 2.2.2) for assessment in thin walled specimen.

Figure 5.1a gives an overview of the model, in this case is an overview of the two dimensional model for the friction stir welded specimen. All the specimens had a similar geometry except for the weld zone which was developed in four different configuration depending on the type of welding and the type of joint. Thus, as is shown in Figure 5.1, two sections were designed for the friction stir overlap welded joints Figure 5.1b and Figure 5.1c, one section for the laser beam overlap welded joints Figure 5.1d and one for the laser beam butt welded joints Figure 5.1e. Sketches that define how each model geometry was designed are available in Appendix B.

Figure 5.2: Cross section pictures for the FSW overlap welded joints taken from [Kra14] and from the "Allegro" project specimen

Something interesting was found out for the FSW overlapped joints. The cross section pictures available in literature, e.g. Figure 5.2a, had always reported a symmetric behaviour for the notches, which exhibited a tendency to reduce the effective sheet thickness on the loaded side of the upper sheet by assuming a so called "hook" conformation. Though, the notches in the "Allegro" specimen section, shown in Figure 5.2b, used to have an antisymmetric disposition resulting in being turned in opposite directions thus without affecting the effective sheet thickness. All the cross section pictures used to develop FE models are shown in Figure B.3 in Appendix B.

It is not clear how the different behaviours of the notches could be explain. One thing that seems reasonable to assert is that the employed pin could have partially affected the phenomena. While at the Fraunhofer Institute the weld was achieved using a conical threaded pin, other experiments claimed to have used specifically designed tool for overlap joints, e.g. in [Kra14] the Triflute^{TM} pin. However, it could be stated that due to a lack of many samples, this fact should be addressed by producing and then testing more FSW specimens using different tools.

Figure 5.3: Comparison between actual cross section and the cross section generated in Abaqus®

Geometries were designed based on the cross section pictures available. All the necessary measures were derived from CorelDraw®, as explained in Section 3.3.

An example is shown in Figure 3.6b at 22. Then, the correspondence between geometry and the real cross section was validated by overlaying the the 2D section form the FE model and the correspondent cross section picture, an example of the result picture is shown in Figure 5.3.

Table 5.3: Values of the misalignment observed in the specimens

Max	Min	Average
0.01°	2.20°	0.89°

In Table 5.3 are shown maximum, minimum and average misalignment angles, deriving from the laser measurement described in Section 3.3. It was decided not to take their effect into account since the biggest angle between the jointed sheets was smaller than three degrees, the error committed by neglecting the misalignment in the finite element analysis was not expected to be remarkable. Although this was hold to be true at least for a first approach analysis, further researches should consider the idea of evaluating how much indeed the misalignment affects the results. In Appendix A is available Table A.1 in which is given a complete overview of all the misalignment angles detected in each of the three measures taken each specimen.

5.4 Mesh and element type

Parameters:

- Reference radius r
- j elements over 360°
- i elements over t^*
- Factor $f_{r,i} = r_{i+1} / r_i$
- Factor $f_{u,j} = u_{j+1} / u_j$
- Aspect ratio $V = u_1 / r_1$
- Factor $Z = f_{r,i} / f_{u,i}$
- Aspect ratio $X = h / u_1$

Table 5.4: Parameters initially set for the mesh.

Mesh setting	
j	32
V	1
fr	1.3

Figure 5.4: Mesh parameters [BW15]

By the fact that local stress in vicinity of notches tips for FSW joints as well as in vicinity of weld toes and root in LBW joint were addressed, the recommendation in [BB12] were followed. Aspect ratio V , number of elements over 360° j and the increasing factor were initially chosen according to the advices in the paper. The previously mentioned parameters are shown in Figure 5.4 and the settings initially used to create the model are given in Table 5.4.

Also recommendations concerning the element types were given in the paper, therefore the elements CPE8 and CPE6 were chosen for the mesh. The former is a quadrilateral element which has eight nodes and a bi-quadratic integration. The latter is a six nodes triangular element with quadratic integration. Both the types are meant for the plane strain condition. Plane strain allows to carry out

a two dimensional analysis of stresses for three dimensional objects. Therefore, it is equal to apply a constraint of no displacement on the third axis at all the elements belonging to the section.

A global seed value was assigned and the mesh was set to structured with QUAD elements in all the regions adjacent the notches as well as in the free ends of the sheets, where a very coarse mesh with quadratic elements is generally accepted. Figure ?? shows an example of the mesh aspect near the notch. Mesh transition from fine to coarse needed to take place in the region that separated the resized areas around the notches, with a very fine mesh, from the zone characterized by a coarser one. Therefore, in that surface meshing control was set on free with quadrilateral elements and a specific edges seeding with bias was performed within the region.

5.5 Load and Constraints

Before introducing load and constraints, it worth it specifying that a partition was created for each sheet in order to delimit an area each side that represented the clamping zone where actions between clamping device and specimen are exchanged. This resulted in the model having a free length of 150mm in which strain was allowed to take place all over the plane on which the section lay.

Figure 5.5 gives an overview of the model and the applied load and constraints. On the load side, all the nodes belonging to the free horizontal edges (in purple) of the clamping zone on the right were bounded to a reference point by using the command “kinematic coupling”. Thus, the nodes were forced to behave as the reference point since all the degree of freedom were linked to it. The reference point had only one degree of freedom, it could only move along the X-direction same direction along which the load was applied. Since the model was bi dimensional a nominal stress for the section was defined but to be applied it had to be multiplied by the thickness. The software itself took care about distributing the load to the linked nodes.

Figure 5.5: Model section showing an overview of load, coupling and constraints.

The clamping zone at the other end of the specimen needed to be set as fixed therefore the “encastre” constraint was applied to the correspondent nodes of the lower and upper horizontal edges (in red) so that they had no degrees of freedom remaining.

As already mentioned in Section 5.4, by selecting the element types associated with the condition of plain strain a constraint of no displacement along the third axis was implicitly imposed to the entire two dimensional section.

5.6 Script

All the model that had to be designed were very similar so the Abaqus® scripting feature using python was suiting a case like this when repetitive tasks need to be executed.

Indeed, to carry out the finite elements analysis of the papers in Table 5.1 was used a model for each of them. Thus, five base models were developed and for each a correspondent script was available. Two models were designed for the FSW overlap joints since as explained in Section 5.3 two different configurations for the notch were observed. Then, one model for the LBW overlap joint and two for the LBW butt joint. Also the butt welded joints needed two model because some of them did not exhibit the typical weld reinforcement but rather a thickness reduction where the metal was melted.

The problem in developing a FSW butt joint was linked to the fact that either the defects deriving from the welding process were particularly small or often the specimens used in the papers had the upper and lower surfaces milled so that they resulted defect free, e.g. [Uem+09]. Thus, this kind of models were not leading to any stress gradients thus only to a nominal stress and they could not be taken into account in the local stress approaches.

In term of equations, scripted geometry of the section was always fixed but all the defined relations were governed by some parameters. Thus, for each section some measures were required. In Appendix B are attached some sketches with the geometry of the models and instead of numerical quotas, the name of the main parameters are given. E.g. some parameters were the radius of the rounded roots and toes, thickness and length of the sheets, in case of an overlap weld the length of the overlapped section and so on. In Table B.1. As the parameters were setted up the model was ready to be submitted in Abaqus®.

The script was made up of a main part in which the parameters had to be defined and five more sections each one representing a task to accomplish. Indeed, each section was a Python definition, due to how this programming language works they had to be defined before the parameters were assigned and then called to operate with them. At the end of the script the definition were called in the desired order so that a model ready to be submitted for the simulation was created as the script was run by the sotware. Example of the script are given. Respectively an example of a definition (Listing 5.1), the begin of the main part wehre some parameters are defined (Listing 5.2) and the last lines of the script in which the definition are called (Listing 5.3).

Listing 5.1: Example of a definition, Macro1 in this case

```

38 def Macro1():
39     import section
40     import regionToolset
41     import displayGroupMdbToolset as dgm
42     import part
43     import material
44     import assembly
45     import step
46     import interaction
47     import load
48     import mesh
49     import optimization

```

```

50     import job
51     import sketch
52     import visualization
53     import xyPlot
54     import displayGroupOdbToolset as dgo
55     import connectorBehavior
56     #SKETCH##
57     s1 = mdb.models['Model-1'].ConstrainedSketch(name=
58         '__profile__', sheetSize=250.0)
59     g, v, d, c = s1.geometry, s1.vertices, s1.dimensions,
60         s1.constraints
61     s1.setPrimaryObject(option=STANDALONE)
62     s1.Line(point1=(p1), point2=(p2))
63     s1.Line(point1=(p2), point2=(p3))
64     ...
65     ...
66     ...

```

Listing 5.2: Script section in which the parameters are defined

---

```

605 #PARAMETERS
606 #rf1 radius fatigue assessment 1-LEFT , 2-RIGHT
607 rf1 = 0.05
608 rf2 = 0.05
609 #roc radius outer circle 1-LEFT , 2-RIGHT
610 roc1 = 0.1
611 roc2 = 0.1
612 #t = sheet thickness: 1-upper, 2-lower
613 t1 = 1.5
614 t2 = 1.5
615 #ol overlap length
616 ol = 29.27
617 #el extra length
618 el = 95.
619 #g gap width 1-left gap, 2-right gap
620 g1 = 0.01
621 g2 = 0.01
622 #gl gap length
623 gl1 = 11.26
624 gl2 = 10.73
625 #alpha angle of the curvature of the gap [rad]
626 alpha1 = 23.64/180.*pi
627 alpha2 = 23./180.*pi
628 ...
629 ...
630 ...

```

Listing 5.3: Script section in which the definition are called

---

```

862 #Macro#####
863 Macro1()      #GEOMETRY
864 Macro2()      #PARTITION
865 Macro3()      #SEEDING

```



```

866 Macro4()      #MESHING
867 Macro5()      #LOAD STEP

```

5.7 Convergence Study

Once the model was ready and it was established that simulation were running with no issues, carrying out a convergence study was necessary to find out which was a proper value for the factor j , i.e., the number of elements over 360° . The local stress in proximity of the two notch tips was addressed since local maximum stress value was expected to occur there. Therefore, aim of the study was to evaluate if, by increasing the number of the element in which the arcs at the rounded end of the notch were divided, the received maximum stress was converging to a value or not.

As a consequence of a finer mesh in the notch tips proximity, an increment in the overall number of elements generated within the model occurs entailing longer times of computation when the model was submitted for the analysis. Thus, was stated that 100 elements around the notch circumference was a proper amount of elements leading to a sufficient accuracy in the analysis. Figure 5.6 shows the maximum stress values evaluated both with Von Mises and Max principal plotted over the number of elements in abscissa. Moreover, the two pictures below the lines in the plot give an idea of how the increasing of the parameter j affects the mesh density in the notch proximity.

Last step of this evaluation was to create a bottom up meshed three dimensional model in Abaqus® so that a final comparison of the maximum stresses calculated with both three and bi dimensional models was possible. Since an optimal number of elements was already fixed, the 3D model was built only for the case $j = 100$ in order to evaluate the difference between the obtained results. Also the stresses for this model were derived with both Von Mises and Max principal criterion and they were plotted in the same Figure 5.6 as two dots.

$$\%err = \left| \frac{\sigma_i - \sigma_{i-1}}{\sigma_i} \right| \quad (5.2)$$

The absolute value of the percentage relative error committed at the increment i -th is described in the equation 5.2. The relative error is calculated as a ratio that results by dividing the difference of the i -th resulting maximum stress value and the $i-1$ -th maximum stress by the i -th maximum stress. The same error is evaluated in case a 2D instead of a 3D model is used for the same number of elements $i = 100$. In Table 5.5 the results of the calculation are shown. The evaluation was carried out for both Von Mises and Max Principal criterion.

Figure 5.6: In the plot are shown the maximum stress values for both Von Mises and Max principle extract from Abaqus® simulation

Table 5.5: Percentage relative error in mesh convergence study

Nr. of Elements	Percentage relative error	
	Von Mises stress %	Max Principal stress %
32	--	--
50	0.81	0.095
75	0.77	0.30
100	0.13	0.16
125	0.082	0.10
150	0.052	0.020
160	0.043	0.053
170	0.012	0.015
180	0.016	0.015
2D/3D	4.17	3.46

5.8 Parametric Study

Figure 5.7: Local maximum in case of increment of the curvature of the notch path in the section. Results for symmetric model

When collecting information in the available literature on the friction stir weld also process parameters were addressed. As explained in Section 4.4, it was found out that different conditions in the joining process were affecting by some manner the geometry features of the section. It was not clear how, and if, this was affecting the local maximum stress and, as a consequence, the predicted fatigue life.

Attention was paid exclusively on the overlap joints because the application turn out to be the weaker among the two types addressed. It was not possible to clearly highlight any direct or indirect connection between geometrical feature and some parameter defining the weld process.

It was observed though that all the crack like defects were not straight but they were curved and the possible configuration were two, one symmetric and the other asymmetric. Also the horizontal distance tip to tip of the notches was measured in all the available cross section pictures but it seemed to be closely related to the tool pin diameter. Nonetheless, the angle between the horizontal direction and the end of the notch curvature was varying with non deducible trend.

This notch deviation seems to be typical of the joint type and it is believed to be produced by non melted superficial oxides situated on the overlapped surfaces. In [Xu+12] was observed that the hook defect in overlap welded is not easy to avoid and causes a reduction of the effective sheet thickness (EST) which seriously affects the fatigue life of the specimen.

This said, it was decided to carry out an investigation in Abaqus® developing a systematic analysis of how the worsen in terms of height in the thickness

Figure 5.8: Local maximum in case of increment of the curvature of the notch path in the section. Results for asymmetric model

was affecting the local maximum stress. By comparing what came up from the literature research, it was observed that reduction of the effective sheet thickness (EST) due to the arise of the hook defect was not bigger than 20% of total thickness. Thus, in whether symmetric or asymmetric model it was imposed to the angles of the notches deviation to be equal in modulus on both sides. Then, to the angle increment was associated an increment in the height of defect through the sheet thickness. The horizontal distance between the tip was kept fixed and then simulation with different angles and heights were submitted.

In Figure 5.7 and in Figure 5.8 the results of the simulation are plotted separately respectively for the symmetric and asymmetric models. The angle was increased with step of 5° in a range $[0^\circ; 25^\circ]$, the linked height were included in the range $[0\%, 20\%]$ of the thickness with an increment of 5% of the thickness each step.

From the graphs it can be observed that the asymmetric geometry is the one entailing smaller local stress. This should results in longer fatigue life when compared with the other geometry. This configuration that was observed in the actual specimens available it has no other feedback in literature. The smaller maximum stresses achieved can be explained with a smoother stress flow between the specimen ends. This should happen in this case, and in contrast to the symmetric model, because the flow does not need to circumvent the notch that at the same time does not hinder it even when getting bigger.

5.9 Path evaluation

The effective stress approach, in case of $r_{ref} = 0.5$, requires to averaging the stress in the notch ligament. This stage was accomplished in two stages.

Figure 5.9: Contour plot showing the path with 65° inclination and its stress gradient plotted on the side.

Figure 5.10: Figure showing the 0° location and how the path are created over the notch edge.

The first one was to implement a second script that could fit the correspondent model geometry. When Abaqus® ran the script, the “*.odb” file containing all the results of the simulations was open. Then, the software was guided into creating linear paths starting from the notch edge and perpendicular to that. Figure 5.9 shows an example of a path drawn for an angle of 65°. All the paths were 1 mm long and were created through a loop that was increasing at every step the angle. As shown in Figure 5.10 the zero was set on the horizontal line and the angle was increased in counter clockwise direction. Every time a path was drawn, a local system of coordinate was generated and both max principal and Von Mises stress values were evaluated in 100 equally spaced point along the line. Finally, the data were stored in database to be transferred to Spyder.

Now a discrete stress gradient in the notch ligament was available for the averaging step so the second stage could be addressed. The created database was opened in Spyder using a third script. Just a few steps were necessary.

Initially the maximum stresses were derived both using the Von Mises and Max Principal criteria and the paths in which each of them was occurring were located. The angle, that had been previously included in the path name, was helping to define its position in the model.

Then, for both hypothesis again average stresses were calculated using either the microstructural distance or the critical distance as described in section 2.2.3.

CHAPTER 5. FINITE ELEMENT ANALYSIS

In this manner, more than a unique averaged stress were available since usually the maximum averaged stress was occurring on a path different from the ones in which the maximum local stresses were placed. In this case, the actual state of the art does not clearly defined which should be the value to take into account for the assessment. Thus, to proceed in a conservative manner it was decided to consider the maximum effective stress achieved even if it was not occurring on the same path on which the maximum notch stress was located.

Chapter 6

Fatigue assessment

In this chapter the assessments are carried out using only elastic approaches, i.e., nominal, notch and effective stress approaches. No actual recommendations are available on which between Von Mises and Max Principal criteria must be used in the assessment. Thus, in local and effective methods the Von Mises yield criterion is used to address the stress gradients deriving from finite elements analysis. The reason that suggested to proceed in this manner is the fact that the addressed designed S-N curves from [Stö+11] for the local approaches were derived using the same criterion. A recommended designed S-N curve with a survival probability of $P_\sigma = 97.7\%$ for each method was considered. From time to time, in the following sections inverse slope k and FAT classes will be specified and compared to the chosen data sets. However, the designed S-N curves that are evaluated share a common location for the knee point set at $N_k = 1 \times 10^7$ cycles.

6.1 Test series for finite element analysis

Table 6.1: Test series used for the assessment.

Ref	“Allegro”	“Allegro”	[Bal+18]	[Inf+16]
Aluminium	AA 7075	AA 7075	AA 7075	AA 6082
Temper	T6	T6	T6	T6
Technique	FSW	LBW	FSW	FSW
Joint type	Overlap	Overlap	Overlap	Overlap
No of series	1	1	4	1
Ref	[Kra14]	[Son+97]	[Son+97]	
Aluminium	AA 6082	EN AW-6005A	EN AW-6005A	
Temper	T6	-	-	
Technique	FSW	LBW	LBW	
Joint type	Overlap	Butt	Overlap	
No of series	2	5	2	

From the data pool which is described in Chapter 4 some test series were chosen, they are given in Table 6.1. Only the sets that were accompanied by a cross section picture of the specimen were isolated. They were necessary to carry out a finite elements analysis each as a step of the assessment. Later, the data

were filtered based on welding technique, type of joints and material. Aluminium alloys belonging to the series 5000, 6000 and 7000, joints type analysed are butt welds and overlap welds either welded using LBW or FSW techniques. Finally, 7 test series were isolated, each of them is identified with its reference in the bibliography except the “Allegro” series whose experimental data are available in section 3.4 of the present work.

6.2 Nominal stress approach

Figure 6.1: Nominal stress assessment butt welded joints.

For the nominal stress assessment it was necessary to split the sets into two groups on the base of the joint type. A FAT class for each group was derived from the IIW recommendations [HOB09].

In the guidelines the element 216 suggests a FAT class 28 MPa. That value is meant for butt welded joints with a full penetration weld seam and misalignment smaller than ten percent of plate thickness, moreover the root must be checked by non destructive tests (NDT) and even a visual inspection is admitted, [HOB09].

No structural detail that suited the available overlap welds was found. Therefore, structural details with root crack initiation were addressed and, among them, the FAT class 12 MPa recommended in the element 614 was chosen to be compared with the endurable nominal stresses applied on the overlap welds.

Inverse slope is fixed to $k = 5$ and a second value $k^* = 22$ intended for the curve

Figure 6.2: Nominal stress assessment overlap welded joints.

in the fatigue range bigger than 1×10^7 cycles.

The FAT class chosen for the butt welded joints resulted very conservative. Figure 6.1 shows the plot containing both the S-N curve and the correspondent data sets. The welds addressed show high fatigue strength that is closer to the values recommended for higher quality structural details in [HOB09], e.g., 211, 212.

The overlap welded joints resulted to be slightly critical instead, as shown in Figure 6.2. Some of the results from [Bal+18] and [Kra14] lay on the curve or below that. This cannot be considered an acceptable results in light of the fact that the curve is meant for a survival probability $P_\sigma = 97.7\%$.

Although the nominal approach does not address microscopical aspect of the joint, this result could not be explained without considering the typical cross sections geometry of the overlap weld. This structure typically presents two crack-like notch at the interface between the sheets. Moreover, in the FSW case this notches show a trend to entail an effective sheet thickness reduction which contributes in reducing the fatigue strength.

Therefore, based on this non conservative result together with the nominal method procedure which does not take into account the internal defects defining a lower FAT class for the overlap joints seems to be necessary.

6.3 Notch stress approach

Figure 6.3: Notch stress assessment.

In [Stö+11] laser beam welded aluminium joints were addressed and recommendations given. Since the characteristics of the considered data pool were similar with the one considered in this work it was decided to assess the design S-N curve suggested there. In case of a notch stress approach a FAT class of 160 MPa is proposed together with an inverse slope $k = 5$. The suggested curve is meant for a survival probability $P_\sigma = 97.7\%$.

In this approach the nominal stress were enhanced using the K_t derived trough the numerical simulations. The achieved results stated that $K_{t, FSWoverlap sym} < K_{t, LBWoverlap} < K_{t, FSWoverlap asym} < K_{t, LBWbutt}$, therefore the welds that showed a higher nominal fatigue strength resulted to have a lower K_t so they were closer to the designed S-N curve in this approach.

In Figure 6.3 the local stresses and the S-N curve are plotted in the Wöhler's diagram. The proposed FAT class could have resulted conservative if it was not for the butt welded joints. Thus it can be asserted that a FAT class 160 resulted conservative in this case for overlap welded whether friction stir or laser beam welded.

This approach may not be the best one in case of butt welded joints since it was not observed for sound welds to have severe defects that could lead to very remarkable value of the K_t . Their K_t is very close to the limit $K_t > 1.6$ suggested in [Bau17]. Nonetheless, their notches are defined as mild notches and

the influence they exert on the stress can sometimes result as not particularly significant.

6.4 Effective stress approach

In [Stö+11] was also found a design S-N curve evaluated for the effective stress approach. Moreover, a microstructural length $\rho^* = 0.125$ mm that was minimizing the scatter of its considered data pool. This value was used also in combination with the formulation that connect microstructural and critical length $\rho^* = a \cdot 4$, originally proposed in [TH09], resulting in $a = 0.031$ mm. As a first approximation it was assumed for these lengths to suit the actual data pool. In the following section, a proper microstructural length as well as a proper critical length will be evaluated to suit the considered data.

The FAT class derived in the paper was 80 MPa and the inverse slope used in this case was $k = 5.5$. This designed S-N curve was assessed with both of the two following procedures.

6.4.1 Effective stress using microstructural length

Figure 6.4: Effective stress assessment. $\rho^* = 0.125$ mm

As explained in section 2.2.3, given a fixed ρ^* , the stress in the notch ligament is averaged in a direction perpendicular to the notch edge. For the sake of completeness, the stress gradients in the notch proximity is available only as a

discrete set of stress values along paths orthogonal to the notch tip. The paths are evaluated for each FEM model and then used to average the stress.

Thus, stress gradient on every path was addressed in Spyder using the class “InterpolatedUnivariateSpline” from the subpackage “scipy.interpolate” and its method “integral(a,b)” that return definite integral of the spline between two given points. The extremes of integration were set to 0 and ρ^* and the stress was averaged over ρ^* , equation 2.6 at page 17 was used. In the end, for each model was taken into account the path on which the maximum averaged stress was laying that was often observed to be different from the one with the maximum local stress for the model. This was considered the most conservative manner to proceed.

In Figure 6.4 the sets are plotted over the S-N curve previously described. The suggested curve resulted not to be conservative with the considered set of data since the LBW welds from the “Allegro” project and LBW butt welded joints from [Son+97] lay beneath the curve or are overlaying it. Thus, using a FAT class lower than the FAT 80 that was used should be considered.

The microstructural length used is not derived for the actual data pool, this will be evaluated in the following section 6.5.

6.4.2 Effective stress using critical length

Figure 6.5: Effective stress assessment. $a = 0.031$ mm

In this approach the averaged stress is derived as the stress along a path at

a given distance a from its origin, see equation 2.7 at page 17. Here too, the stress evolution along the path is interpolated using the same class “Interpolated-UnivariateSpline” as explained in the previous section. This time, instead of averaging the integral on the given length, the derived function is simply evaluated at $x = a$ and the obtained stress is considered as a constant value on the entire path length, $\sigma_{eff} = \sigma(a)$.

When averaging the stress with this method the stresses achieved resulted a bit higher but they entailed no significant change in what was observed above. In Figure 6.5 the actual plot for the data sets is given. The designed S-N curve is still not conservative, a considerable amount of LBW butt weld data are laying below the curve as well as some of the point from the “Allegro” project are overlaying it. Thus, in this case also a lower FAT class should be used to carry out conservative assessment.

6.5 Evaluation of a microstructural length

At this stage, it was appropriate for a microstructural length proper of our data to be evaluated. When doing so it must be taken into account that no clear recommendations exist that define a unique way to proceed. Moreover, it came out for many model that the path on which the maximum stress occurred was different from the one on which the maximum local stress was located. To overcome this it was supposed that no matter on which path it was located but using the maximum effective stress for each model should have been a conservative approach.

Thus, a script was used to loop the value of the microstructural length. At each step the maximum effective stress was derived for all the models, then the data pool was rallied enhancing the experimental nominal stresses and later a S-N curve was evaluated at each step of the ρ^* value and the scatter stored. Finally, the gathered scatters were plotted over the microstructural length and the one resulting with the minimum scatter was chosen as the proper length for our data.

The result is given in Figure 6.6, the bigger graph at the top plots the data pool for the ρ^* derived. The other two show the trend of respectively the inverse of the scatter in the cycles direction $1/T_N$ and the inverse of the scatter in the load direction $1/T_S$ plotted over the microstructural length.

Initially this evaluation was carried out using a fixed location at 1×10^7 cycles for the knee points. This was done to have a results that was comparable with the others and in accordance with the definition of the designed S-N curves. For the sake of completeness, in Figure D.2 in Appendix D could be found instead the result for the same evaluation with no fixed knee point. It can be observed that the scatter and the inverse slope derived are not remarkably smaller than the one achieved here and that the knee point is not far from the location where was fixed above.

Therefore, this validate the approximation used when assessing the data pool isolated because the errors in the results are not significant, at least as a first approximation.

6.6 Evaluation of a critical length

Using the new derived microstructural length and the its link to the critical length proposed in [TH09] even the new a can be considered pretty defined.

Figure 6.6: Plot with the minimized scatter in load direction based on the ρ^* parameter. Fixed $\rho^* = 0.280 \text{ mm}$. The lower two plots show the trend of the scatter in cycles direction (left) and load direction (right) over the ρ^* .

To state if the link between the two length could be applied also to the actual data, it was decided to carry out the same investigation done for the ρ^* , this time varying the a . It was used the same script as well as the same procedure but at every step of the loop a new critical length was tested. Finally, the length entailing the minimum scatter was chosen.

The value resulting was $a = 0.073 \text{ mm}$ that confirmed the above mentioned connection between the two length. The scatter achieved is slightly bigger than the one achieved in the previous procedure. In Appendix D the plot achieved from the critical length looping could be found in Figure D.1.

6.7 effective stress approach using actual ρ^* and a

Using the actual microstructural length and critical length the effective stress was carried out again. The two value that were circa two times the older ones led to

Figure 6.7: Effective stress assessment. $\rho^* = 0.280$ mm.

less scattered data pool with as drawback averaged values for the stresses that were lower than the ones evaluated previously. Thus, the designed S-N curve resulted even less conservative. In Figure 6.7 and Figure 6.8 the new plot are given.

Reason for this behaviour is that the further the stress is addressed from the notch edge the smaller is the influence exerted from the defect on the stress gradient.

Figure 6.8: Effective stress assessment. $a = 0.073$ mm.

6.8 Results comparison

Figure 6.9: Comparison of the assessments carried out using the three different approaches.

In this section a comparison between the results achieved in the previously described assessments is made.

Figure 6.10: Comparison of the effective stress assessments carried out using different ρ^* .

Figure 6.9 plots side by side nominal assessments together with the notch stress and effective stress ones. It can be observed for the scatter to be decreasing moving from the nominal stress plot to effective stress one. Butt welded joints, that have a mild notch, resulted very far from the nominal stress of the overlap welded joints. As the microscopical influence of the defects was taken into account they got closer to the rest of the data and in the local assessment placed themselves at the bottom of the data pool. To sum up, the effective stress approach seemed to give a better assessment among the three method used.

Figure 6.10 shows side by side the two plots achieved using the microstructural length found in [Stö+11] and the one evaluated in section 6.5. In both cases it was used the FAT class 80 from [Stö+11] even if that was meant only for $\rho^* = 0.125$ mm. The bigger microstructural length entailed a smaller scatter but a little lower fatigue strength. However, in both cases its observed the need for a lower FAT class that can shift to lower stress values the designed S-N curve in this assessment approach.

6.9 FAT classes

After having made a comparison between recommended design S-N curves and the data from the test series, some FAT values that could lead to conservative assessments based on the actual data are shown in Figure 6.11.

For each approach the S-N curve for the data collected is derived using a script which used the maximum likelihood criterion. To achieve values following the definition of FAT class, all the data were initially transformed to a stress ratio $R = 0.5$ following the IIW recommendations [HOB09]. Then, the inverse slope was fixed to $k = 5$ as it is recommended for the design S-N curve and the knee point is fixed at 1×10^7 cycles. Then, the curve which assure a survival

CHAPTER 6. FATIGUE ASSESSMENT

Figure 6.11: Proposed FAT classes

probability $P_\sigma = 97.7\%$ is evaluated and its endurable stress at 2×10^6 cycles derived.

In order to suggest reasonable FAT classes, the endurable stresses calculated were rounded to the nearest lower integer and then compared with the already

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existing FAT value in [HOB09]. Finally, the FAT nearest to each of the evaluated stresses was chosen.

In Table 6.2 the FAT classes previously used for the assessments are listed together with the new endurable stresses that should lead to a conservative assessment with the considered data.

In only two cases the proposed FAT class is higher than the one recommended: the nominal approach for butt welded joints, shown in Figure 6.11a, and the notch stress approach only for the FSW overlap welded joints, shown in Figure 6.11c. Respectively the new endurable stresses are 40 MPa and 220 MPa.

In Figure 6.11b, the FAT proposed is FAT 8. Actually, this value is very low and it should be pointed out that there are no recommended elements in the IIW recommendations [HOB09] which suggest endurable stresses lower than 12 MPa. As it has already been said, the overlap welding is a very critical application due to the inevitable developing of the crack-like notches at the sheets interface. This defect weakens significantly the static strength as well as the fatigue strength of these welds.

Table 6.2: FAT classes achieved to

Assessment approach	Welding technique FSW/LBW	Type of joint	FAT class	
			recom- mended [MPa]	proposed [MPa]
Nominal stress	LBW	Butt	28	40
Nominal stress	FSW & LBW	Overlap	12	8
Notch stress	FSW & LBW	Both	160	80
Notch stress	FSW	Overlap	160	220
Effective stress $\rho^* = 0.125 \text{ mm}$	FSW & LBW	Both	80	40
Effective stress $\rho^* = 0.280 \text{ mm}$	FSW & LBW	Both	80	36

Chapter 7

Summary and outlook

In the present work LBW and FSW specimens were tested to familiarise with the two welding techniques and learn more about their strengths and weaknesses. Based on the experimental results achieved at the Fraunhofer LBF, friction stir welding emerged as valuable competitor for the Laser beam in joining hardly weldable aluminium alloys such as the AA 7075.

First steps are moved towards a fuller comprehension of the factors which influence the attainment of sound friction stir welds. From the investigation carried out in Chapter 4 was observed that tool geometry and size play a significant role when welding because the former exerts an influence on the metal flow around itself and the latter affects the heat generation due to the metal wear. Nonetheless, an influence of the material was observed thus to stronger material in static loading correspond higher fatigue strength.

The experimental results from the FSW and LBW overlap welded joints tested at the Fraunhofer LBF were presented. Friction stir welded joints showed an overall higher fatigue strength compared to the one of the laser beam welded joints. Having carried out a literature research offered also the chance to compare the experimental data from the test carried out at the Fraunhofer LBF with all the other available in the paper. LBW joints tested returned a fatigue strength that was consistent with the results available from [Son+97]. FSW joints had a significantly higher fatigue strength compared to all the collected data for the same type of joints and welding technique. The comparison is shown in Figure 4.5a. Though this result was not completely unexpected, the load cell of the test rig was verified to ward off errors in its calibration.

The specimens available resulted in having an unusual asymmetric disposition of the crack-like roots typical of the overlap joints, different cross sections are shown in Figure B.3. The finite elements analysis of this geometry was leading to lower notch factor K_t compared with the ones derived from models based on the other cross sections found in the articles. Thus, this situation was further investigated as explained in Section 5.8 with a parametric investigation. Iterative simulations were carried out in which the curvature of the notches were made steeper at each step. The results suggested that symmetric model had an increasing K_t with steeper curvature of the defect, as shown in Figure 5.7, asymmetric model showed the opposite behaviour with a decreasing K_t , as shown in Figure 5.8.

Finally, the above mentioned experimental results confirmed this prevision returning a fatigue strength that was remarkable higher in comparison with the

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entire overlap welds data pool.

The fatigue assessment, which was also the main purpose of this works, was carried out using the nominal stress approach and two local approaches, i.e., the notch stress approach and the effective stress approach. The results confirmed however the average weakness of the overlap joints when undergoing cyclic loading.

Among the used approaches for the assessment, only the design S-N curve for butt welded joints in the nominal stress approach resulted conservative, Figure 6.1. The nominal method for the overlap welds was critical and two are the weaknesses at the moment: no structural detail was suiting the addressed overlap joints and the defect in this case is very severe therefore needs to be addressed more in detail and not from a macroscopic point of view.

In case of notch stress approach when the entire data pool was addressed the design S-N curve was not conservative but only the data of butt welded joints were overlaying or laying below the curve. If these points were excluded the curve was instead slightly conservative. This is related to the nature of the notch in the butt welded joints since their stress peak was located at the weld toe that is a mild notch. In the overlap welds the crack like notches were instead severe notches entailing very high notch factor. When these data with so different defect nature were addressed together, the scatter was particularly high. Moreover, taking into account the butt welds was leading to a borderline condition.

The effective stress approach resulted as the best among the three considered, though the designed S-N curve was not conservative. This because it was entailing the smaller scatter in the data on the plot. The reason in this result is based on the fact that the stress peaks are averaged, thus mitigated, moving closer the overlap data with the butt welded ones, characterized by a mild notch and a smaller stress peak. This behaviour can be observed in Figure 6.10 where the effective stress method assessments carried out with a $\rho^* = 0.125 \text{ mm}$ (left) and with a $\rho^* = 0.280 \text{ mm}$ (right) are shown side by side. Using a longer microstructural length was not leading to any changing in the averaged stress for the butt welded joints, but was shifting to lower stresses all the other data. The explanation for this is that by getting further from the defect its enhancing effect on the stress decreases in importance and in case of butt welded joints it was already exerting no influence. The effective stress approach was carried out using both microstructural and critical length but the latter was leading always to slightly higher overall stresses. Hence, a conservative manner seemed to base our conclusions on the stresses deriving from the microstructural length formulation.

As discussed in Section 6.9, lower endurable stresses are necessary to derive conservative approaches in case of a nominal stress assessments for the overlap welds as well as for the local assessments in general. In Table 6.2 endurable stresses with $P_\sigma = 97.7\%$ occurring at 2×10^7 cycles are given. The stresses were evaluated, after having transformed all the data to the stress ratio $R = 0.5$, using the maximum likelihood criterion with fixed $k = 5$ and knee point at 1×10^7 cycles. The achieved results suggest that the endurable stress of LBW butt welded joints, evaluated as described above, is higher then the FAT class proposed in [HOB09] for similar structural details since they are meant for arc welds. Furthermore, overlap welded joint resulted as a critical application due to its typical crack like notch defects. Nonetheless, the endurable stress derived in case of nominal stress approach were so low that the resulting 8 MPa had no correspondence with any of the structural detail in [HOB09].

7.1 Outlook

The present work locate itself as a very small part of the freshly born “Allegro” project which is targeting a well rounded exploitation of ultra high strength aluminium alloys potential.

Next steps could be:

- Perform a stress strain based approach for the assessment, e.g., using the P_{SWT} parameter. Thus, taking into account the elastic-plastic material law and making a comparison with the already addressed elastic approaches
- Focus on FSW and LBW butt welded joints to improve the database and get familiar also with this types of welding
- Carry out further tests with FSW aimed to:
  1. Derive a more reliable mean stress sensitivity. Thus, specimens from a same batch should be tested with three different stress ratio in order to evaluate a sole line in the Haigh’s diagram
  2. Investigate more in depth the effects of the welding parameters to achieve some empirical trends describing their influence on the fatigue life, e.g., the effect of the speed, both travelling and rotating speed, should be addressed
- Consider the opportunity of training a neural net to makes prevision on the fatigue life based on welding condition (as drawback it requires a big set of data). The neural net could have as inputs the welding parameters, material joined, the type of joint and the applied load. As output, it could return an estimated fatigue life making a prevision on the number of cycles until failure.

Appendix

Appendix A

Misalignment

Table A.1: Misalignment evaluated in the specimens. Since small values are obtained, was chosen to neglect them.

Specimen	Top	Middle	Bottom
FSW_LJ_1_1	0.37°	0.38°	0.24°
FSW_LJ_1_2	0.01°	0.01°	0.11°
FSW_LJ_1_3	0.77°	0.77°	0.79°
FSW_LJ_1_4	0.07°	0.06°	0.08°
FSW_LJ_1_5	0.93°	0.93°	0.94°
FSW_LJ_2_1	2.20°	2.17°	2.13°
FSW_LJ_2_2	0.72°	0.79°	0.78°
FSW_LJ_2_3	0.56°	0.62°	0.51°
FSW_LJ_2_4	1.63°	1.61°	1.58°
FSW_LJ_2_5	0.53°	0.54°	0.53°
FSW_LJ_2_6	0.40°	0.47°	0.45°
LBW_LJ_AL1_1	1.62°	1.62°	1.64°
LBW_LJ_AL1_2	1.31°	1.38°	1.36°
LBW_LJ_AL2_1	0.66°	0.70°	0.68°
LBW_LJ_AL2_2	0.63°	0.62°	0.46°
LBW_LJ_AL3_1	0.41°	0.45°	0.46°
LBW_LJ_AL3_2	0.69°	0.75°	0.84°
LBW_LJ_AL4_1	0.70°	0.77°	0.75°
LBW_LJ_AL4_2	1.01°	1.01°	1.02°
LBW_LJ_AL5_1	0.34°	0.31°	0.31°
LBW_LJ_AL5_2	0.25°	0.19°	0.25°
LBW_LJ_AL7_1	0.74°	0.74°	0.77°
LBW_LJ_AL7_2	1.08°	1.20°	1.14°
LBW_LJ_AL8_1	2.02°	2.09°	2.07°
LBW_LJ_AL8_2	1.94°	1.87°	1.96°
LBW_LJ_AL11_1	0.84°	0.95°	0.78°
LBW_LJ_AL11_2	1.42°	1.39°	1.43°
LBW_LJ_AL12_1	0.86°	0.82°	0.88°
LBW_LJ_AL12_2	0.86°	0.85°	0.88°

Appendix B

Model sketches

Figure B.1: Sketch for the Fraunhofer FSW overlap welded joint with antisymmetric notches

Figure B.2: Sketch for the Fraunhofer FSW overlap welded joint with symmetric notches

Table B.1: Measures used to design the FS overlap welded models Figure B.1 and Figure B.2. All the non listed measures are derived in the script through geometrical relationship.

Parameter	[Bal+18]				[Inf+16]	[Kra14]	Allegro
Geometry	sym				sym	sym	asym
t1 [mm]	3.175	3.175	3.175	3.175	2	4	1.5
t2 [mm]	3.175	3.175	3.175	3.175	2	4	1.5
ol [mm]	50	50	50	50	60	50	30
el [mm]	70	70	70	70	85	75	95
lsincepl1 [mm]	35	35	35	35	20	20	20
g1 [mm]	0.02	0.02	0.02	0.02	0.01	0.01	0.01
g2 [mm]	0.02	0.02	0.02	0.02	0.01	0.01	0.01
r1 [mm]	1.03	0.88	0.81	1.06	1.55	4.87	1.91
r2 [mm]	1.27	1.61	1.77	1.39	0.83	1.93	2.35
$\alpha 1$ [°]	70.47	54.13	47.4	31.95	32.17	22.15	23.64
$\alpha 2$ [°]	42.29	34.25	36.87	28.25	47.66	19.35	23
distance [mm]	4.3	4.3	4.3	4.3	4	11.5	5.2
gsls1 [mm]	0.3	0.3	0.3	0.3	0.4	0.4	0.4
gsls2 [mm]	0.2	0.2	0.2	0.2	0.2	0.2	0.3
rf1 = rf2 = 0.05 mm reference radius							

APPENDIX B. MODEL SKETCHES

Figure B.3: Cross section pictures for the FSW overlap welded joints taken from the cited papers and for the "Allegro" project specimen

Figure B.4: Sketch for the Fraunhofer LBW overlap-welded joint

Table B.2: Measures used to design the LB overlap welded models Figure B.4. All the non listed measures are derived in the script through geometrical relationship.

Parameter	[Son+97]		Allegro
t1 [mm]	1.5	1.5	1.5
t2 [mm]	1.5	1.5	1.5
ol [mm]	30	30	30
el [mm]	95	95	95
lsincepl1 [mm]	35	35	35
g1 [mm]	0.01	0.01	0.01
g2 [mm]	0.01	0.01	0.01
ra [mm]	2.2	2.2	2.8
distance [mm]	1.75	1.82	1.76
gl1 [mm]	16.58	16.54	16.57
gl2 [mm]	16.58	16.54	16.57
fltlradius [mm]	0.05	0.05	0.05
rf1 = rf2 = 0.05 mm reference radius			

Figure B.5: Sketch for the Fraunhofer LBW butt welded joint

Table B.3: Measures used to design the LB overlap welded models Figure B.5. All the non listed measures are derived in the script through geometrical relationship.

Parameter	[Son+97]				
t1 [mm]	1.5	1.5	1.5	1.5	1.5
tl [mm]	220	220	220	220	220
lsincep11 [mm]	35	35	35	35	35
lsincep12 [mm]	35	35	35	35	35
wt [mm]	1.83	2.17	2.62	2.63	1.66
toeHeight [mm]	−0.08	0.15	0.12	0.02	0.13
wr [mm]	1.77	1.98	2.33	2.32	1.728
rootHeight [mm]	0.02	0.32	0.3	0.23	0.15
flt1radius [mm]	0.05	0.05	0.05	0.05	0.05
flt2radius [mm]	0.05	0.05	0.05	0.05	0.05

Figure B.6: Sketch for the Fraunhofer FSW butt welded joint

Appendix C

Haigh's Diagrams

Figure C.1: Haigh's Diagram for butt welded joints.

APPENDIX C. HAIGH'S DIAGRAMS

Figure C.2: Haigh's Diagram for overlap welded joints.

APPENDIX C. HAIGH'S DIAGRAMS

Table C.1: Available article from which the data to evaluate a mean stress sensitivity were taken

Nominal stresses evaluated at 2×10^6 cycles				
Source	Aluminium alloy	Stress ratio R	Nominal mean stress [MPa]	Nominal stress amplitude [MPa]
Butt welded joints				
[BKB12]	AW 5754 H22	0.50	84.29	28.10
[Bes+17]	AA 5024 H111	-1.0	0.00	176.09
[Cir+06]	AA 6082 T6	0.20	35.54	23.69
[Cos+12]	AA 6082 T6	-1.0	0.00	61.21
[Cos+12]	AA 6082 T6	0.00	33.46	33.46
[Den+17]	AA 7050 T7451	-1.0	0.00	126.12
[Dic03]	AA 5083 H321	0.10	29.44	24.09
[Dic03]	AA 6082 T6	0.10	61.38	50.22
[Dil06]	AA 5083 O	-1.0	0.00	31.33
[Dil06]	AA 5186 H111	-1.0	0.00	27.09
[Dil06]	AA 5083 H111	-1.0	0.00	37.87
[Eri03]	AA 6082 T6	0.50	96.35	32.12
[Eri03]	AA 6082 T4	0.50	84.23	28.08
[Eri05]	AA 6082 T4	0.50	96.64	32.21
[Eri05]	AA 6082 T6	0.50	102.06	34.02
[Gio+09]	AA 6082 T6	0.10	44.70	36.57
[He+15]	AA 7075 T6	-1.0	0.00	92.97
[He+16]	AA 6061 T651	-1.0	0.00	81.84
[Inf+16]	AA 6082 T6	0.10	46.96	38.42
[MFC07]	AA 6082 T6	0.10	44.26	36.21
[Sci+08]	AA 6082 T6	0.10	52.43	42.90
[M R96]	AA 6005 T1	0.50	132.62	44.21
[M R96]	AA 6082 T1	0.50	83.40	27.80
[HMR70]	AA 6082 T4	0.50	83.49	27.83
[Uem+09]	AA 5083 O	-1.0	0.00	159.67
[Uem+09]	AA 6061 T6	-1.0	0.00	96.14
[Uem+09]	AA 7075 T6	-1.0	0.00	106.39
[Son+02]	AW 6005a	-1.0	0.00	33.01
[Son+02]	AW 6005a	0.00	20.87	20.87
Overlap welded joints				
[Bal+18]	AA 7075 T6	0.01	5.01	4.91
[BKB12]	AW 5754 H22	0.50	37.66	12.55
[Eri05]	AA 6082 T6	0.10	11.94	9.77
[Inf+16]	AA 6082 T6	0.10	12.70	10.39
[Rei+14]	AA 6082 T6	0.10	12.53	10.25
[Xu+12]	AA 6061 T6	0.10	12.30	10.06
[Xu+12]	AA 6061 T6	0.30	12.96	6.98
[Xu+12]	AA 6061 T6	0.50	23.45	7.82
[Xu+12]	AA 6061 T6	0.10	9.71	7.94

APPENDIX C. HAIGH'S DIAGRAMS

Table C.2: S-N curve with a survival probability of 50 %

Fixed knee point at 1×10^7 cycles					
Source	Stress ratio R	Endurable stress at knee point [MPa]	Inverse slope k	Endurable stress at 2×10^6 cycles [MPa]	Scatter $1/T_s$
Butt welded joints					
[BKB12]	0.50	20.47	5.08	28.10	1.35
[Bes+17]	-1.0	159.61	16.38	176.09	1.16
[Cir+06]	0.20	19.09	7.46	23.69	1.53
[Cos+12]	-1.0	45.43	5.40	61.21	1.83
[Cos+12]	0.00	22.28	3.96	33.46	1.52
[Den+17]	-1.0	84.45	4.01	126.12	1.38
[Dic03]	0.10	19.54	7.70	24.09	1.74
[Dic03]	0.10	45.56	16.52	50.22	1.10
[Dil06]	-1.0	18.32	3.00	31.33	1.27
[Dil06]	-1.0	15.84	3.00	27.09	1.57
[Dil06]	-1.0	23.53	3.38	37.87	1.23
[Eri03]	0.50	21.23	4.08	32.12	1.20
[Eri03]	0.50	16.35	3.00	28.08	1.25
[Eri05]	0.50	22.15	4.30	32.21	1.14
[Eri05]	0.50	21.88	3.65	34.02	1.29
[Gio+09]	0.10	27.45	5.61	36.57	2.91
[He+15]	-1.0	78.56	9.55	92.97	1.21
[He+16]	-1.0	69.82	10.13	81.84	1.09
[Inf+16]	0.10	30.01	6.52	38.42	1.29
[MFC07]	0.10	28.79	7.02	36.21	1.15
[Sci+08]	0.10	34.04	6.96	42.90	1.34
[M R96]	0.50	39.06	13.00	44.21	1.08
[M R96]	0.50	20.50	5.28	27.80	1.05
[HMR70]	0.50	20.55	5.31	27.83	1.05
[Uem+09]	-1.0	143.86	15.44	159.67	1.11
[Uem+09]	-1.0	90.18	25.15	96.14	1.05
[Uem+09]	-1.0	96.33	16.20	106.39	1.17
[Son+02]	-1.0	21.56	3.78	33.01	1.45
[Son+02]	0.00	14.61	4.52	20.87	1.26
Overlap welded joints					
[Bal+18]	0.01	2.87	3.00	4.91	1.68
[BKB12]	0.50	10.75	10.40	12.55	1.19
[Eri05]	0.10	7.68	6.69	9.77	1.56
[Inf+16]	0.10	7.66	5.27	10.39	1.12
[Rei+14]	0.10	7.52	5.19	10.25	1.11
[Xu+12]	0.10	8.05	7.21	10.06	1.27
[Xu+12]	0.30	5.34	6.01	6.98	1.22
[Xu+12]	0.50	6.40	8.03	7.82	1.10
[Xu+12]	0.10	6.21	6.53	7.94	1.20

Appendix D

Effective stress Approach

Figure D.1: Critical length a with minimum scatter in load direction. Evaluated with a fixed knee point at 1×10^7 cycles.

Figure D.2: Microstructural length ρ^* with minimum scatter in load direction. Evaluated without a fixed knee point.

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