
**Giga-Cycle Fatigue Behavior of high pressure
die-casting aluminum alloys**

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Abstract

The conventional fatigue limit has been set at around 10 million cycles, mainly due to limitations in performing fatigue tests above this number of cycles. Due to technological advances, it is already possible to carry out tests exceeding this number of cycles in acceptable testing times and at economically appealing costs. Technological advancements in resonance systems allow testing well above the fatigue limit of 10 million cycles (10x, 100x, or 1000x this value) in affordable times. For example, resonance systems at 20kHz ultrasonic frequencies can reach 1E10 in 6 days.

Flat geometries are critical when specimens are extracted from real parts like automotive cast components. For the smooth specimens, analytical formulations for stress analysis are available. But, for the plane-thin specimens, there is a need to develop a new testing procedure, including the required stress solutions. Thus in this work, a new plane specimen geometry was designed using numerical simulation and tested under ultrasonic frequencies in bending mode.

This work presents two S-N curves for the same Al6082-T6 alloy but obtained with different geometries, smooth and flat specimens, and loading modes.

Results obtained are compared with ones derived from cylindrical specimens, to show the S-N curves of the material as a function of the type of loading.

Keywords: Fatigue, Aluminum alloys, Giga-cycle, resonance, size effect, frequency, S-N curves.

Resumo

O limite de fadiga convencional foi fixado em cerca de 10 milhões de ciclos, principalmente devido a limitações na realização de ensaios de fadiga acima deste número de ciclos. Devido aos avanços tecnológicos, já é possível realizar ensaios que excedam este número de ciclos em tempos de ensaio aceitáveis e a custos economicamente apelativos. Os avanços tecnológicos nos sistemas de ressonância permitem efetuar ensaios muito acima do limite de fadiga de 10 milhões de ciclos (10x, 100x, ou 1000x este valor) em tempos aceitáveis. Por exemplo, os sistemas de ressonância a frequências ultra-sônicas de 20kHz podem atingir $1E10$ em 6 dias.

As geometrias planas são críticas quando os espécimes são extraídos de peças reais, como componentes de fundição automóvel. Para os espécimes lisos, estão disponíveis formulações analíticas para a análise de tensões. Mas, para os espécimes planos e finos, é necessário desenvolver um novo procedimento de ensaio, incluindo as soluções de tensão necessárias. Assim, neste trabalho, foi concebida uma nova geometria de espécime plano utilizando simulação numérica e testada sob frequências ultra-sônicas em modo de flexão.

Este trabalho apresenta duas curvas S-N para a mesma liga Al6082-T6, mas obtidas com geometrias diferentes, espécimes lisos e planos e modos de carregamento.

Os resultados obtidos são comparados com os obtidos com provetes cilíndricos, para demonstrar as curvas S-N do material em função da tipologia de carregamento.

Keywords: Fadiga, ligas de alumínio, ressonância, efeito de tamanho, frequência, Curvas S-N.

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List of Acronyms

3D	Three-Dimensional
AM	Additive manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer aided design
DAQ	Data aquisition
DIC	Digital image correlation
DN	Displacement Nodes
EDM	Electrical discharge machining
FCG	Fatigue Crack Growth
FEA	Finite element analysis
FEM	Finite element method
FEUP	Faculty of Engineering - University of Porto
FFT	Fast Fourier transform
FGA	Fine Granular Area
HCF	High Cycle Fatigue
HM	Hardness Method
HPDC	High Pressure Die Casting
HSS	High Strength Steel
ISO	International Organization for Standardization
LBW	Laser Beam Welding
LCF	Low Cycle Fatigue
SN	Stress Nodes
UFT	Ultrasonic Fatigue Testing
UHCF	Ultra high-cycle fatigue
UML	Uniform Material Law
USM	Universal Slopes Method
UTS	Ultimate tensile strength
VHCF	Very High Cycle Fatigue

List of Symbols

	A	Area
	E	Young's Modulus
	f	Frequency
	f_n	Natural frequency (Hz)
	f_r	Resonance frequency (Hz)
	G_{amp}	Gain
	G_f	Gauge factor
	h	Thickness
	I	Inertia
	l	length
Latin Symbols	L_G	Resistor length
	R	Load ratio
	R^2	Coefficient of determination
	$S - N$	Fatigue Strength Curve
	T	Wave period
	T_{off}	Stop time
	T_{on}	Oscillation time
	V_0	Output voltage
	V_S	Supply voltage
	x	Cartesian coordinate
	y	Cartesian coordinate
	y_p	Predicted logarithm of the stress level

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Greek Symbols	$\Delta\sigma$	Stress Range
	ω	Angular frequency
	ω_i	Natural Frequency (rad*s ⁻¹)
	ω_r	Resonance Frequency (rad*s ⁻¹)
	ρ	Volume mass
	σ	Stress on the specimen
	σ_f	Fatigue limit
	σ_a	Stress amplitude
	σ_{max}	Maximum stress
	σ_{min}	Minimum stress
	σ_{mean}	Mean stress
	ε	Strain

List of Publications and Conferences

In the scope of this thesis

David Peliteiro, Filipe G.A. Silva, Abílio de Jesus, “New specimen design for ultrasonic fatigue testing of Al6082-T6 plates”, The third European Conference on the Structural Integrity of Additively Manufactured Materials, September 4-6, 2023

Introduction

1.1 Background and motivation

The demand for CO₂ emission reductions and energy efficiency is increasingly present nowadays. Energy efficiency and electric mobility are topics very much discussed due to their multiple and almost countless aspects. In line with these concerns, we have the weight reduction in the car body, which will allow for a reduction in consumption and an increase in autonomy. However, this topic of weight reduction opens new avenues for changes to the manufacturing process of the structural components to be replaced, in order to maintain the properties and, if possible, increase the lifetime. The replacement of the material of the structural components by light Aluminum alloys with high performance is one of the most adopted paths. Nowadays, the high-pressure die casting (HPDC) process is characterized by being the most competitive production process for large series of aluminum alloy components, guaranteeing tight dimensional tolerances, good surface finishes and thin-walled pieces. Promoting innovation in the production processes of high-performance light weight alloys is essential to promote the offer of new products that can meet emerging demands, in line with the concept of electric mobility and energy efficiency and management of resources and raw materials.

1.2 Objectives

The objectives of this thesis are based on the latest needs for fatigue life studies of light metal alloy components and structures. Increasingly, due to the socio-economic environment, the life of components is being extended beyond the conventional fa-

tigue limit (10^7 cycles). The frenetic pace of society, with the movement of loads and people, increases in energy production and so on, is requiring an assessment of existing and end-of-life structures for use beyond the previously defined limit. This brings us to the area of fatigue known as ultra-high cycle fatigue (UHCF) or extremely high cycle fatigue. However, conventional testing equipment is not suitable for carrying out these studies within viable time horizons. It is known that conventional fatigue limits have been defined according to technical and economic limitations, and that extending life beyond this limit can lead to potentially unsafe uses.

Technological advances are allowing the emergence of strategies that were on standby, such as resonance systems. Ultrasonic fatigue testing machines (20kHz) are thus emerging on the market and are being proposed as an alternative method for assessing fatigue behavior in extremely high cycle domains. However, this technology still presents some challenges to solve, such as determining possible frequency effects on damage, as well as thermal effects due to heating during the test, defining new specimen geometries, and obtaining specimens from thin components.

The ambition of this work lies in the possibility of extracting samples from real thin components by testing them under ultrasonic conditions and defining a new procedure suitable for thin samples in resonance at frequencies of 20 kHz.

A lightweight cast metal alloy that is used for energy-efficient transportation will be investigated. Knowing that cast components are usually designed to exhibit thin cross-sections, this makes it difficult to extract samples and impossible to extract traditional circular cross-section samples. In order to understand the possible effects of the test frequency and to understand the equivalence between the new test procedures and traditional methods, tests at lower frequencies are also aimed, and their relationship with fatigue resistance will be established.

1.3 Host institution

The INEGI - Institute of Science and Innovation in Mechanical and Industrial Engineering from the University of Porto is an industry-oriented RTO with research activity in the areas of new technologies for advanced production processes, experimental mechanics, applied mechanics, energy, new materials, biomechanics, and the development of new products and systems. INEGI's research infrastructure includes a broad set of well-equipped laboratories and extensive engineering tools base for supporting its R&D activity as well as the production of industrial or commercial

prototypes. INEGI is actively participating in several national and international expert panels, consulting committees, groups and societies and sectorial industry clusters. In addition to the research team with experience in different areas, INEGI has excellent technical conditions and partnerships with companies that are the basis of this project. In addition, INEGI has the capacity to carry out the casting of metal alloys, and the different alloys to be studied have already been cast and injected with different techniques in the form of a necessary component for the automotive industry, for electric mobility. At this moment, the casting processes are fine-tuned and there is enough stock of the respective component to carry out this study about very high cycle fatigue characterization. Noteworthy that the INEGI has recently acquired an ultrasonic (USF2000, Shimadzu) and electromagnetic (Rumul) testing machines, key pieces for this project.

1.4 Content of the Dissertation

This master's thesis is structured into six chapters that present the research conducted for it.

The purpose of Chapter 2 is to provide information on the state of the art of fatigue over the past few years. It addresses the principles of fatigue and details several experiments into ultrasonic fatigue testing and very high cycle fatigue. The Shimadzu USF-2000 working principles are exposed.

In the Chapter 3, particularities of both the aluminum alloys Al6082-T6 and AlSi10MnMg (Silafont-36) are presented. The Al6082-T6 alloy is tensile tested in order to obtain its Yield and Ultimate Tensile Strength. The density is obtained by the Archimedes principle. And the Young Modulus is determined by an iterative method that involves the resonance frequency estimation in Abaqus and comparison with experimental results. The achieved design for the flat specimen and its fixture is supported by FEM performed in Abaqus.

Chapter 4 presents the process for specimens manufacturing. The apparatus for the 20 kHz tests performed at the Shimadzu USF-2000 with smooth and flat specimens is described, as well as the stress validation performed with strain gauges measurements. The experimental apparatus for the tests performed in the electromagnetic Rumul machine is also described here.

The Chapter 5 is reserved to present the outcome of the tests performed within the dissertation. It is also presented an analysis and discussion of the behaviour of the tested specimens.

To finalize, in the Conclusions and Future Work chapter the findings and deductions from the tests and analysis performed with the smooth and flat specimens of Al6082-T6 and the AlSi10MnMg flat specimens are presented as well as suggestions and ideas to extend the work done during this dissertation.

Chapter 2

Literature review

This chapter will be reserved to expose the advances regarding fatigue studies, more specifically in aluminum alloys. A greater focus will be given to the Al6082-T6 alloy as well as to the aluminum AlSi10MnMg (Silafont-36) alloy.

2.1 Fatigue

Fatigue is a process that materials go through when subjected to repeated stress or strain cycles. The study of this process is essential when it comes to the design of structural parts that will be subjected to different variable amplitude loads. Fatigue is characterized by cyclic stresses, even though the maximum stress reached does not exceed the yield strength of the material. Fatigue causes an estimated 90% of all the mechanical failures [1][2][3].

Beginning in the first half of the 19th century, mechanical failures were observed in metals subjected to repetitive stresses, even below their yield strength. This phenomenon was described as "fatigue" or "metal fatigue," indicating that the material became "tired" [4][5]. In 1829, Wilhelm August Julius Albert, a German mining administrator, made notable observations and conducted studies on the failure of mine hoist cables resulting from repeated small loadings. His work represents the first systematic about metal fatigue. Jean-Victor Poncelet, during his lectures at the military school in Metz in 1839, described metals as being "tired" when subjected to cyclic loading [5].

In 1843 the first technical document recognising the failure due to cyclic loading was published. William John Macquorn Rankine examined numerous broken railway axles and identified that their failures were caused by the progressive growth of brittle cracks originating from stress concentrations or shoulders on the shaft. Rankine

presented his findings in a paper to the Institution of Civil Engineers [4].

In 1870, August Wohler, with the results from a rotating bending fatigue tests performed on railroad axles, defined the Wohler curve, that would be known as the S-N curve. In this curve, the number of cycles until failure was represented in one axis and the stress range ($\Delta\sigma$) in the other. With the results of multiple test, and the representation of their values in the graph, a curve could be obtained. This will be discussed in more detail in sub-chapter 2.1.1. With his tests, the german engineer noticed that the range of cyclic stress applied to the axles were of greater importance than the peak stress [6].

The ASTM (American Society for Testing and Materials) defines fatigue as "the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations" [7].

The cyclic stress can either cause plastic strain that initiates the crack that propagates due to tensile stresses, or microscopic plastic strains when the cycle is totally in the elastic regime [8] [9].

The most common approach to describe the fatigue life of a component is the stress-based approach, considering the component is loaded bellow the Yield Stress, that is, in elastic regime. Following this approach, the life of the component is dependent on the stress amplitude of the cycles it was subject to. Higher stress magnitudes will lead to smaller number of cycles until the component reaches failure [8] [9].

A constant amplitude loading is represented in the figure 2.1. The following parameters and equations were obtained from [10][11]. The horizontal axis represent time and the vertical axis the stress applied. σ_{max} represents the maximum applied stress and σ_{min} the minimum counterpart. The mean value of this two parameters is the mean stress, σ_{mean} , determined by the equation 2.1.

$$\sigma_{mean} = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (2.1)$$

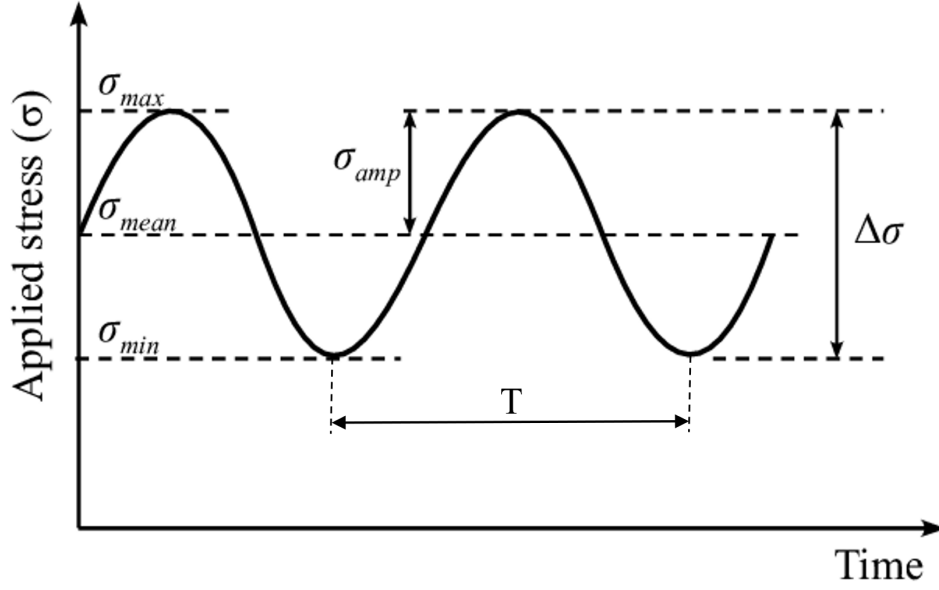


Figure 2.1: Constant amplitude loading, adapted from [12]

The difference between the maximum and minimum stress, is represented by the stress range, $\Delta\sigma$, represented in the equation 2.2.

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \quad (2.2)$$

Equation 2.3 represents the calculation of half of the stress range, called the stress amplitude, σ_a .

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

The stress ratio, R , is defined by the ratio between the minimum and the maximum stress, calculation shown in the equation 2.4.

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

The maximum value of this parameter is 1. There are two characteristic values for R :

- When the value of R is 0, the load is called pulsated loading, and the region of study is never under compressive stresses since the minimum stress is null.
- When the value of R is -1, the denomination of the loading is fully reversed, being the values of the maximum and minimum stress symmetrical.

Another parameter represented in the figure 2.1 is the period, T , which is the time taken to a complete cycle (in the figure it is represented by the time between two consecutive minimum values but can also be measured between two consecutive maximums). The value of this parameter is the inverse of the frequency, f .

2.1.1 S-N curve

The stress-based approach has the advantage of its easy implementation. In this approach there is a relation between the stress on a region and the number of cycles to failure. This is represented in the S-N curves from which fatigue analysis heavily rely [13].

Different materials exhibit distinct fatigue behaviours, and S-N curves provide a mean to quantify and compare these behaviours. Usually there are two kinds of materials behaviours regarding their fatigue life. Some materials show a fatigue limit, i.e. if these materials are subject to stress ranges bellow this fatigue limit, infinite life will be observed. The figure 2.2 shows two S-N curves, where the blue line represents a material with a fatigue limit. The typical materials showing a fatigue limit are ferrous and titanium alloys, where this limit usually starts between 10^6 and 10^7 cycles. Other materials like aluminum, magnesium and copper alloys don't show this behaviour and if the number of cycles applied are high enough it would lead to fatigue failure even with small stress ranges[10][14]. The red line in the Figure 2.2 shows this behaviour.

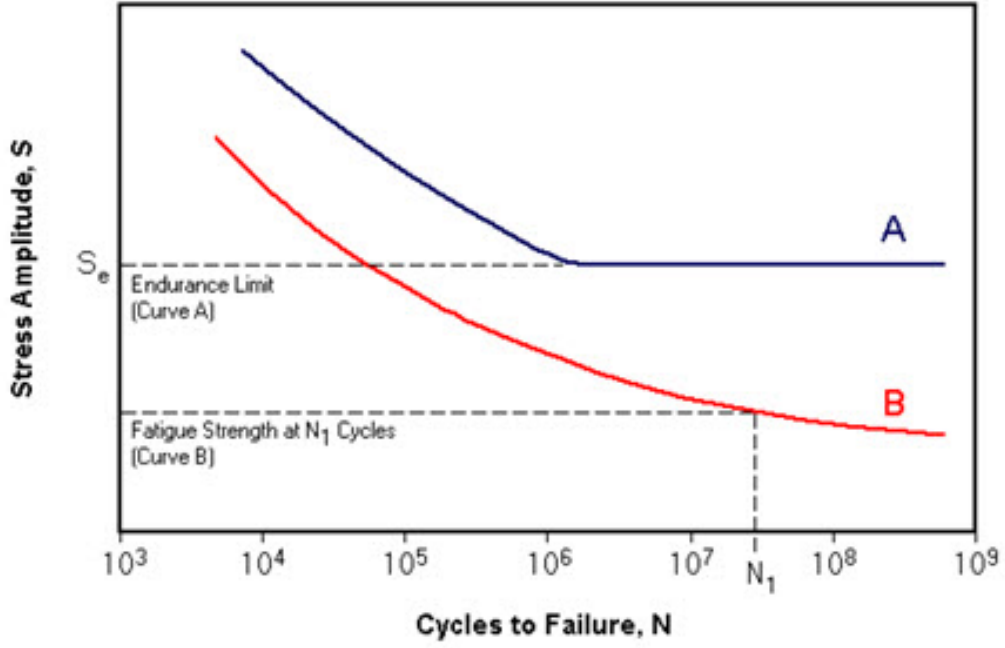


Figure 2.2: S-N curve for materials with different behaviours [15]

From the ISO 12107 Standard [16], it is possible to obtain the mean S-N curve in the finite life region as:

$$\log(\sigma_a) = A + B \log(N) \quad (2.5)$$

B and A being given by equations 2.6 and 2.7 respectively (with $y = \log(\sigma_a)$ and $x = \log(N)$). To obtain B , the stress is considered as the independent and number of cycles as dependent variable.

$$B = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^n (x_i - \bar{x})^2} \quad (2.6)$$

$$A = \bar{y} - B\bar{x} \quad (2.7)$$

The values of $\bar{x}$ and $\bar{y}$ are obtained by equations 2.8 and 2.9 respectively.

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (2.8)$$

$$\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i \quad (2.9)$$

These values allow to obtain R^2 , the coefficient of determination, that refers to the estimation accuracy by the calculation of y_p , the predicted logarithm of the

stress level. The closer the value of R^2 gets to 1, the closer the experimental fatigue points get to the curve. The equations 2.10 and 2.11 show how to obtain the values of the predicted logarithm of the stress level and the coefficient of determination respectively.

$$y_p = A + Bx \quad (2.10)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - y_p)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (2.11)$$

The cycles prediction is given by equation 2.12, value needed to the calculation of the standard deviation given by equation 2.13 where $n - 2$ represents the degrees of freedom.

$$x_p = -\frac{A}{B} + \frac{1}{B}y \quad (2.12)$$

$$\hat{\sigma}_x = \sqrt{\frac{\sum_{i=1}^n (x_i - x_p)^2}{n - 2}} \quad (2.13)$$

To establish a S-N curve for a specific probability of survival (PS) and a confidence level (CL) a shift factor is needed. This factor is calculated by:

$$factor = k_{(PS,CL,n-2)} \hat{\sigma}_x \sqrt{\left(\frac{1}{n} + 1\right)^2} \quad (2.14)$$

With this, the S-N curve is defined by:

$$\log(\sigma_x) = A + B * factor + B \log(N) \quad (2.15)$$

2.1.2 Factors that affect fatigue life

The fatigue life of a specific specimen from a determined material can be affected by multiple factors being the most important the following:

- Specimen size: the dimensions of a determined specimen may have a big impact in its fatigue life. A specimen with bigger dimensions is more likely to have defects like micro defects that would lead to a shorter fatigue life [17].
- Frequency of tests: high frequencies usually are coupled with higher temperatures, which could lead to a decrease in the mechanical strength properties of the material resulting in lower fatigue strength. The high frequency also leads to high strain rates which influences the mechanical behaviour [11].

- Surface finish: specimens with higher roughness, or worse surface finish, usually have shorter fatigue life due to roughness of the surface leading to higher local stress, favoring crack initiation [18].
- Loading: the kind of loading that the specimen is subjected to has a great impact in the fatigue life of the specimen. For comparison an axial load usually leads to lower fatigue strength than bending [3].
- Stress ratio: usually is expected better performance from specimens under smaller stress ratios since compressive stresses are less favourable to crack growth [10].
- Grain size: microstructure has an impact in the fatigue life of specimens and smaller grain size usually has better fatigue performance [19].
- Inclusions and porosity: this aspect of the microstructure also has an important effect on fatigue performance since these defects act like a concentration of stress. The proximity of these defects to the surface has a bigger impact and greatly reduce fatigue life [20].
- Environmental conditions: higher corrosion of the environment tend to reduce the fatigue life impacting the crack propagation. Depending on the material, the humidity of the air can also be a variable with an impact in the results [21]
- Residual stress: lastly the residual stress presence has an impact in the fatigue life of the specimen since it affects the stress ratio that is being applied in a specific zone. If a zone is under compressive residual stress, it would perform better because when a tensile stress is applied the resulting local stress would be the difference between the two which would result in a lower effective stress [2].

2.2 Very high cycle fatigue

Very High Cycle Fatigue (VHCF) is a fatigue regime that arouses a lot of interest and is characterized by the study of the fatigue of materials with a number of cycles higher than 10^7 [22].

The fatigue regimes regarding the number of cycles, can be divided in the following ones [23]:

- LCF (Low Cycle Fatigue): under 10^4 cycles
- HCF (High Cycle Fatigue): between 10^4 and 10^7 cycles
- VHCF (Very High Cycle Fatigue): higher than 10^7 cycles

It is also called Gigacycle to the the fatigue regime in the order of 10^9 cycles. This fatigue regimes can be seen in the figure 2.3.

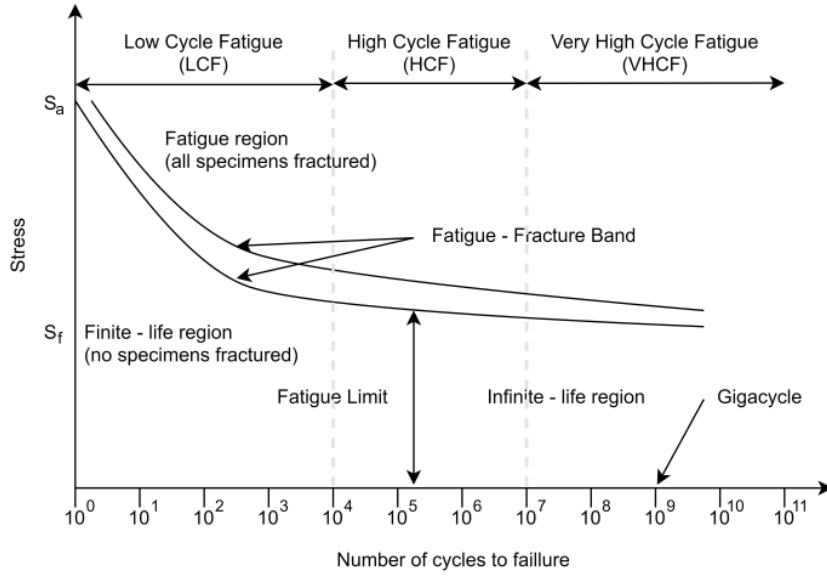


Figure 2.3: Fatigue life regimes (adapted from [24])

Mechanical components of various sectors are designed with data from HCF in mind, however the failure due to fatigue is still possible even with stresses lower than those seen in this region and the crack initiation and propagation can be found in the regime of VHCF.

In some industries like automotive, aeronautics and energy there are many components that can achieve fatigue lives in the VHCF range during their service like:

- Car engines: cylinder heads and blocks can achieve 10^8 to 10^9 during its operation period [25];
- High speed trains and ships can surpass the 10^9 cycles [26];
- Turbine engines can achieve 10^{10} to 10^{11} cycles in few years [27].

2.2.1 Ultrasonic fatigue testing

Due the high number of cycles applied to several components, in many structures and machines, the ultra high life fatigue of materials must be studied. But here is a challenge to solve. If the tests would be performed in a conventional servo-hydraulic machine at 10 Hz it would be needed more than 3 years to achieve 10^9 cycles and 10 times that number, 32 years, to achieve 10^{10} cycles. This fact turns impossible to obtain a S-N curve with fatigue data in the order of 10^{10} cycles. There is also the option for tests with a electromagnetic resonance system with a frequency range of 100 to 200 Hz, that although being faster than a conventional system, isn't capable of performing tests in the very high cycle range in a short period. And from this problem rises the need for ultrasonic fatigue testing (UFT). This method of fatigue testing works in a frequency range of 15 to 30 kHz, with the most usual being 20 kHz, a frequency that does not require a soundproofing chamber due to being above the human hearing spectrum.

Table 2.1 shows the test duration required at different frequencies, in order to obtain lives from 10^6 to 10^{10} .

Table 2.1: Fatigue tests duration

	High Cycle Fatigue		Very High Cycle Fatigue		
	1E6	1E7	1E8	1E9	1E10
Conventional 10 Hz	1.16 days	11.6 days	3.85 months	3.2 years	32 years
Resonance 100 Hz	2.8 hours	1.16 days	11.6 days	3.85 months	3.2 years
Ultrasonic 20 kHz	50 secs	8.3 mins	1.4 hours	14 hours	5.8 days

2.2.2 VHCF ultrasonic machine

The ultrasonic testing method was greatly developed in the 1980s with the evolution of machines with piezoelectric actuators. Figure 2.4 displays the typical layout of a piezoelectric actuated ultrasonic machine.

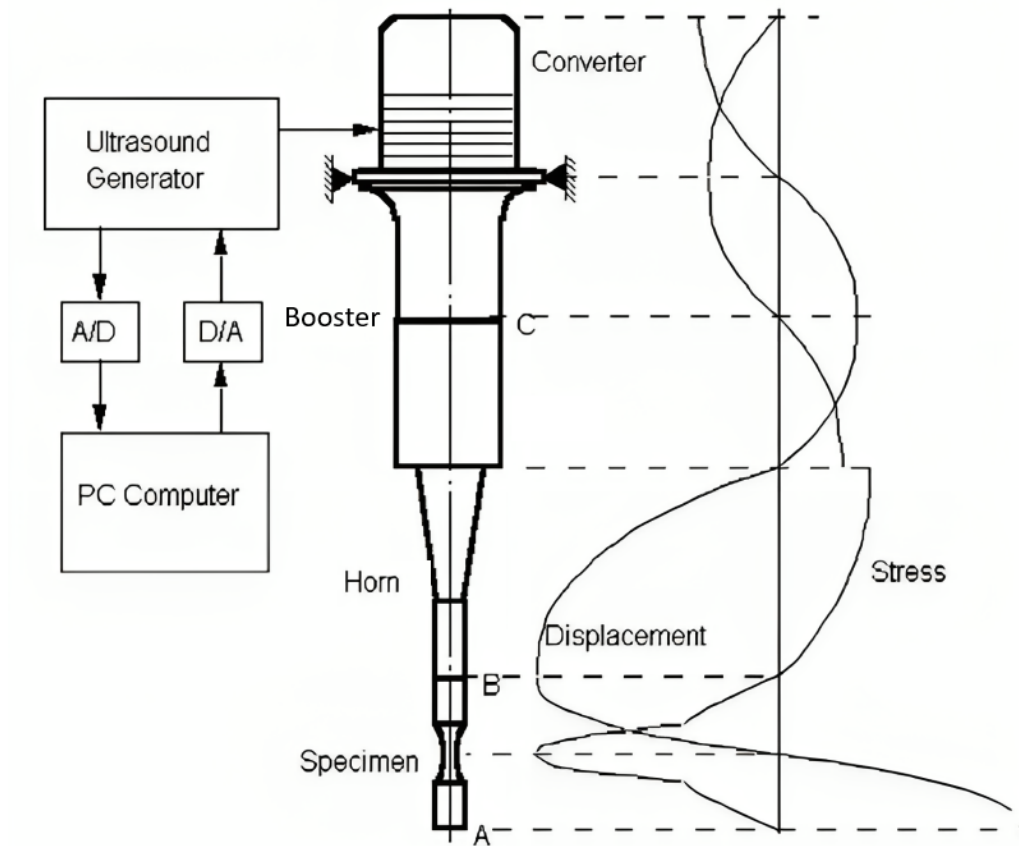


Figure 2.4: Ultrasonic testing machine with displacement and stress representation (adapted from [28])

The system is composed by four main components:

- Generator: It is responsible by feeding the actuator with a 20 kHz sinusoidal electric signal. It controls the resonance frequency and displacement amplitude during the test.
- Converter (piezoelectric actuator): Receives the electric signal from the generator and converts it into longitudinal ultrasonic waves with the frequency of the electric signal. It has a narrow frequency tolerance to accommodate small difference in the resonance of the specimens or changes in them during the test (due to crack propagation or heat of the specimen).
- Booster and horn: they are responsible for amplifying the vibration displacements from the piezoelectric actuator. The booster is also responsible to clamp the system to a static plate at a nodal zone.

The piezoelectric actuator is connected to the booster by a screw. The booster is connected to the steel plate that secures the system and is also connected to the horn by a screw connection. The specimen is then screwed to the horn. Later will be observed that for the flat specimens there is the need for a different fixture.

The system represented in the figure 2.4 represents the load of a tensile compression test with ratio $R=-1$. In this case there is a displacement node in the center of the specimen. This system has three displacement nodes (DN), that is, three nodes where the displacement is equal to 0, and four stress nodes (SN), that is, four nodes where the stress is equal to 0.

2.2.3 VHCF of flat specimens

This section will focus on the literature review on VHCF of flat specimens, tested at ultrasonic frequencies.

The evolution in multiple industries seek for lighter and thinner components. In order to perform fatigue tests with materials from this components rises a problem: it is not possible to cut enough material to manufacture the conventional smooth cylindrical specimens from components with thin walls.

When loaded with tensile compression tests with ratio $R=-1$, these thin specimens are more prone to lateral vibration due to low bending stiffness at transversal directions. A solution for this would be the use of a second horn that would be mounted and fixed, and would stabilize the lower portion of the specimen [24]. This system is represented in Figure 2.5.

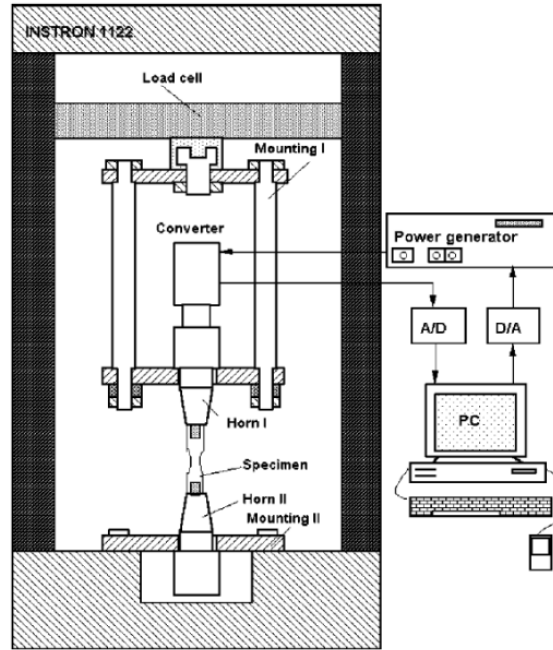


Figure 2.5: UHCF test system with secondary horn [24]

With the relative low thickness of the flat specimens the machining of a thread that would secure the specimen to the horn is not possible. This brings the need for a new specimen fixture.

Two possible solutions were presented:

- Phung et al.[29] tested a flat specimen with a soldered screw represented in Figure 2.6. The specimen was made from copper and the maximum stress amplitude tested was 115 MPa. This connection was successful with this material, but with materials tested at higher stresses the connection might not be strong enough to resist to the applied loads.

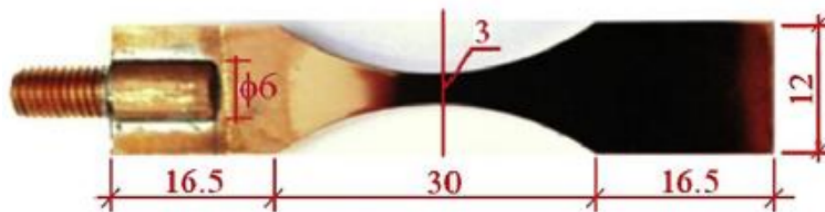


Figure 2.6: Flat specimen with soldered screw [29]

- Tofique et al.[30] proposed another solution. In this system the cold-rolled strip flat specimen was gripped from a component that would screw to the

horn. This solution had an identical gripping system in the lower part of the specimen (the only difference being the lack of the thread that fix the part to the horn) that would allow to a symmetrical load at the specimen, also has an increase in the stress levels loaded to the specimen due to the increase in the systems inertia. This system was tested with stress amplitudes of 500 MPa. In order to improve the fixation of the specimen (that had a thickness of 1.0 mm) the gap in the gripping system was of 0.9 mm. Since the gap is smaller than the specimen thickness it is required flexibility of the gripping system to squeeze the specimen. This flexibility can be adjusted with the grooves in the internal region of the gripping system. This system is represented in Figure 2.7.

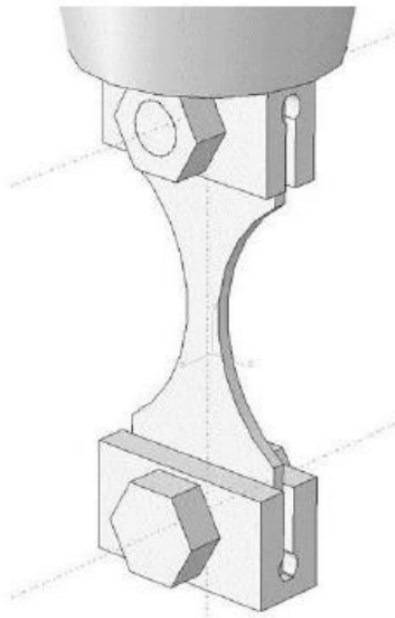


Figure 2.7: Flat specimen with bolt fixture system [30]

This work objective is to present a new system to fix the flat specimen to the horn and that allow to perform bending tests.

Specimens Design

In this chapter, the procedure to design the specimens to be tested at the Shimadzu USF2000 machine is presented. The specimens must have a resonance frequency that matches the work frequency of the machine, so it must range from 19.5 kHz to 20.5 kHz. One of the specimen is called Smooth and the other one Flat. The smooth specimen must have a zero displacement node on the middle of the specimen where the stress is maximum. In the smooth specimen the propagation of the wave is longitudinal. The methodology to calculate the specimens dimensions, displacements and stresses along the axis is exposed on this chapter, so as an introduction to longitudinal waves and resonance frequency. Then, flat specimen has an transversal wave propagation and an area reduction zone where the maximum stress is achieved. The design of the flat specimen is obtained through iterations with the help of simulation software, Abaqus. The smooth specimen results obtained through analytical solutions are compared with the finite element method simulations.

3.1 Introduction to the materials used

3.1.1 The Al6082-T6 Aluminum alloy

One of the alloys investigated in this work is the Al6082-T6 aluminum alloy. Al6082-T6 is a heat-treatable aluminum alloy with excellent strength, corrosion resistance and machinability. It is commonly used in the aerospace, automotive, and construction industries for its high strength-to-weight ratio, durability, and ease of processing [31].

Al6082 is a medium strength alloy with excellent corrosion resistance. It has the highest strength of the 6000 series alloys and it is known as a structural alloy. In

3. Specimens Design

plate form, Al6082 is the alloy most commonly used for machining.

As a relatively new alloy, the higher strength of the alloy has seen it replace 6061 in many applications. The addition of a large amount of manganese controls the grain structure which in turn results in a stronger alloy. The tighter chemical band ensures more consistent anodising between batches. In the T6 temper, Al6082 machines well and produces tight coils of swarf when chip breakers are used.

This alloy meets a variety of industry standards, including those set by the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO). It has been tested and certified for its mechanical and physical properties, as well as its corrosion resistance, ensuring that it meets the highest standards of quality and performance.

The aluminum alloy is typically used in:

- High stress applications
- Ore skips
- Trusses
- Beer barrels
- Bridges
- Milk churns
- Cranes
- Transport applications

Table 3.1 indicates the chemical composition of the Al6082-T6 alloy.

Table 3.1: Chemical composition of Al6082-T6 alloy

%	Mn	Fe	Mg	Si	Cu	Zn	Ti	Cr	Others (each)	Others (total)
min	0.4		0.6	0.7						
max	1.0	0.5	1.2	1.3	0.1	0.2	0.1	0.25	0.05	0.15

The mechanical properties of the alloy depend from the supplied form. The Table 3.2 show the expected difference in the properties of the 3 different supply forms used in this work.

Table 3.2: Mechanical properties in different supply forms

Property	up to 20 mm diameter bar	20 to 150 mm diameter bar	Sheet up to 6 mm thickness
Yield Stress [MPa]	250 Min	260 Min	260 Min
Tensile Strength [MPa]	295 Min	310 Min	310 Min
Density [kg/m ³]	2700		
Young Modulus [GPa]	70		

From various researchers is reported runouts in tests performed with loading of 100 MPa achieving 10^7 number of cycles. One example of this is the S-N curve shown in the Figure 3.1. From this graph is expected lives of around 10^5 cycles for stress amplitudes of 120 MPa.

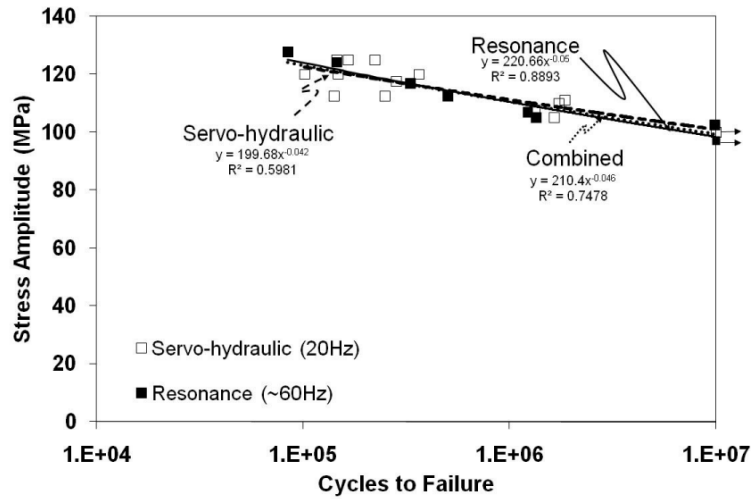


Figure 3.1: Fatigue lives of Al6082 specimens tested on different machines [32]

The same value of cycles was achieved by other researchers for tests with stress amplitudes of 100 MPa like in forged specimens with surface roughness ranging from 0.05 to 0.82 μm [33] or when testing small crack growth in specimens of Al6082-T6 [34]. However, the curves obtained by the latter two present a much steeper slope and for higher stress amplitudes, the tests resulted in longer lives.

3.1.2 The AlSi10MnMg (Silafont-36) aluminum alloy

Silafont-36 is a pressure die casting alloy developed by RHEINFELDEN AL-LOYS. The mechanical properties of this alloy can be improved by various thermal

3. Specimens Design

treatments and an elongation over 15 % can be achieved also as yield strength of 260 MPa.

The AlSi10MnMg alloy has particular properties that make it a good pressure die casting alloy. These properties are:

- excellent die cast castability
- no sticking to the die
- excellent machinability

This alloy also has properties that make it a very good material for components in the car manufacturing such as:

- very good corrosion resistance
- weldability for aluminum profile-cast designs
- suitable for self-piercing riveting and similar joining processes
- suitable for glueing connections in car design

Table 3.3 indicates the chemical composition of the Silafont-36 alloy.

Table 3.3: Chemical composition of Silafont-36 (AlSi10MnMg)

%	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sr	others
min	9.5			0.5	0.1		0.04	0.010	
max	11.5	0.15	0.03	0.8	0.5	0.07	0.15	0.025	0.10

Figure 3.2 shows the yield strength and elongation for various heat treatment states and magnesium contents.

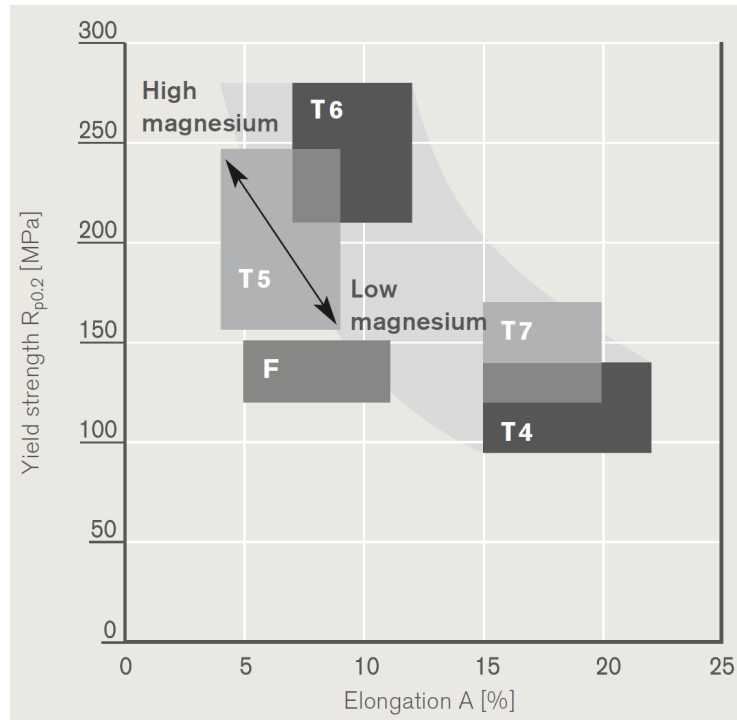


Figure 3.2: Yield strength and elongation for various heat treatment states of Silafont-36

Regarding the fatigue life of the Silafont-36 alloy the Figure 3.3 represents the S-N curve provided from Rheinfelden Alloys Handbook [35]. From it can be expected a fatigue strength around 100 MPa in the as-cast state for a test frequency around 117 Hz.

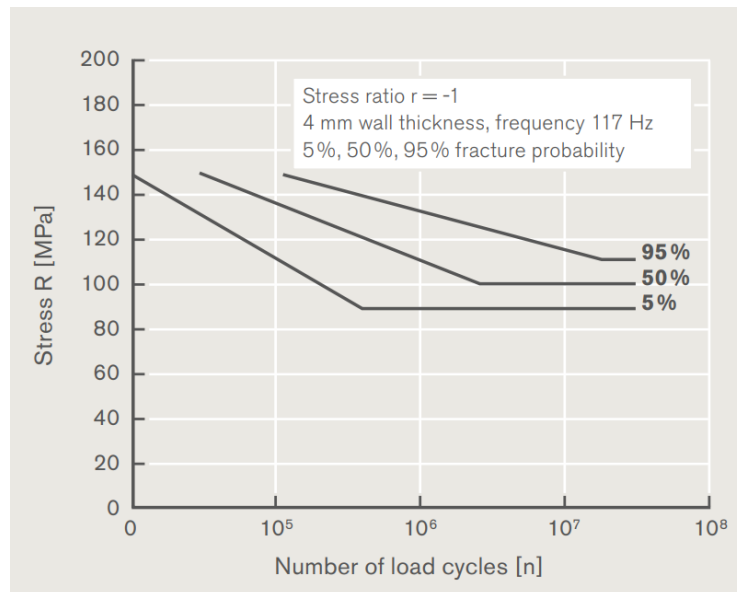


Figure 3.3: S-N curve for Silafont-36 alloy in the as-cast state [35]

3.2 Overview of materials, test campaigns and nomenclature

This chapter is reserved to present an overview of the test campaigns, the specimens materials and their nomenclature. In total were performed 142 tests, 106 with Al6082-T6 specimens and 36 with Silafont-36 specimens. The Table 3.4 shows the test campaigns, their nomenclature and from where the specimens were obtained. The Smooth and Rumul rounds 2 were obtained from bars with the same dimensions and from the same batch and have a "m" in their nomenclature. The Smooth campaigns were tested in a Shimadzu USF-2000 machine as well as the Flat specimens.

All the Silafont-36 specimens are flat specimens and will be refereed by their thermal treatment campaign number.

The specifics of each specimens geometry will be detailed in their respective chapter.

Table 3.4: Overview of fatigue test campaigns of Al6082-T6 specimens

Name of test campaign	Nomenclature example	Preform Material
Smooth, Round 1	Sh1	50 mm diameter bar
Smooth, Round 2	Sh1m	25 mm diameter bar
Rumul, M16 Round 1	16r1	30 mm diameter bar
Rumul, M16 Round 2	16m1	25 mm diameter bar
Rumul, M22 Round 1	22r1	30 mm diameter bar
Rumul, M22 Round 2	22m1	25 mm diameter bar
Flat	Flat1	2 mm thick sheet

3.3 The Al6082-T6 alloy and Properties

In this chapter the measured properties of the aluminum alloy would be expressed. With tensile tests performed on specimens from the thin sheet of Al6082-T6 Aluminum Alloy, performed in an universal testing Instron 5900R, shown at the figure 3.4, resulted the Yield strength, the Ultimate tensile strength and the elongation. The specimens technical drawing is represented in the Figure 3.5. They were obtained by wire EDM from the same sheet as the specimens that were fatigue tested.



Figure 3.4: Tensile test on Al6082-T6 specimen

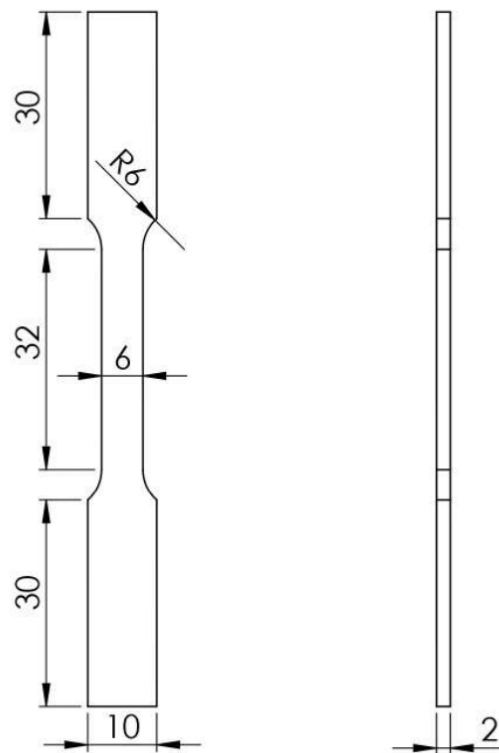


Figure 3.5: Al6082-T6 specimen for tensile test technical drawing

3. Specimens Design

From the tests performed, resulted the graphs shown in the figures 3.6 and 3.7, that show the behaviour of the specimens during the tensile test. The results obtained from the graphs are shown in the table 3.5, where the average value for the Yield strength was 313.40 MPa and the average for the Ultimate Tensile Strength (UTS) was 354.44 MPa. The two graphs show the difference between the engineering stress-strain and the true stress-strain curves.

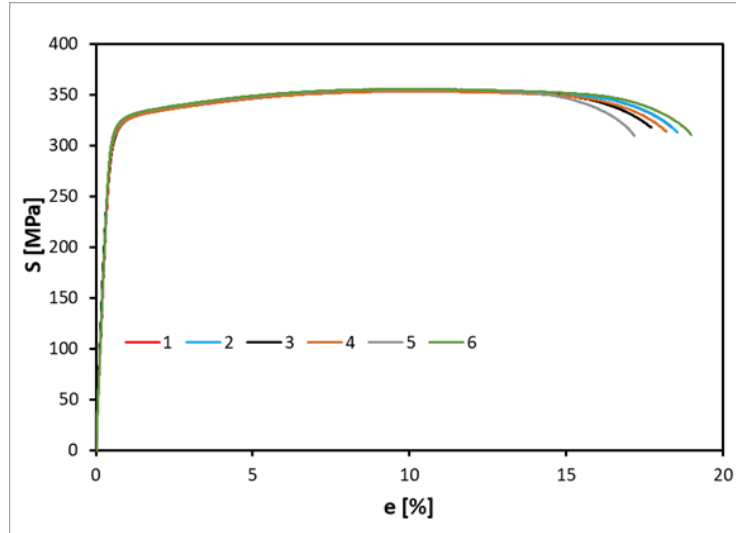


Figure 3.6: Engineering stress-strain graph

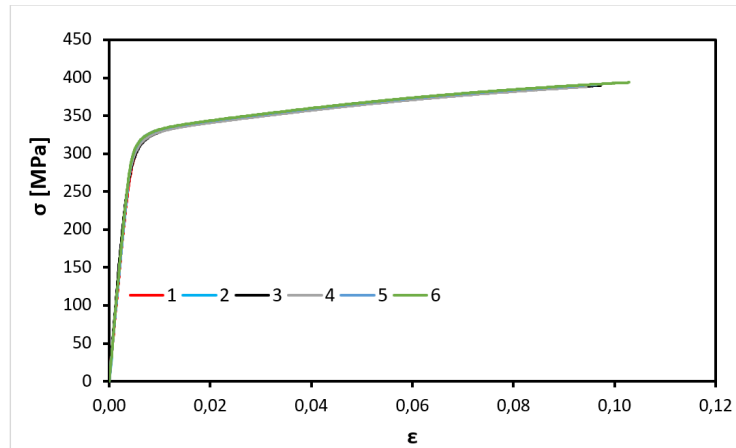


Figure 3.7: True stress-strain graph

Table 3.5: Tensile Test Results

Specimen	Yield Strength [MPa]	Ultimate Tensile Strength [MPa]	Elongation [%]
1	312.49	354.31	18,37
2	314.39	354.18	18,54
3	307.31	353.93	17,72
4	312.12	353.28	18,19
5	312.41	355.27	17,19
6	316.67	355.66	18,97
Average	313.40	354.44	18,16

3.4 Young Modulus determination by dynamic and non-destructive methods

The Young modulus for Al6082-T6 manufactured by rod and sheet needs to be determined accurately. This step is important because the modulus of elasticity influences the resonance frequency and the specimens dimensions must be adjusted to achieve the target frequency. The material's density ρ was also assessed by the Archimedes principle since this property is also relevant for the natural frequency calculation (2731.01 kg/m³ for rod and 2670.58 kg/m³ for sheet). In order to verify the Young modulus, conditions of a beam under natural vibration and "free-free" boundary conditions were replicated using vibration mechanics principles. This procedure was based on the ASTM International (2022) Standard. The material under examination was therefore machined into a bar with a constant circular cross section S , and two elastic bands were strung from the bar at the first vibration nodes. These bands must be very flexible to reduce the support influence. The circular section bar dimensions were: length $l = 200.0$ mm and diameter $D2 = 12.00$ mm. The representation of this apparatus can be seen on the Figure 3.8.

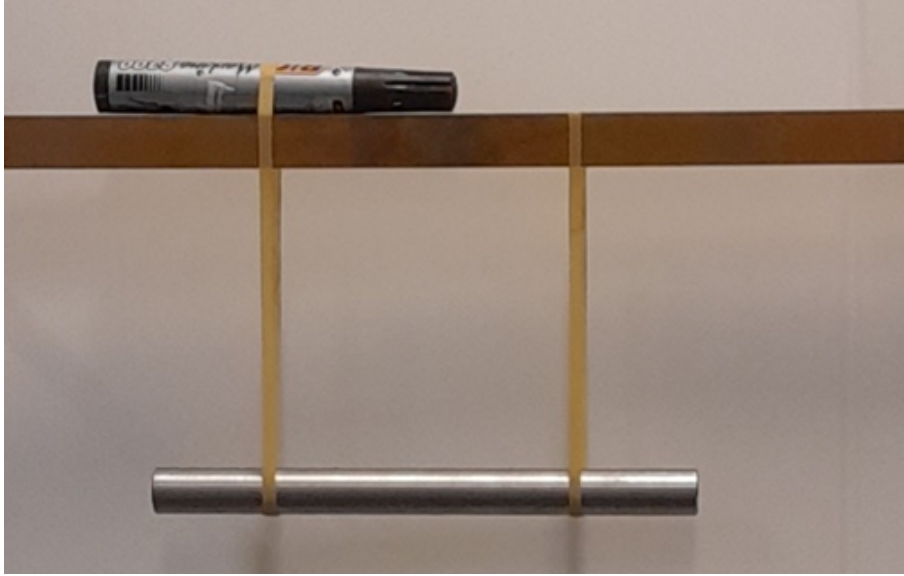


Figure 3.8: Beam supported by elastic bands at vibration nodes

A specimen's geometry and material characteristics affect its natural frequency. For instance, the length and diameter are the only two dimensions that apply to a circular thin beam. In terms of the material's characteristics, the first vibration mode (basic flexural) depends on the material's density, elastic modulus, and Poisson's ratio, where the latter has a negligible impact and can be disregarded for thin beams.

The natural frequency of a thin beam can be written as:

$$\omega_i = (\beta_i l)^2 \sqrt{\frac{E I}{\rho A l^4}} \quad (3.1)$$

where i is the natural frequency of interest, E is the modulus of elasticity, ρ is the material density, I is the cross section inertia, A is the area of the cross section, l is the beam length and β_i is a constant, which depends on the mode of interest and applied boundary conditions. For a thin beam without constraints (free-free), the $\beta_i L$ are presented in table 3.6.

Table 3.6: Value of $\beta_i l$ constants for a free-free slender beam

Mode (i)	1st	2nd	3rd	4th
$\beta_i l$	4.73004	7.8532	10.9956	14.1372

As a result, the elastic modulus of a specimen with known dimensions can be calculated by only measuring their natural frequencies.

The same procedure was performed to determine the elastic modulus of the thin plate of Al6082-T6 from where the flat specimens were machined with rectangles with 100 to 10 mm from the 2 mm sheet.

In the figure 3.9 the mode shapes generated from the equation 3.2 can be seen.

$$\omega_i(x) = \sinh(\beta_i x) + \sin(\beta_i x) + \frac{\sin(\beta_i l) - \sinh(\beta_i l)}{\cosh(\beta_i l) - \cos(\beta_i l)} (\cosh(\beta_i x) + \cos(\beta_i x)) \quad (3.2)$$

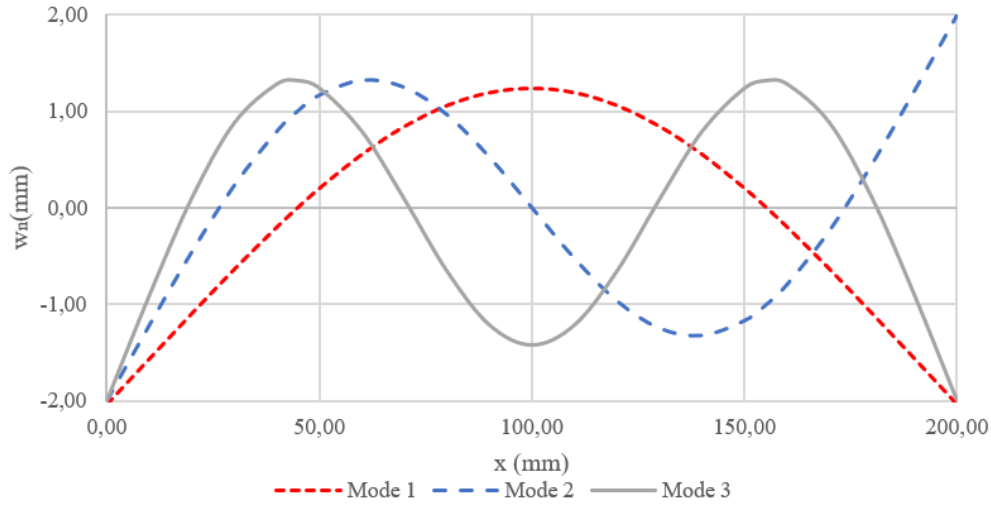


Figure 3.9: First 3 mode shapes for the free-free beam with $l = 200$ mm

From this shapes the vibration nodes coordinates where the elastic bands must be placed to test the mode 1 can be defined. This coordinates can be seen on the table 3.7.

Table 3.7: Vibration nodes

Mode	% of l	x(mm)
Mode 1	22.42	44.835
	77.58	155.165
Mode 2	13.20	26.40
	50.00	100.00
	86.80	173.60
Mode 3	9.40	18.80
	35.60	71.20
	64.40	128.80
	90.60	181.20

The next step was to undertake an initial excitation in order to get the beam to start vibrating. The contact made with a strong metal or ceramic should be executed in the center of the bar in order to achieve an higher amplitude in the first vibration node. The bar must be accurately machined with dimensions that allow the first natural frequencies to be positioned in the audible sound spectrum (from 20 Hz to 20kHz). As a precautionary method the targeted frequencies must be in a smaller range, preferably between 50 Hz and 18 kHz.

With a microphone, the sound emitted by the specimen after the contact and during its vibration was recorded. The audio file was then processed by a Fast Fourier transform in the Scilabs program where the firsts natural frequencies were determined.

With the goal of determining accurately the E of the beam, a comparison is done between the Experimental (f_{exp}) and the FEM (f_{FEM}) frequencies of the beam. When these two values are the same, the iteration process is finished and the E of the material determined. The frequency and the E of the FEM and experimental method follow the relation of equation 3.3:

$$\frac{f_{exp}}{f_{FEM}} = \sqrt{\frac{E_{exp}}{E_{FEM}}} \quad (3.3)$$

To determine the f_{FEM} a 3D object had to be modulated in Abaqus. This part had the exact dimensions of the Al6082-T6 beam, the same density and the elastic modulus used was obtained thought the literature (70 GPa). The Figure 3.10 shows the first 2 bending modes of vibration of the beam.

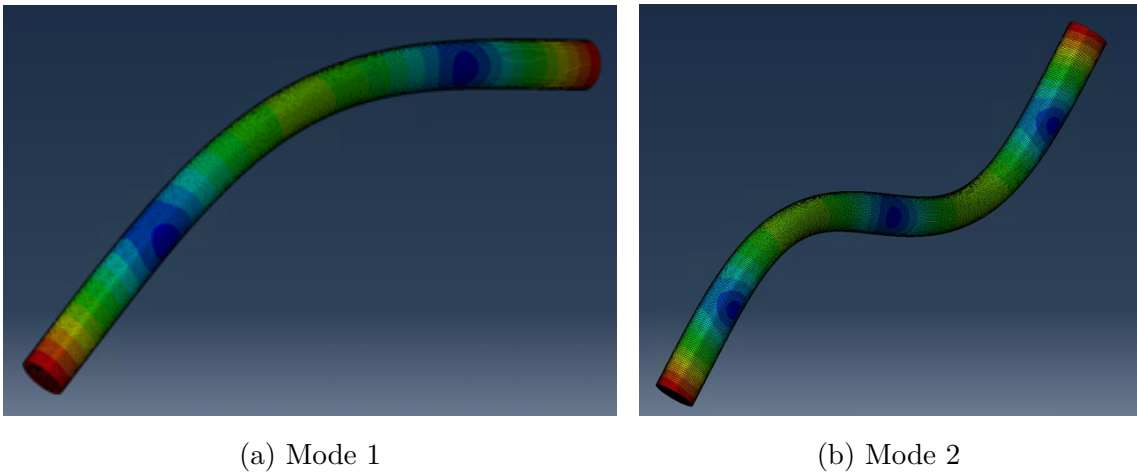


Figure 3.10: Bending modes on y obtained by FEM

The values obtained for the Young Modulus of the bar (used to obtain smooth

specimens) was 70.546 GPa and of the sheet (used to obtain the flat specimens) was 69.490 GPa.

3.5 Design of Smooth specimen for Shimadzu machine

In this chapter the methodology for obtaining the test specimens with smooth design is described. The geometry of these specimens is commonly used and the analytical formulation is well defined. The software from Shimadzu "Supersonic" can output the dimensions of the various parts of the specimen with a few properties inputted. These properties are the Young modulus, that was defined in the chapter "Young Modulus determination by dynamic and non-destructive methods" and the density of the material. The geometry provided from "Supersonic" was then analysed through Abaqus simulation and after the system frequency being the verified, also as the Stress applied in the center of the specimen, one first smooth specimen was manufactured in order to confirm the obtained values. In the figure 3.11 the dimensions of the specimen are represented.

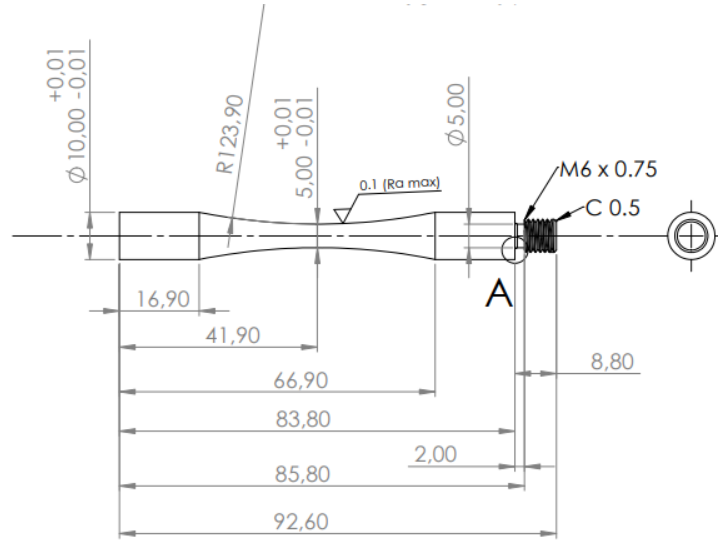


Figure 3.11: Geometry of the Al6082-T6 smooth specimen with resonance frequency of 20kHz

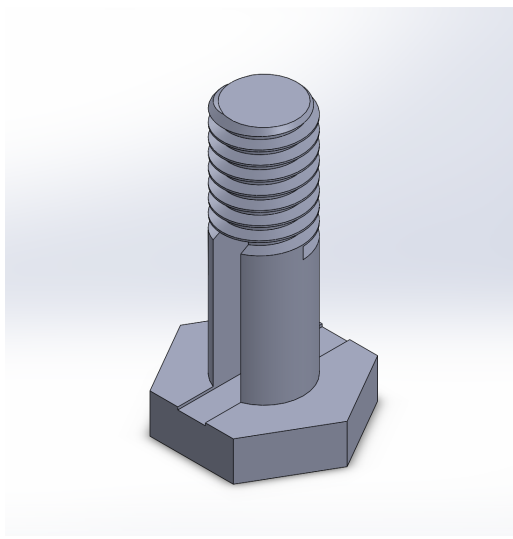
3.6 Design of Flat specimen for Shimadzu machine

In this section a methodology for obtaining test samples with plane geometries obtained from thin plates is presented. To find a new design for the Flat specimens

3. Specimens Design

that would allow to test the material with a plane geometry, a long process of iterations was performed. The goal was to find a design that could be tested in the frequency range of the Shimadzu machine (from 19.5 kHz to 20.5 kHz).

One of the complications with flat specimens testings is how to grip and transmit the mechanical wave from the machine to the specimen. Regarding this problem, the solution found was to manufacture a custom screw with an opening that would allow to fix the specimen between the screw and the horn. Figure 3.12 shows a 3D CAD drawing (3.12a) and a real model (3.12b) of the first designed and manufactured screw.



(a) CAD model



(b) Prototype

Figure 3.12: First aluminum alloy screw

There were defined a couple of requirements for the specimen and for the screw. The thickness of the specimen should be 2 mm, and the height 10 mm. The opening on the screw was designed so that it would allow the specimen to be inserted inside the screw.

With a solution for the fixture of the specimen then the next step was to design the specimen. The goal was to find a specimen design that would allow the system frequency to be close to 20.0kHz. With that, a specimen that produced a bending behavior at a natural frequency of 20 kHz should be designed. From the equation 3.1 the value of L can be defined, which was calculated to be 51.156 mm. Since the equation 3.1 is indicated for thin beams it should have a significant error. With that a FEM calculation was performed and the value of L was then adjusted to 47.925 mm. The specimen described is represented in the figure 3.13.

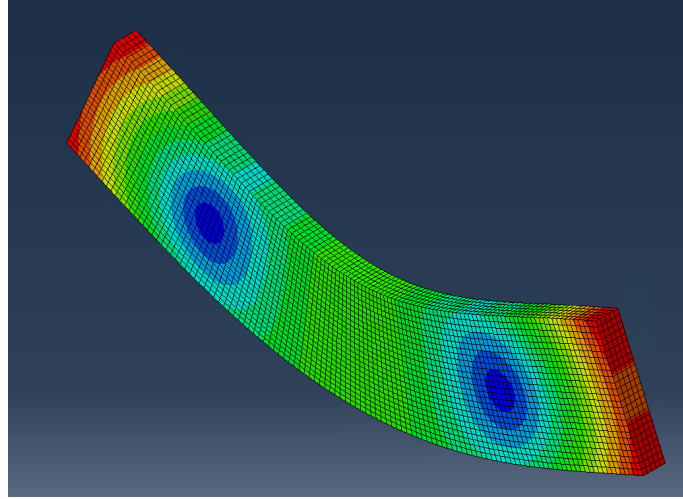


Figure 3.13: Specimen with 20 kHz resonance

When this specimen was tested with the complete system there were two problems. First, the stress caused in the specimen wasn't concentrated in a specific zone. Second, the minimum stress that the Shimadzu machine could apply for 15% of power (the minimum possible) would still be way above the desired nominal stress for the Al6082-T6.

In order to solve these problems there were designed several specimens with area reductions and notches to achieve the optimal geometry. Through multiple interactions, a final specimen that accommodate the intended stress level and the target resonance frequency was obtained. Figure 3.14 represents the final specimen is shown where a stress concentration can be seen in the desired tested region area.

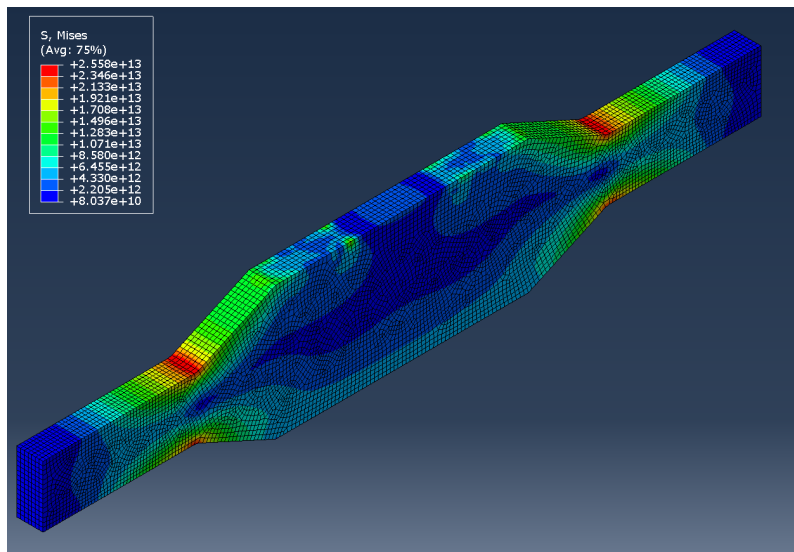


Figure 3.14: Specimen with stress distribution

3. Specimens Design

Proceeding to the design of the screw, with an aluminum alloy one the stress applied with 15% power was 75.9 MPa at 19.68 kHz. Considering that, the aluminum alloy screw would be the best option but this screw would fail very easily due to the low strength. Considering the same geometry and changing the material to a titanium alloy, the values of stress applied with 15% power are 77.2 MPa at 19.55 kHz. The value of frequency is within the working range of the Shimadzu machine but with fatigue damage in the specimen the frequency will drop during the test and the titanium alloy screw is very close to the 19.50 kHz limit. This condition limits the crack growth, preventing it from growing until total rupture. So a new iteration of the titanium alloy screw was needed. In this iteration there was removed mass from the head of the screw. This would bring the system frequency up 50 Hz, to 19.60 kHz what would allow the test to be performed till the failure of the specimen. Figure 3.15 shows the final titanium alloy screw.

There were multiple tries to get a system frequency closer to 20.0kHz, and that was achieved, but it resulted in a new problem, the minimum stress applied in the concentration area became much higher the closer to the 20.0kHz the system was. The final dimensions and design of the specimen and of the titanium alloy screw can be seen in the figure 3.16 and 3.17 respectively.

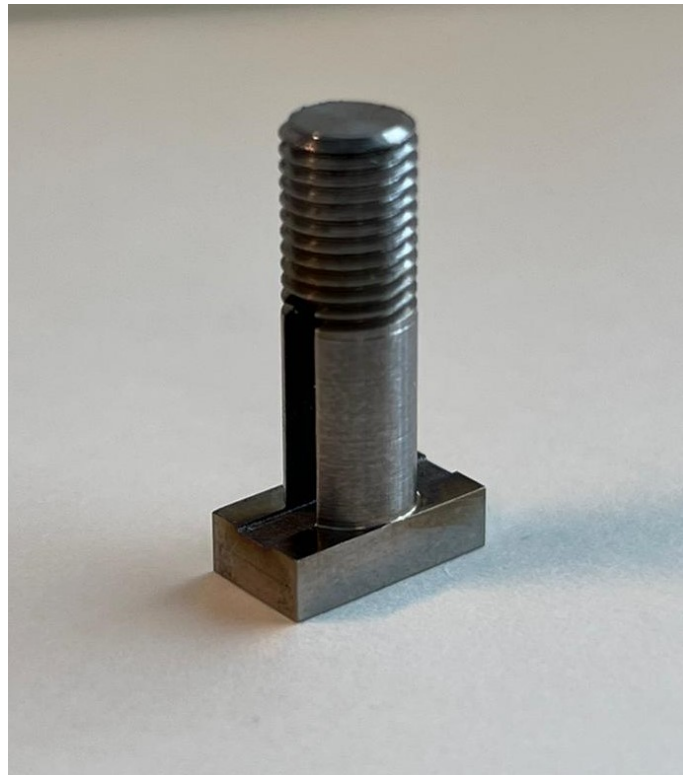


Figure 3.15: Titanium alloy screw

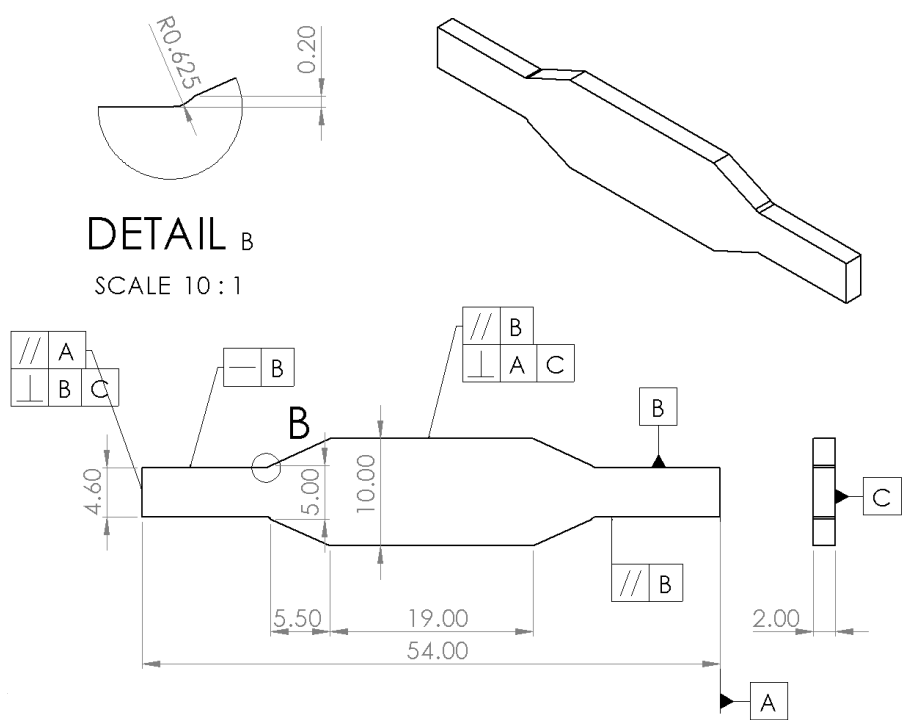


Figure 3.16: Specimen technical drawing

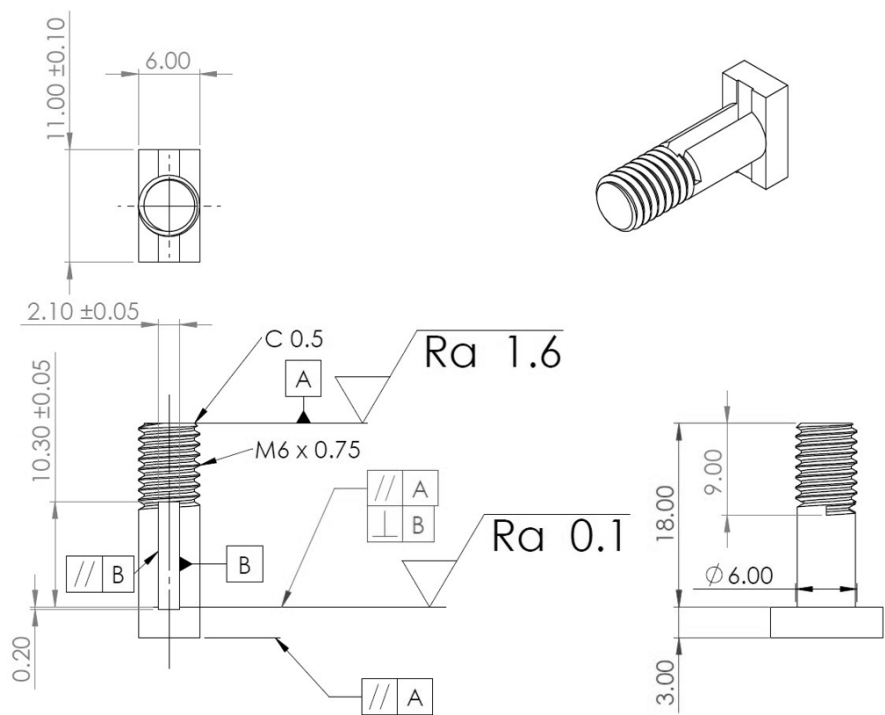


Figure 3.17: Titanium alloy screw technical drawing

3.7 Design of Flat specimens from casting parts for Shimadzu machine

There was also the goal to test flat specimens obtained from aluminum casting parts. The material of these parts is supposed to have different properties from the Al6082-T6 alloy of the specimens designed before. From the information obtained from the supplier it was expected that the casting parts would have a Young Modulus between 74 and 83 GPa and a density of 2.64 kg/dm^3 . There were then performed simulations with specimens with the design of the flat specimens of Al6082-T6 alloy but with the properties of the casting parts. With the adjustment for the new properties, the frequency would increase for 19.634 Hz with 74 GPa and for 19.702 with 83 GPa. With this increase in the frequency the stress applied with 15% power would be between 111 and 166 MPa.

From the iterations done when designing the Al6082-T6 flat specimen was noticed that an elongation in the "wings" of the specimen lead to a decrease in the frequency and in the stress applied. With this a specimen with 56 mm (2 mm more than before) was designed and the values for the frequency obtained were 19.572 Hz and 19.697 Hz and the values for the stress were 73 and 93 MPa. These values are under the desired range. With this, the final design of the specimens was obtained and is shown in the figure 3.18.

After manufacturing, the system frequency must be obtained in order to determine the exact Young Modulus of the material. After, by a iterative process the Young modulus was adjusted in the FEA until the frequency is matched. This way the real value of E is determined, which is used to final calculation of the applied stress.

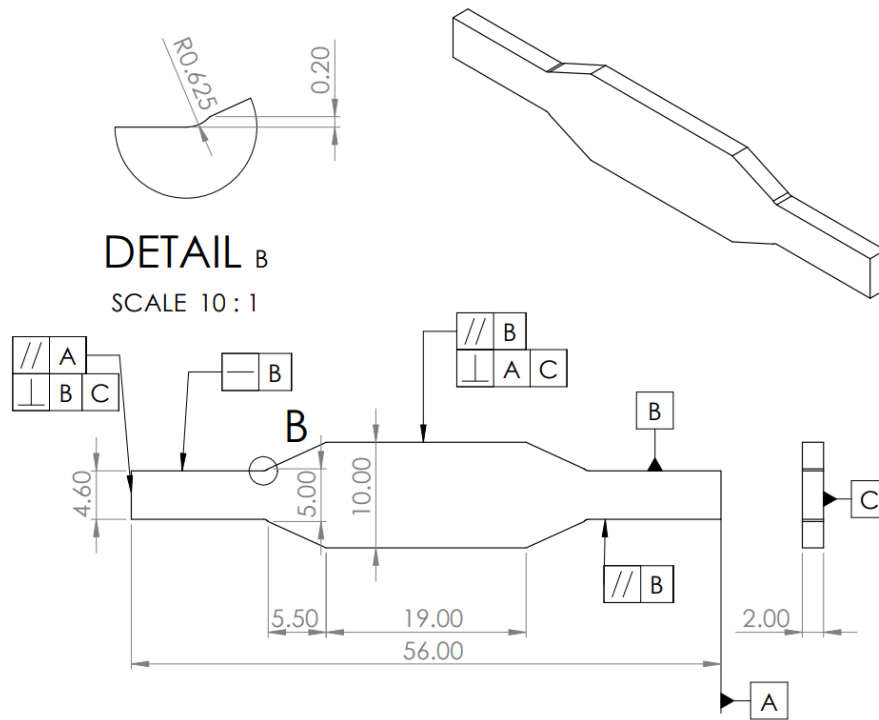


Figure 3.18: Specimen from casting parts technical drawing

3.8 Design of specimens of Al6082-T6 for Rumul machine

This section is reserved to express the methodology to design the specimens that are tested at the Rumul machine. In this machine there is not a need for a specific frequency as with the USF2000 machine. Here, the system frequency can also be adjusted with masses that compose the machine. The specimens follow a geometry that is proposed by the resonance machine manufacturer and the frequency ends in a level close to 100 Hz. Stress is computed from load measurement. There were manufactured two different specimens, one with a M16 fixture and other with a M22 fixture. The dimensions of these two specimens is represented in the Figure 3.19. In the Figure 3.19a the specimen has a smaller section with 7 mm of diameter while the specimen shown on the Figure 3.19b the smaller section has a diameter of 10 mm.

3. Specimens Design

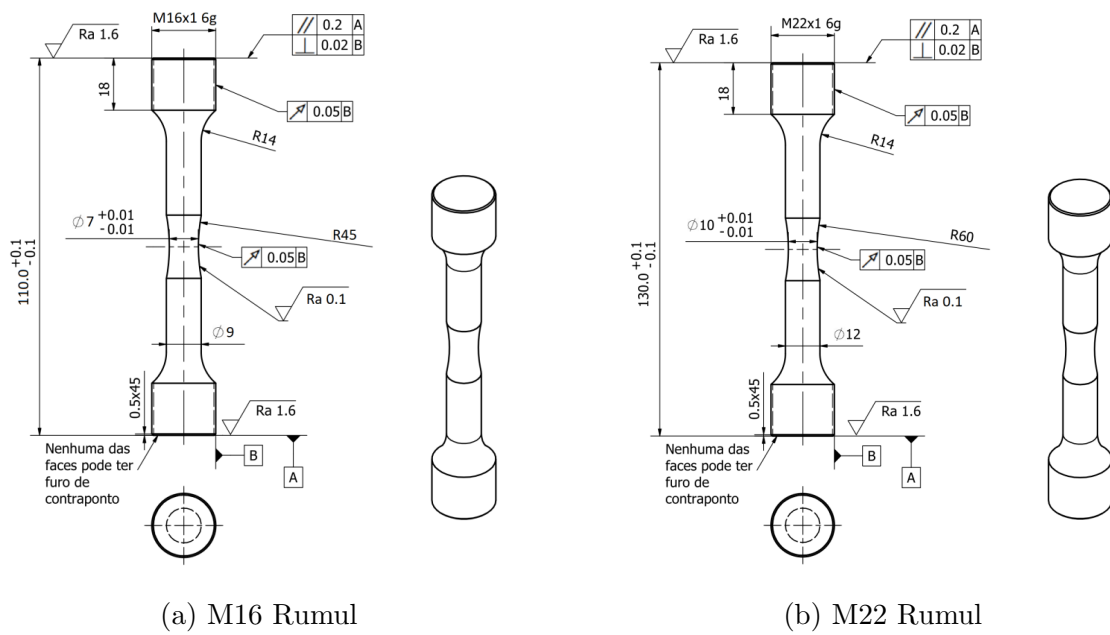


Figure 3.19: Rumul specimens geometry

Experimental Fatigue Programme

4.1 Specimens manufacturing

4.1.1 Smooth specimens (20 kHz)

There were manufactured two series of smooth specimens. The first batch was obtained from a bar of Al6082-T6 with 50 mm of diameter. From every section it was possible to get 7 specimens, except from the first section where one of the blocks had to have bigger dimensions in order to manufacture the bar that would be used to determine the Young modulus. Figure 4.1 shows the planning drawing for the order to get the blocks from a bar with 50 mm diameter, for later obtaining the smooth specimens.

The second batch of smooth specimens were obtained from bars with 25 mm of diameter. The goal was to obtain one specimen from every section and were produced 21 specimens from 3 bars with 1 meter length each. The parameters used on the CNC for the production of these specimens were 2500 rpm as rotational speed and 0.07 mm/rev of feed rate. Figure 4.2 shows the Goodway GA 2600M CNC lathe, where the specimens where manufactured.



The surface roughness of the specimens from this second batch compared with the first batch was worse. This could be seen with the help of a magnifying glass or even by running a fingernail across the surface [36] since the geometry of the specimens does not allow to perform a correct measuring with a Mitutoyo Surftest SJ-210. From the tests performed the roughness (R_a) of the specimens ranged from $0.078 \mu\text{m}$ to $0.289 \mu\text{m}$. The values displayed from the Mitutoyo Surftest SJ-210 are displayed in the Figure 4.3. A group of 6 specimens from this second batch was polished with the goal of comparing the effect of the surface roughness in the fatigue life of the specimens. In order to proceed to the polishing of these specimens, an ultra fine sandpaper with P2500 grit was used. Figure 4.4 shows the surface roughness of a specimen without polishing (4.4a) and the surface roughness of a specimen with polishing (4.4b). The specimens of both testing campaigns are displayed in the Figure 4.5 where the specimens on bottom correspond to the first and the ones in the top to the second campaign.

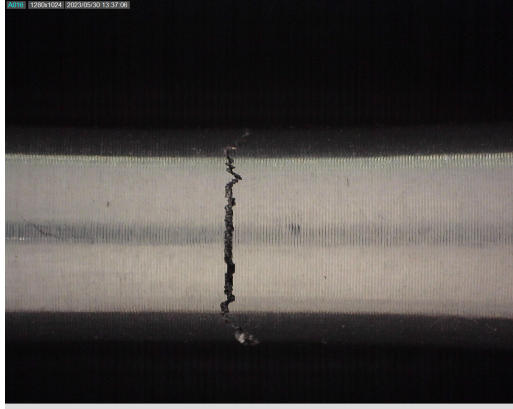


(a) Surface roughness of non polished specimen

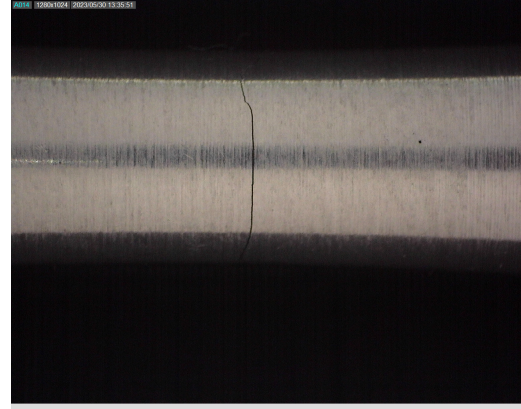


(b) Surface roughness of polished specimen

Figure 4.3: Comparison of smooth specimens surface roughness measurements



(a) Specimen without polishing



(b) Specimen with polishing

Figure 4.4: Comparison of smooth specimens surface without and with polishing



Figure 4.5: Campaign 1 (bottom) and 2 (top) of Smooth 20 kHz specimens

4.1.2 Smooth specimens Rumul

Regarding the smooth specimens that were tested at the Rumul machine, there were manufactured two batches. The first batch of M16 and M22 specimens were obtained from bars with 30 mm of diameter and were used to preliminary tests. The

second batch was obtained from bars with 25 mm of diameter, similar to the second batch of the smooth specimens tested at the USF-2000 machine. This second batch was composed by 15 specimens of M16 threaded smooth specimens and 15 of M22 threaded smooth specimens. The parameters used on the CNC lathe (represented in Figure 4.2) for the production of these specimens were 2500 rpm as rotational speed for both types of specimens and 0.08 mm/rev of feed rate for the M22 specimens and 0.1mm/rev of feed rate for the M16 specimen.



(a) M16 Smooth Specimens ($\phi 7$ mm at gauge section)



(b) M22 Smooth Specimens ($\phi 10$ mm at gauge section)

Figure 4.6: First campaign of M16 and M22 smooth specimens extracted from $\phi 30$ mm Al6082-T6 bar

4.1.3 Flat specimens

Flat specimens of Al6082-T6 were obtained from a thin rolled sheet with 2 mm of thickness. From this sheet a rectangle with 150x180 mm (represented by Figure 4.7) was used to obtain 20 specimens by wire EDM. The first batch of flat specimens was polished with a sandpaper with P1000 grit.

The flat specimens obtained from casting parts of AlSi10MnMg had a more complex process to be produced since the original part wasn't a thin sheet like the case of the Al6082-T6 specimens. As the geometry of the parts from where the specimens were obtained was confidential, the part had to be machined to around 2.5 mm of thickness before being delivered to the workshop where the wire EDM was performed. The workshop then proceeded to obtaining the desired design and just after the specimens thickness was reduced to 2 mm. In this process the thickness was only reduced in the end because the part being from an aluminum alloy and

4. Experimental Fatigue Programme

with residual stresses, EDM was shown to be the best process to obtain straight specimens. The specimens of this batch were not polished because in the first batch was observed that the polishing of the surface did not improve the fatigue life because the crack initiation was at the notched zone, zone that was not possible to polish with the available tools. Due to the complex geometry of the base material and the complex process to obtain the specimens, in some cases the number of specimens successfully obtained was not the expected. In total were obtained 36 well produced Silafont-36 flat specimens.

The wire used for the EDM process had 0.15 mm of diameter in both batches and the figure 4.8 shows the Sodick AQ325L CNC Wire EDM where the flat specimens were manufactured.

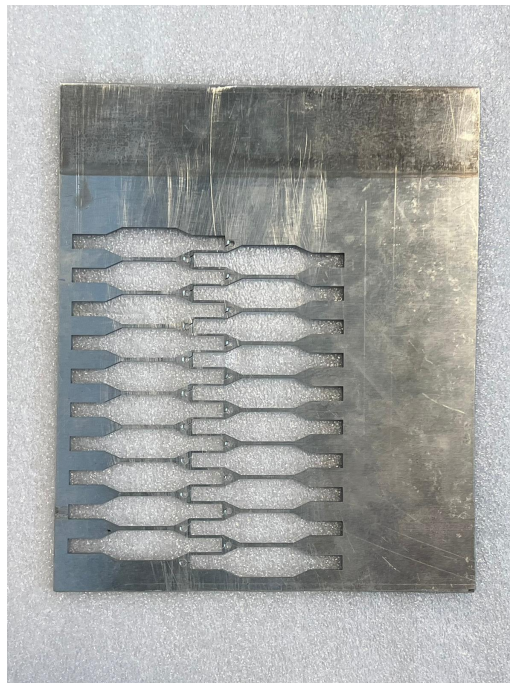


Figure 4.7: Al6082-T6 sheet used to obtain 20 flat specimens



Figure 4.8: Sodick AQ325L CNC Wire EDM

4.2 Experimental apparatus for Ultrasonic tests

To perform the 20 kHz tests, the USF-2000 machine from Shimadzu, shown in the Figure 4.9 was used. In the Figure 4.10 the multiples components and parts used to perform the test in the USF-2000 machine are labeled and their designation is in the Table 4.1.



Figure 4.9: Shimadzu USF-2000 Machine

All the components and peripherals from the system are powered from the current stabilizer. The functions from the components 7 to 10 was described before at the section 2.2.2. The Operation Box can turn the machine on/off, reset after errors and also beholds the emergency button. The Eddy Current Generator is used to read the displacements from the probe (when placed under the specimen) and transforms it for the Kistler DAQ which is used to calibrate the machine and the system gain for the specimen to be tested. The Eddy Current Generator (ECL101-U8-SMM-3.0) has a resolution of 500 nm and 80 kHz bandwidth, and the range of 2.00 mm and near gap of 0.35 mm. Its typical linearity is 0.50 % of the range.

Table 4.1: Components Figure 4.10

Label	Component
1	Current stabilizer
2	Operation box
3	Signal generator
4	DAQ box from Kistler
5	Eddy current signal generator
6	Piezoelectric Transducer
7	Booster
8	Horn
9	Flat specimen
10	Compressed air nozzle
11	Electromagnetic probe
12	Pyrometers
13	PC to control the test
14	Air dryer
15	Elsys DAQ System

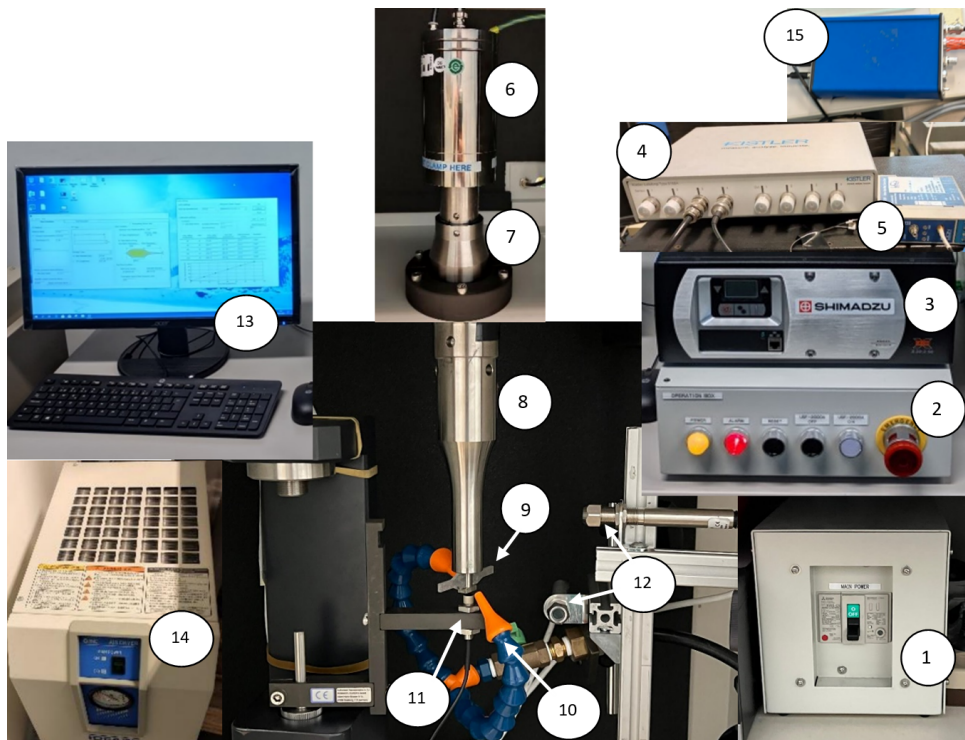


Figure 4.10: UFT Machine components

The compressed air is dried and is used to control the temperature from two parts. It cools down the transducer during the time that the machine is turned on, and with the guidance of the pair of nozzles, it cools down the specimen during the test, allowing to keep it under controlled temperatures.

The pyrometers (optris CS infrared thermometer) are used to monitor the desired component temperature. It can be two points of the smooth specimen (back and side), the horn or even the screw head on the flat specimen test. The pyrometers must be at a distance of 10 mm of the component to measure in order to only acquire its temperature. It is recommended to paint the measured area black to assure the compatibility with the pyrometers due to them not being able to measure the temperature in metals surface because of their emissivity and reflectivity.

The emissivity of the metal painted with black paint and the temperature measured by the pyrometer was compared with the values measured by a termocouple on a metal plate.

Due to the difficult job of measuring the temperature on the flat specimen a termo-camera was used. As the results obtained with the camera were positive, later it was also used to measure the temperature of the smooth specimens. The termo-camera allowed to see the zones subjected to higher stresses and in the flat specimens the propagation of the crack could be monitored too.

4.2.1 Sequence to execute a UHCF test in the Shimadzu USF-2000

In order to execute a fatigue test in the Shimadzu machine a whole sequence is required, as summarized in Table 4.2

Table 4.2: Sequence to execute a UHCF test in the Shimadzu USF-2000 machine

Step	Task	Device/component
1	Make sure the level of water in the compressed air reservoir is low	
2	Open the compressed air feeding valve	
3	Turn on the current stabilizer	1
4	Turn on the air dryer	14
5	Turn on the computer (and monitor)	13
6	Turn on the operation box, which turns on the ultrasonic power supply that controls the piezoelectric	2
7	Open Supersonic software	

Before starting the first tests, the horn must be checked with a torque wrench and a special tool to make sure that it is tightened to 25 Nm. To assure this value of torque applied to the horn, 21.4 Nm must be set on the torque wrench. With the use of the special adapting tool, the value set on the wrench corresponds to the desired value on the horn.

This values were calibrated with the load cell Dynamometer Type 9272, from Kistler. In the Figure 4.11a the steel fitting tool can be seen. In the figure the tools needed to perform the task of tightening the horn are also shown, see Figure 4.11b. Through the process represented in the Figure 4.11c the horn is tightened to the booster.



(a) Accessory to calibrate the torque wrench for 25 Nm (b) Tools to tighten the horn (c) Direction to tighten the horn

Figure 4.11: Horn tightening

Before performing the task 6 and 7 it is mandatory to make sure that there are no components in contact with the horn inside the USF-2000 machine because of the risk of movement of the horn on startup.

After the tasks completion it is recommended to perform a "Check Frequency" in the Supersonic software to verify the correct assembly of the machine and to verify the system resonance frequency.

With the verification of the correct behavior of the system then follows the sequence to tighten the specimens to the horn. There were tested two types of specimens at 20 kHz. First the process of tightening the smooth specimens is described.

4.2.1.1 Smooth Specimen test in the Shimadzu USF-2000

In the Figure 4.12 the process of tightening the smooth to the horn is illustrated.

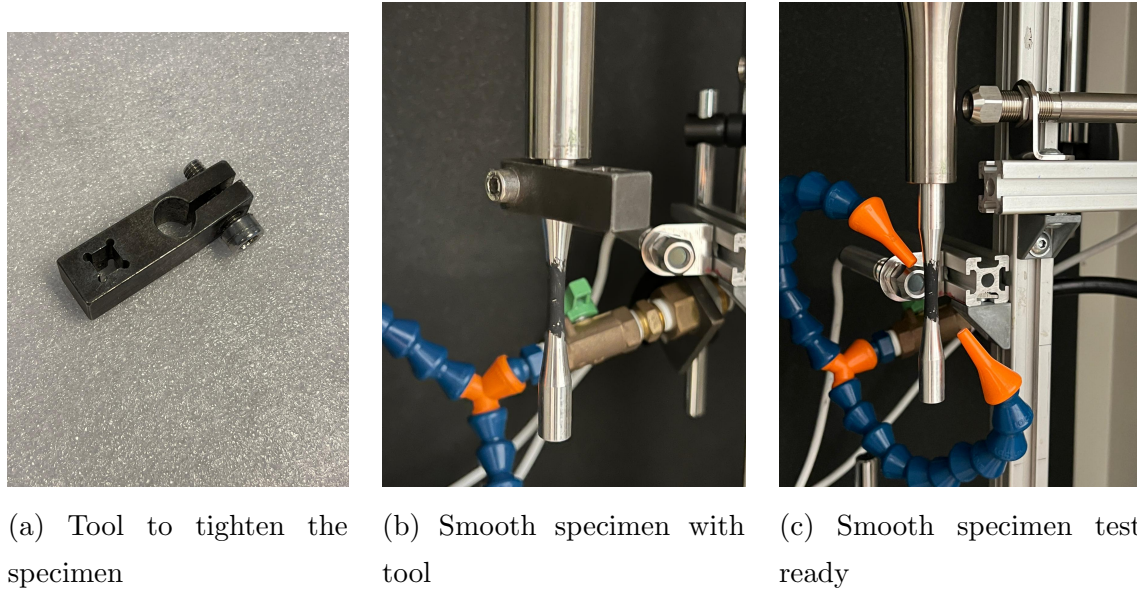


Figure 4.12: Smooth tightening

To start the sequence, the specimen is screwed to the horn by hand, being secured on the top part, in order to avoid torsion on the test piece. After the smooth specimen being screwed, the tool (shown in 4.12a) is tightened to the top of the specimen with a 5 mm hex key with caution to avoid contact with the lower part of the horn. Following this the torque wrench is set to 9 Nm which corresponds to 10 Nm being applied to the specimen. The wrench is connected to the tool and the specimen is tightened clockwise. After the torque wrench click for the first time, the operator stops and applies force again until a second click is heard in order to confirm the torque applied.

The wrench is then disconnected from the tool, the tool is unscrewed and carefully removed from the smooth specimen avoiding contact to make sure that the test piece is not scratched that could lead to unwanted results.

The compressed air nozzles are then positioned to guarantee the cooling of the specimen, the valve opened and a check frequency is again performed to assure that the specimen is well secured and that will not unscrew, when the test is started. After this verification the electromagnetic probe can then be securely placed under the specimen avoiding any contact of the probe with objects.

After this, the probe must be used to calibrate the Shimadzu machine displacement system. The Kistler software (DAQ) must be opened and the distance of the

probe must be adjusted until it shows 7 V on the software. When the voltage read is at 7 V the height of the probe must be measured with a resolution of 0.001 mm. After reading and writing this value the probe's height should then be changed until a voltage of 9 V is reached and the process must be repeated. With this process and using an Excel spreadsheet the value of the gain of the probe is calculated, which would allow to convert the values read by the probe and determine the experimental displacement. This value can change depending of the material that is being measured and the position of the probe. For our smooth specimens this value ranged from 187.00 to 189.50 mV.

In order to do the fatigue test a calibration curve is necessary to be inputed into the Supersonic Software. This curve will allow the system to deliver and apply a determined power in order to achieve a desired nominal stress on the specimen. To start this process, data from a loading with the minimum allowed power (15 % through the Check Frequency operation) of the machine is collected by the DAQ generating a data file. The same process is repeated for higher values (20 and 40 % for example) and a combination of the values obtained would allow to interpolate the displacement (and correspondent nominal stress) for higher values that are not intended to be applied to the specimen.

The data file obtained by the DAQ is then read by a Scilabs Fourier Function Transformation program that outputs an image like the Figure 4.13. In this image the values of the resonance frequency, the scale factor and the displacement measured can be seen.

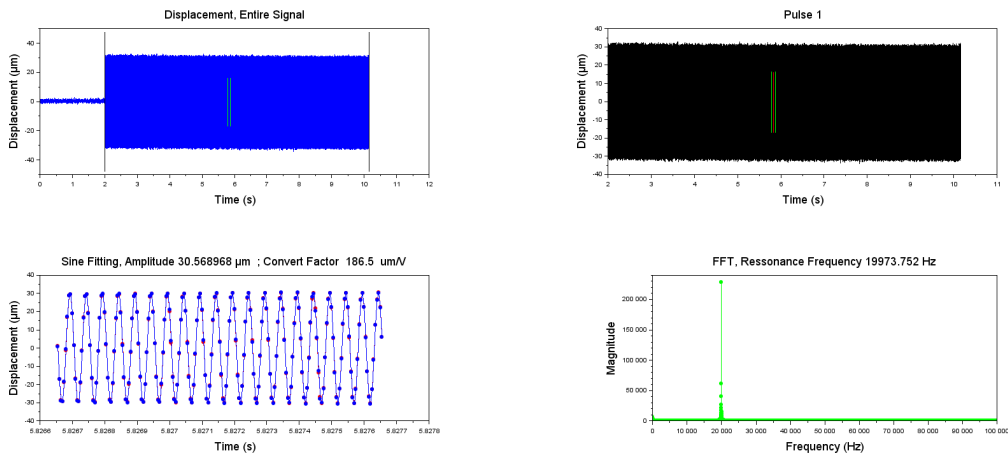


Figure 4.13: Scilabs output image for specimen Sh7

With the first three points from the Table 4.3 (that are represented in the Figure

4.14) a linear regression is determined that would allow to determine the higher values of displacement (in this case 60, 80 and 100 %). Those higher values are not performed due to its higher damage to the specimen.

Table 4.3: Calibration data for smooth specimen Sh2-round1

Power (%)	Displacement (μm)
15	9.35
19.88	12.46051
39.83	25.18009
60	38.04 (Extrapolated value)
80	50.79 (Extrapolated value)
100	63.54 (Extrapolated value)

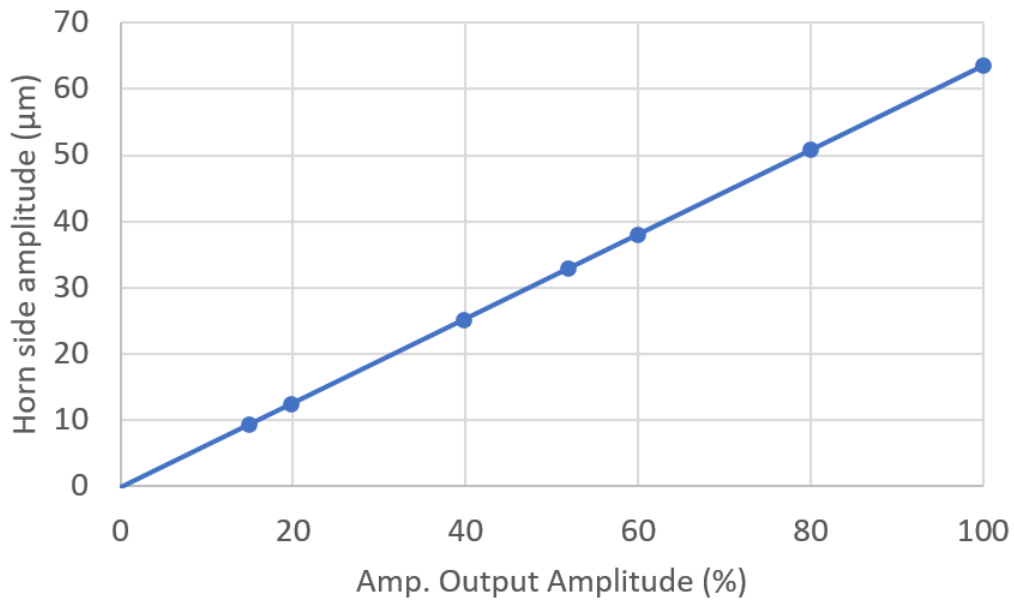


Figure 4.14: Calibration Curve

As the desired values of stress to be applied to the specimens only require less than 60% of the machine power, only the values for 20, 40 and 60 % are filled in the System Settings of the Supersonic software. This allows the software to calculate the power percentage to apply in order to achieve the displacement correspondent to the required stress. In the Figure 4.15 the tab for the System settings where this values are filled is represented.

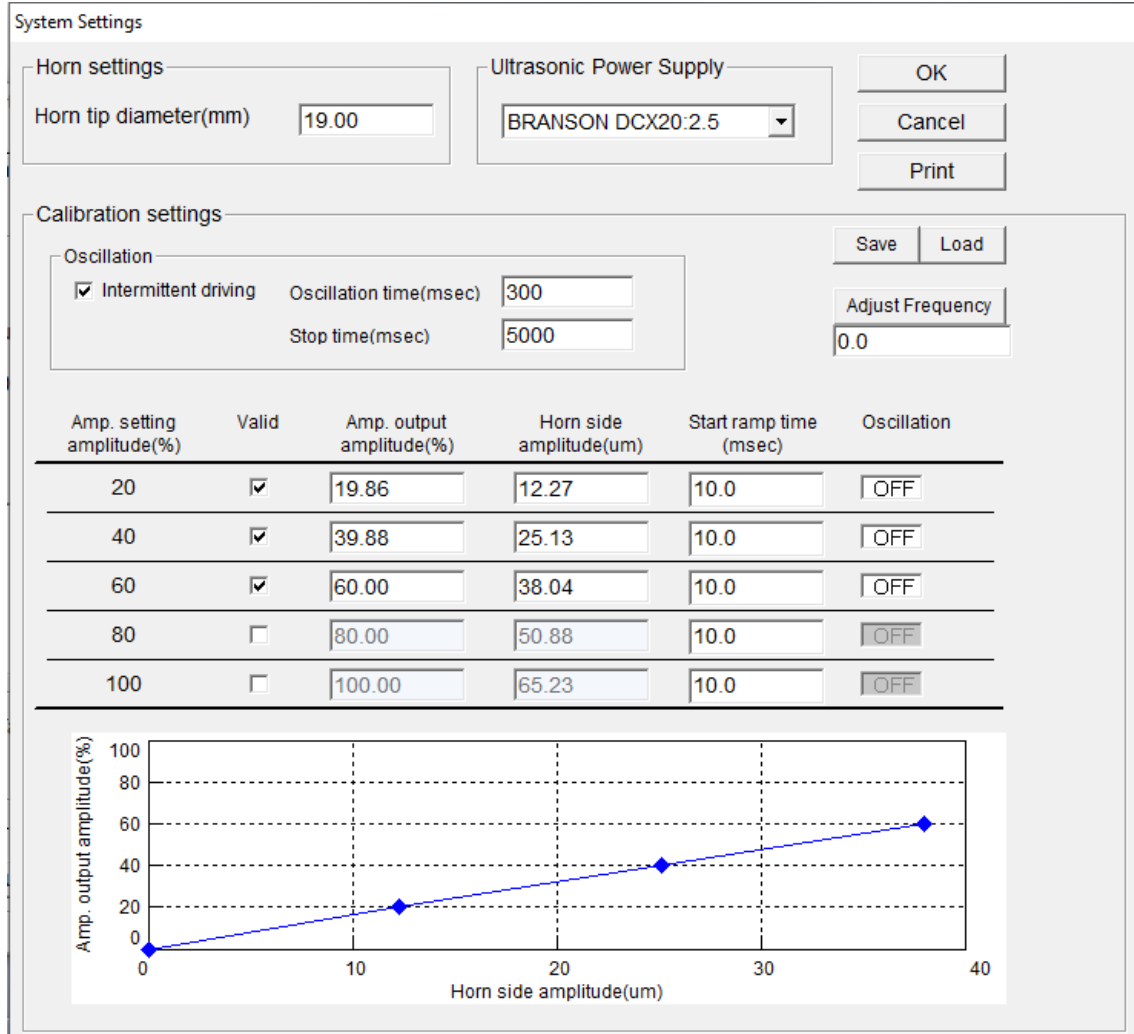


Figure 4.15: System settings Sh2-round1

After the System settings tab correctly filled, follows the Test Condition page which can be seen in the Figure 4.16. In this page on the left side, inside the TP Material window the material properties must be introduced. On the middle there is the TP Type window where the specimens geometry must be chosen and the dimensions introduced. With this dimensions, geometry type and material properties the Supersonic software calculates the stress conversion factor which is represented in the bottom left. On the right there is a cell to input the desired stress and under the cell the program displays the correspondent displacement. There is also an option for intermittent driving tests that allows materials that can not be run continuously due to high temperatures to cool down during the stop time(T_{off}). As the material tested has an high heat dissipation factor, the tests in this research can be run continuously which allows the experimental test to be done faster. In the lower right part of the page is a Test End Condition where the maximum number

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of cycles is set (which usually is set for the defined runout) of $1E9$ cycles and the software indicates the estimated test time for that number of cycles with the T_{on} and T_{off} set before. The maximum frequency fluctuation is also set in this window and for the Al6082-T6 smooth specimens was set for 160 Hz.

The screenshot shows the 'Test Condition' tab of the 'UltraSonic Fatigue Software Ver1.02'. The interface is divided into several sections:

- TP Material:** Material Name (AL6082_T6), E : Young's modulus(MPa) (70546), ρ : Density(g/cm³) (2.73), and a Comment field.
- TP Type:** A diagram of a specimen with dimensions L1, L2, D1, and D2. Below the diagram, 'Sarcutapa Type(Chord)' is selected. Dimensions are listed: D1 : Max diameter(mm) [10.00, 5.99 - 20.00], D2 : Min diameter(mm) [5.00, 1.00 - 8.35], L1 : Chord Length(mm) [50.00, 1.00 - 100.00], and L2 : TP Shoulder Length(mm) (16.90).
- Test Condition:** Includes 'Fluctuating Stress Test' (unchecked), 'Nominal Test Amplitude(MPa)' (112), 'TP Side Amplitude(um)' ([39(51) - 158], 26.95), and 'Intermittent driving' (unchecked) with 'Oscillation time(msec)' (500) and 'Stop time(msec)' (100). A diagram shows a specimen with a length of 490.0.
- Test End Condition:** Includes 'Max Cycle (cycle)' (1.000E+09), 'Estimate test time' (13:53:20), and 'Fluctuation band of test frequency (Hz)' (160).

Figure 4.16: Supersonic Test Condition

In the Table 4.4 a comparison between the test duration of specimens of Al6082-T6, that can be run continuously, with specimens of S690, that needs a T_{off} of 400 ms for every 180 ms on, which lowers the number of cycles per second from 20.000 to 6.101.

Table 4.4: Test duration for S690 vs Al6082-T6 materials

Material	Duration			
Cycles	1e6	1e7	1e8	1e9
S690	3min	27min	4h 33min	1day 21h 31min
Al6082-T6	1min	9min	1h 24min	14h 24min

To start the test it is needed to switch for the Test Execution page shown on the Figure 4.17. In this page the number of cycles done can be monitored, also as the frequency of the test and the stress and displacement applied to the specimen. The collected data can be chosen between logarithm or linear. In this research the linear option was chosen and after the test interval was defined and adjusted for

the number of cycles pretended. For a test with an end condition (runout) of $1E9$ cycles, the chosen interval for data acquisition was $2E4$ cycles, from a start cycle of $2E4$ (minimum allowed value) to an end cycle of $1E9$ cycles. In the end of each test the data must be saved with the name of the test.

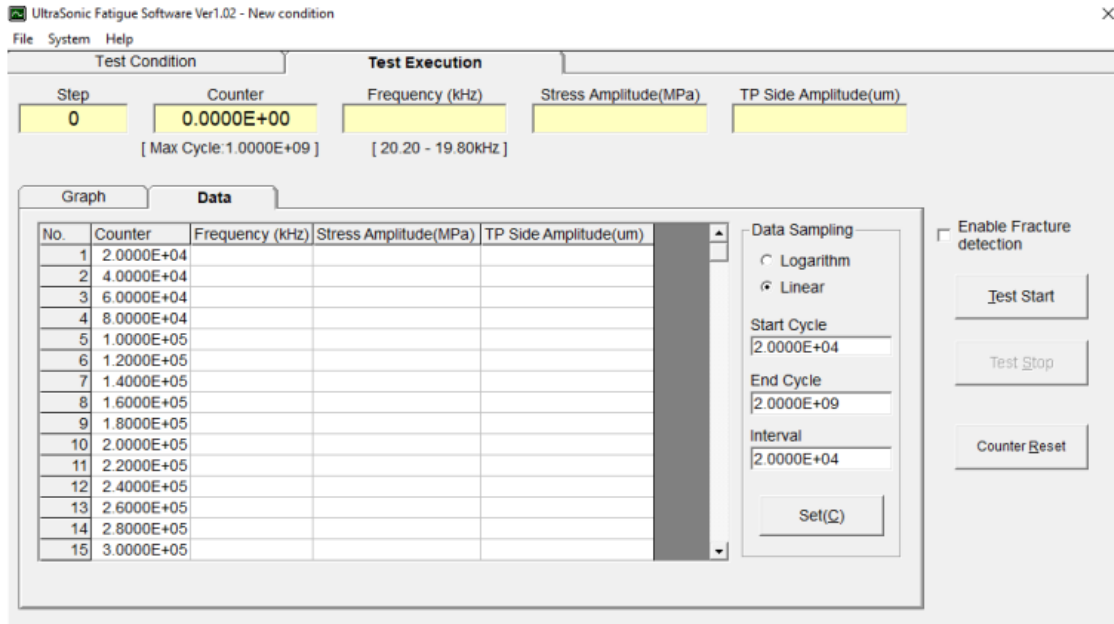
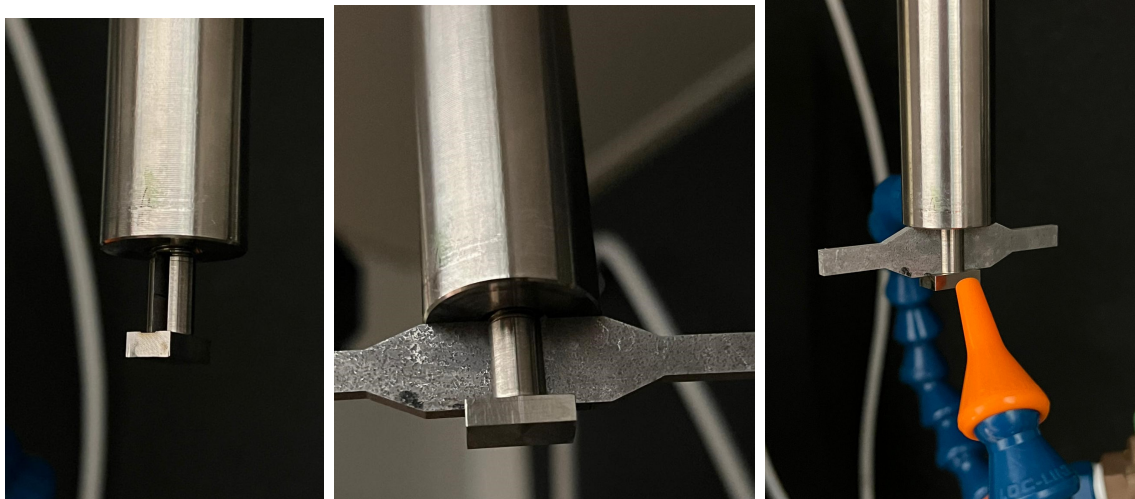


Figure 4.17: Supersonic Test Execution page

4.2.1.2 Flat Specimen test in the Shimadzu USF-2000

Now the process of tightening the flat specimen will be described. This process is illustrated in the Figure 4.18. First the custom screw must be screwed by hand to the horn (Figure 4.18a). It must be screwed until an opening close to 10mm is left. At this point the flat specimen must be inserted into the opening of the screw. The flat specimen has a contact zone with the horn of 19 mm, the same dimension of the diameter of the horn. This helps to center the flat specimen. After centered it must be screwed by hand (Figure 4.18b). After being tightened by hand it must be checked to make sure it is still centered and then it is tightened with an 11 mm head and the torque wrench to 5 Nm. This value is lower than the 10 Nm on the smooth specimen due to the opening in the screw lowering its strength and to the thin thickness of the specimen. As with the smooth specimen, the tightening of the specimen is repeated until the click, twice to make sure of the torque applied and specimen being well secured. Figure 4.18c shows the flat specimen ready to start the test.



(a) Screw in horn (b) Specimen ready to tightening (c) Flat specimen test ready

Figure 4.18: Flat specimen tightening at USF-2000 machine

Before positioning the electromagnetic probe under the screw a check frequency must be performed to ensure that the system is in good operational state. The same process of calibration of the probe must be performed and for the flat specimen with a titanium screw the values for the calibration factor ranged from 174.00 to 179.00 mV.

Unlike the smooth specimens that the Supersonic software calculates the applied stress depending on the material properties and dimensions, for the flat specimens the stress conversion factor must be calculated with the help of the simulations done through Abaqus and then inputted into the window Stress conversion factor (MPa/ μm) on the Test Condition page as it shows in the bottom left of the Figure 4.19.

The screenshot shows the 'UltraSonic Fatigue Software Ver1.02' window. The 'Test Condition' tab is active, displaying various parameters for a flat specimen test.

TP Material:

- Material Name: AL6082_T6
- E :Young's modulus(MPa): 70546
- ρ :Density(g/cm³): 2.73
- Comment: (empty text area)

TP Type:

- Diagram: A schematic of a flat specimen with dimensions L1, L2, D1, and D2.
- Sarcutap Type(Chord): (dropdown menu)
- D1 :Max diameter(mm): 10.00 [5.99 - 20.00]
- D2 :Min diameter(mm): 5.00 [1.00 - 8.35]
- L1 :Chord Length(mm): 50.00 [1.00 - 100.00]
- L2 :TP Shoulder Length(mm): 16.90

Stress conversion factor(MPa/um):

- ☒ Use input value: 8.505

Amplifier output correction factor:

- 1.000 [Adjust correction factor]

Test Condition:

- ☐ Fluctuating Stress Test
- Nominal Test Amplitude(MPa): 124
- TP Side Amplitude(um): [79(105) - 323] 14.58
- ☐ Intermittent driving
- Oscillation time(msec): 500
- Stop time(msec): 100
- Diagram: A schematic of a specimen with a central section of length 490.0.

Test End Condition:

- Max Cycle (cycle): 5.0000E+09
- Estimate test time: 2days 21:26:40
- Fluctuation band of test frequency (Hz): 200

Figure 4.19: Test condition flat

4.3 Experimental apparatus for Rumul Electromagnetic system

For the tests performed at 114-130 Hz an HCF machine from Rumul was used. This machine is equipped with a 150 kN load cell. Compared with the Shimadzu machine, the tests performed at Rumul are usually longer due to the lower frequency. The frequency of the tests depends of the material, the type of specimens and the activated masses of the oscillating system. There are 3 masses on the top of the machine that allow to vary the frequency of the test. These frequencies range from 40 Hz to 260 Hz.

The Ruumul machine can apply dynamic loads superimposed to static loads. This allows to perform tests with various stress ratios, opposed to the USF-2000 Shimadzu machine where a ratio of -1 is mandatory.

The static part of the load is applied by a ball spindle with a preloaded double-nut which is driven by a low-backlash gearbox and a servomotor. This allows to adjust the static load during the dynamic operation in the complete range of the nominal load (100% compression up to 100% tension).

The dynamic part mainly consists of the mass m_1 (1), the counter mass m_0 (2), the elasticity of specimen (3), springs and all other elasticities and masses within

the dynamic load flow. These parts form the oscillating system (resonator) which is controlled and excited by the Rumul Magnodyn drive in its resonant frequency. The load cells measure the load applied.

Table 4.5: Rumul legend

Number	Component
1	Main mass m_1 variable in 8 steps
2	Counter mass m_0 (T-slotted table)
3	Specimen
4	Rumul load cell
5	Rumul Magnodyn excitation system,
6	Preload springs for static load
7	Load frame columns
8	Ball bushings
9	Movable lower cross head
10	Screw spindle
11	Spindle drive with servomotor
12	Vibration absorbing supports

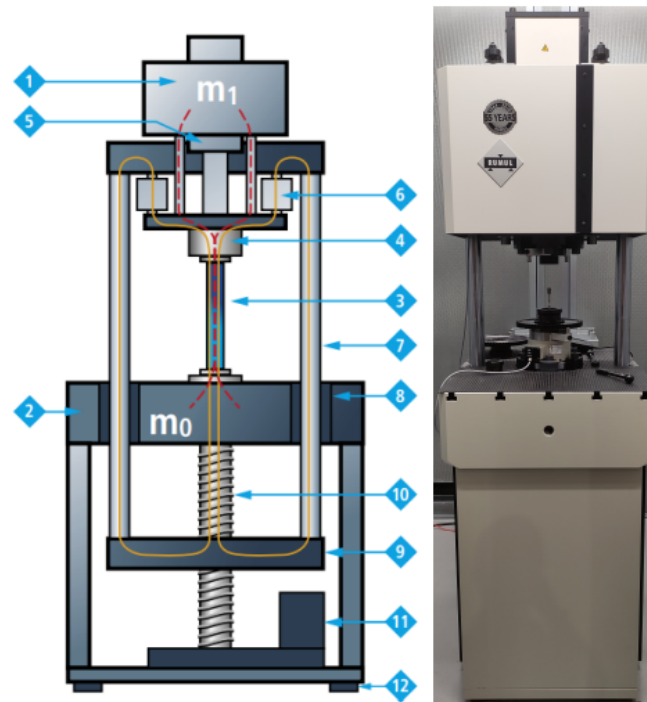


Figure 4.20: Rumul resonance system scheme

The specimen is mounted on a threaded component, which is coupled by toothed disks and attached to the machine. Here the specimen protection is turned on, which allows the spindle drive to move automatically to avoid overloading the specimen.

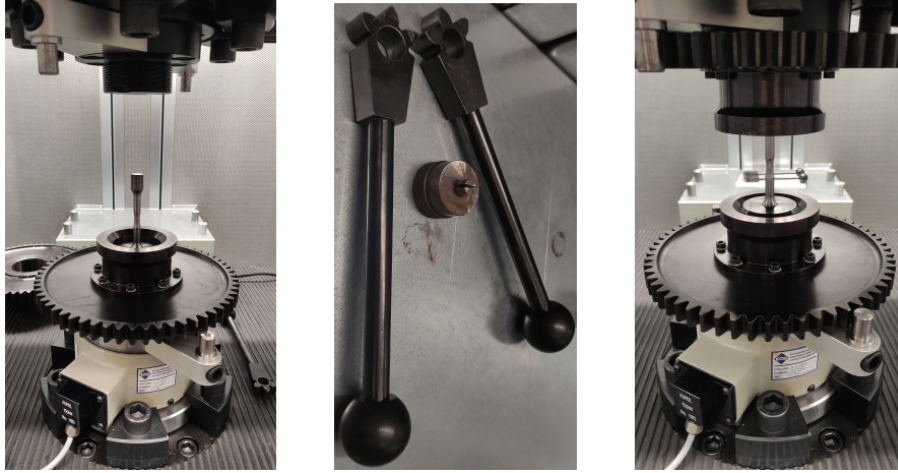


Figure 4.21: Rumul assembly components

4.4 Stress validation for 20 kHz cyclic tests

In order to validate the experimental campaign and to assure the values presented from the Supersonic software the use of strain gauges is essential.

In the smooth specimens the strain gauge was positioned in the zone of smaller area. In the flat specimens the strain gauge was positioned under the reduction zone where the stress is higher. For the 115-130 Hz specimens the stress validation with the use of a gauge was not performed because the Rumul machine has a load cell.

4.4.1 Strain gauge preparation

In order to glue the strain gauge (C5K-06-S5145-350-33F) to the specimens, it is needed to follow a process, which is summarised in table 4.6.

Table 4.6: Steps to use strain gauge

Step	Task
1	Degrease specimen surface with acetone
2	Place a drop of M-Prep Conditioner A
3	Clean the surface with M-Prep Neutralizer 5A with gauze
4	Place strain gauge with welds facing the glue tape
5	Stick tape with the gauge to the specimen in the critical section
6	Confirm that the grid is close to the desired location and well oriented
7	Bend the tape revealing the strain gauge
8	Pass M-Bond 200 catalyst 10 times in the bottleneck and then on the gauge surface
9	Apply glue to the specimen in the critical section
10	Press the strain gauge to the specimen for 1 minute
11	Remove the tape and check with multimeter the 350 Ω resistance between red and black wire

The three wires (red, black and white) were then connected to the circuit. To obtain the voltage difference it was used Elsys Strain Gauge Amplifier MK2 (where the gain (G_{amp}) was defined as 10 and for this gain the amplifier has a bandwidth of 1.5 MHz) and the Kistler LabAmp Type 5165A DAQ and software. All the gauges used had a gauge factor (G_f) of 1.93.

The value of the gauge factor is related to strain measurements through the equation 4.1:

$$G_f = \frac{\Delta R_3/R_3}{\Delta L_G/L_G} = \frac{\Delta R_3/R_3}{\varepsilon} \quad (4.1)$$

with L_G standing for the resistor length.

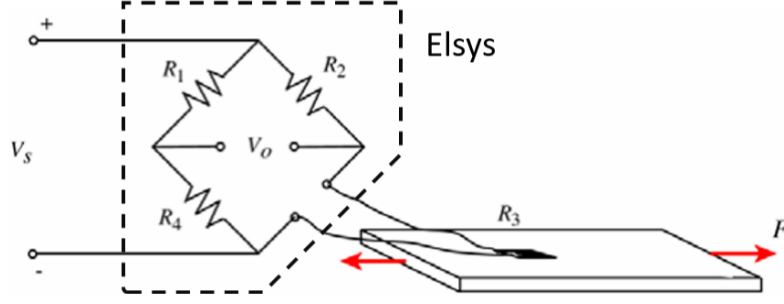


Figure 4.22: Quarter bridge installation-one active gauge

Figure 4.22 shows a quarter bridge circuit installation to measure the axial strain on a bar, with one active gauge, with the output voltage (V_0) dependent from the supply voltage (V_S) and calculated by:

$$V_0 = \left(\frac{-\Delta R_3/R_3}{R_1 + R_2 + R_3 + \Delta R_3/R_3 + R_4} \right) V_S \quad (4.2)$$

and due to the same resistance of all the resistors:

$$V_0 \approx \left(\frac{-\Delta R_3/R_3}{4} \right) V_S \quad (4.3)$$

If the gauge factor and gauge amplifier factor are implemented in the equation 4.3, the value of V_0 can be represented by:

$$V_0 = -\frac{G_f \varepsilon}{4} G_{amp} V_S \quad (4.4)$$

and from this the value of the strain can be calculated as shown in the equation 4.5.

$$strain(\varepsilon) = -\frac{4V_0/V_S}{G_f G_{amp}} \quad (4.5)$$

To obtain the stress, the measured strain must be multiplied by the Young Modulus has shown in the equation 4.6.

$$\sigma = \varepsilon * E \quad (4.6)$$

Then the Scilabs Fourier Function Transformation program reads the wave from the acquired file and provides the highest value.

4.4.2 Measurement results with strain gauges on smooth specimens (20 kHz)

The specimen Sh16 from the first batch was one of the ones where a strain gauge was used. For this specimen the value of 136 MPa was desired and inputted into the Supersonic software. In the table 4.7 there is a comparison between the values obtained from the gauge reading and values obtained by the electromagnetic probe, also as a percentage difference between both. In the last line of the table there is an error evaluation of the value inputted into Supersonic and the value read by the gauge.

Table 4.7: Strain gauge and probe measurements on specimen Sh16

Solicitation	Gauge (MPa)	Probe (MPa)	Error Gauge-Probe (%)
20% (calibration)	52.66	52.84	0.33%
40% (calibration)	103.56	104.02	0.45%
136 MPa	131.02	131.29	0.20%
Solicitation	Gauge (MPa)	Error Supersonic-Gauge (%)	
136 MPa	131.02	3.80%	

While the error between the readings of the strain gauge and the readings of the electromagnetic probe is very small (less than 0.5 % in every measurement) there is a significant error (3.80 %) when comparing the values read with the probe and the value inputted into Supersonic.

This discrepancy is seen in the Sh16 specimen but in others, like the Sh6, the Supersonic stress is coherent with the values read by the strain gauge and the probe. Table 4.8 shows the difference between the values read by the probe and the strain gauge, where the difference is only 0.06 %, but in this case the difference between the strain gauge and the value inputted into the Supersonic is 0.19 %, an error that indicates that Supersonic is accurate.

Table 4.8: Strain gauge and probe measurements on specimen Sh6

Solicitation	Gauge (MPa)	Probe (MPa)	Error Gauge-Probe (%)
140 MPa	139.73	139.65	0.06%
			Error Supersonic-Gauge (%)
140 MPa	139.73		0.19%

The data read by the strain gauge and the corresponding stress is displayed on the Figure 4.23. The left top image represents the complete signal read. The right top image represents the pulse to be analysed. The left bottom image shows the sinusoidal wave of displacements and the right bottom image uses the conversion factor (MPa/ μm) to obtain the stress applied.

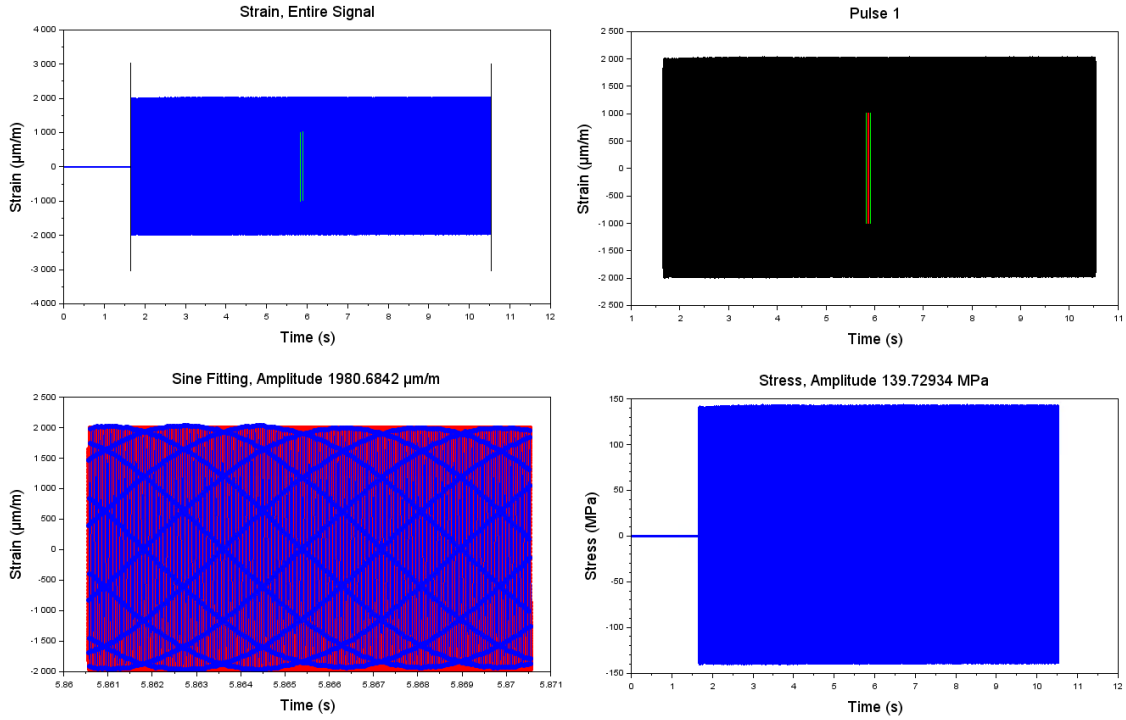


Figure 4.23: Strain measured on Sh16 by the gauge and corresponding stress

4.4.3 Measurement results with strain gauges on flat specimens (20 kHz)

Using a strain gauge on flat specimens is more complex than using them on smooth specimens. The geometry of the flat specimen does not allow to place the strain gauge in the critical section due to the radius of the zone. This radius would deform the gauge and that would impact the values read.

In order to obtain useful and reliable values the strain gauge was glued to the side of the specimen, as shown in the Figure 4.24.

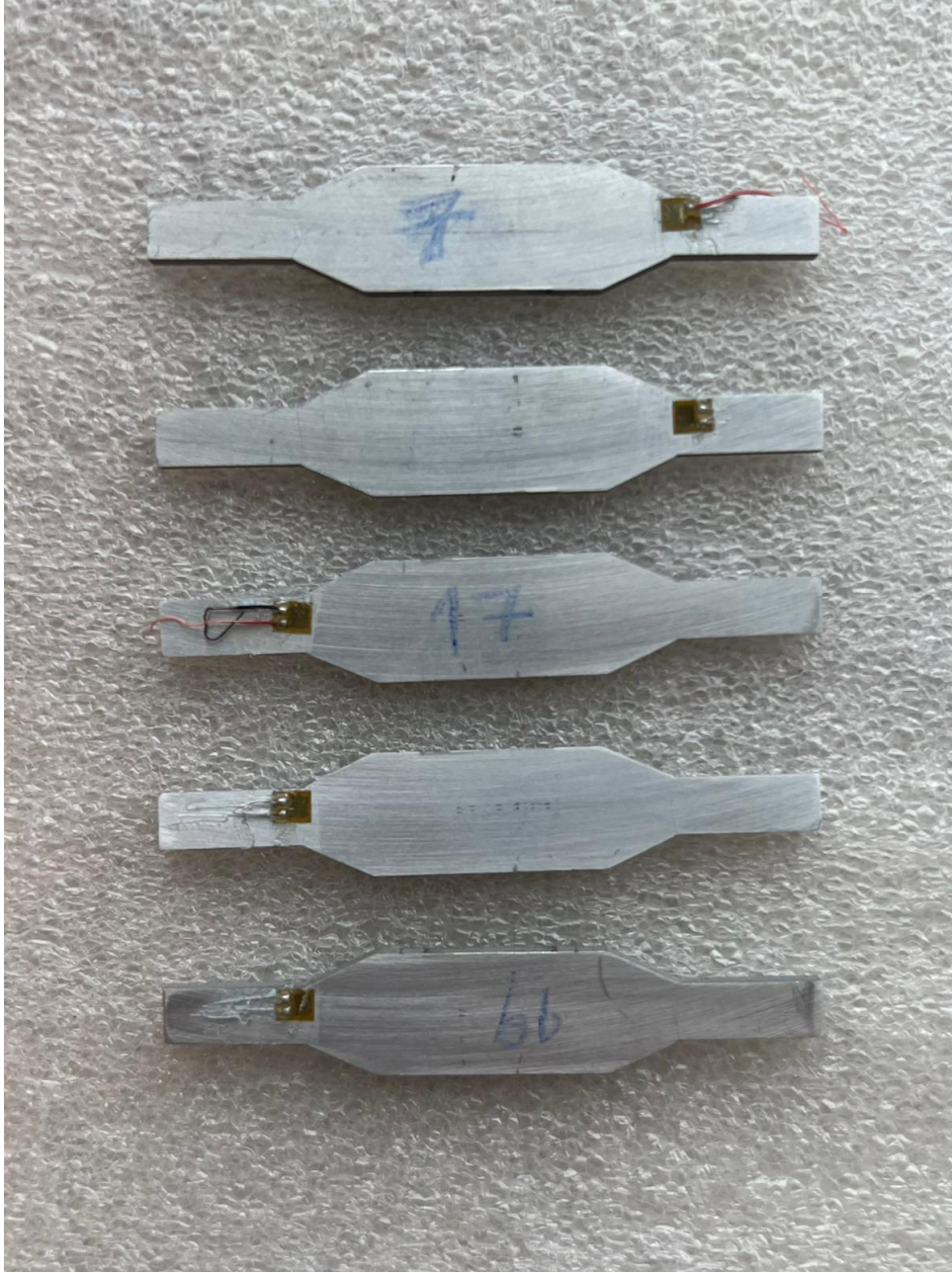


Figure 4.24: Flat specimen with strain gauge

After the gauge had been glued, the specimen was placed in the Mitutoyo measuring microscope (represented in Figure 4.25), that allows to obtain the relative position of the gauge to the corner of the specimen. This relative position must be precise in order to obtain the correct value from the simulation in Abaqus. In this software the element that corresponds to the measured location is selected and the strain values corresponding to a certain displacement of the base of the screw is obtained and a factor is calculated (MPa/μ).



Figure 4.25: Flat specimen in Mitutoyo measuring microscope

After this the test can start. During the test the displacement of the base of the screw is measured with the electromagnetic probe. This value of displacement, together with the factor calculated before, allows to obtain strain in the strain gauge area.

The Figure 4.26 shows the two points where the horizontal (x) and vertical (y) distance is measured. The white dot indicates the corner of the specimen and the square the center of the gauge.

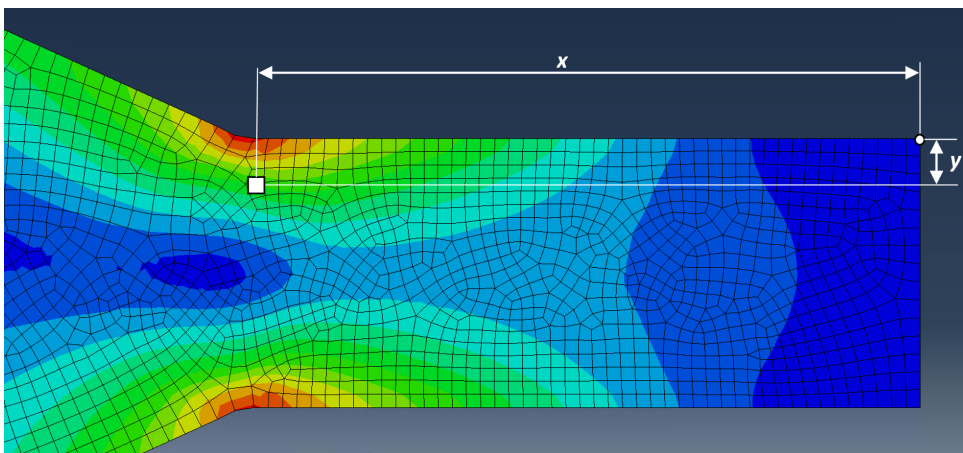


Figure 4.26: Strain along flat specimen and distance to corner

The table 4.9 indicates the relative position of the strain gauge in the flat specimens and the process to obtain this values can be seen in Figure 4.25.

Table 4.9: Gauge relative position on flat specimens

Specimen	Horizontal distance (mm)	Vertical distance (mm)
flat7	11.576	1.469
flat8	10.030	1.469
flat17	11.278	1.696
flat18	11.324	1.531
flat19	11.394	1.363

In the table 4.10 is represented the values of strain measured in two flat specimens with the strain gauge and the expected values (from the FEA) in that zone. The error percentage (FEA/Gauge) is also shown. There is a significant error between the expected and measured strains, with the measured being around 10 % lower. This value of error was considered acceptable because of how sensible the gauge is to the position and also because it measures an area and not an exact point.

Table 4.10: Strain gauge measurements on specimens Flat7 and Flat18

Specimen	Max strain (MPa)	Measured (MPa)	FEA (MPa)	Error (%)
flat7	100	24.24	26.42	8.9 %
flat18	140	25.43	28.42	11.7 %
flat19	124	32.05	34.57	7.9 %

Figure 4.27 displays the data read by the strain gauge and the corresponding stress on the specimen flat7. Each of the images of the figure represent the same that was mentioned for the Figure 4.23, but the signal is acquired from the strain gauge instead of the eletromagnetic probe.

4.4. Stress validation for 20 kHz cyclic tests

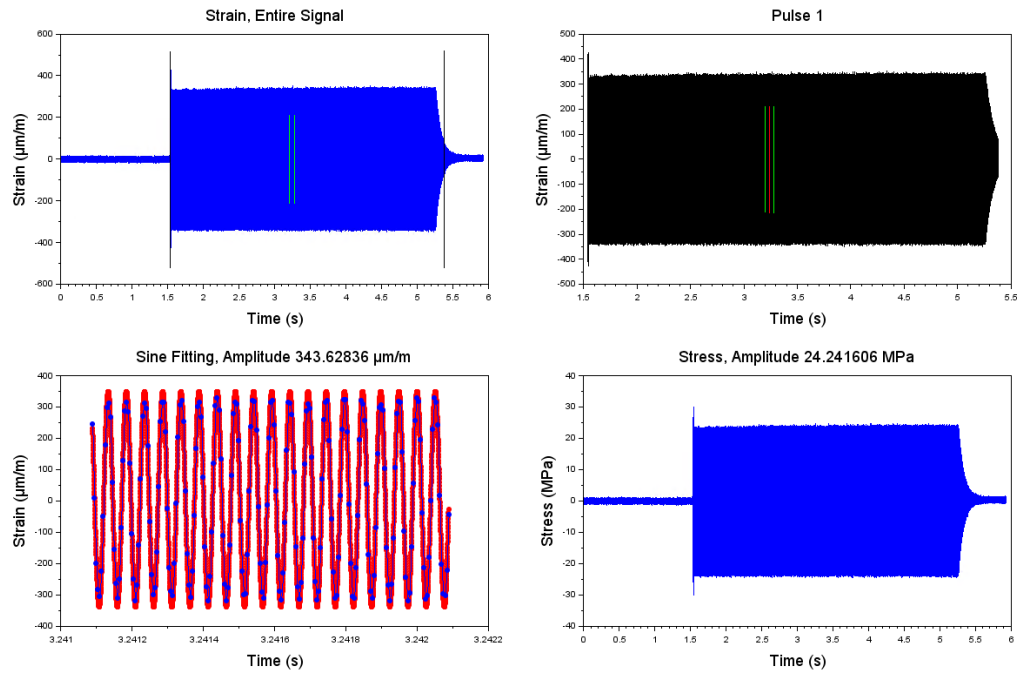


Figure 4.27: Strain measured on Flat7 by the gauge and corresponding stress

Results

In this chapter the results obtained from all the tests performed will be presented and discussed. The S-N curves from all the campaigns are presented here. There will also be done an analysis of the fracture surface from the specimens.

5.1 Fatigue S-N curve - Al6082-T6 data

During this dissertation various fatigue tests of the Al6082-T6 aluminum alloy were performed with the goal of obtaining the S-N curve of the material. One of the difficulties in the execution of tests at supersonic frequencies (20 kHz) is to dissipate the heat generated during the test. Fortunately, this was not a problem for this material. Despite a slight increase in temperature (around 2 Celsius degrees) at the start of the test, it stabilized shortly afterwards and remained the same even for long tests (6 days). When crack propagation begins, there is a peak temperature increase due to the reduction in the resistant section area, but crack propagation was very limited comparing with crack initiation,

In total 106 tests were performed with this alloy. From those tests, 86 were tension compression tests of smooth specimens with stress ratio $R=-1$. The other 20 tests were bending tests with ratio $R=-1$ with specimens named "Flat" obtained from thin (2 mm) metal sheets.

In the Table 5.1 the name of the test campaigns is presented with the number of valid tests performed in each campaign, the starting frequency and for the hourglass specimens the diameter of the smaller section.

All the round 2 test series of hourglass specimens were performed in order to compare the results of specimens with different size section and to compare the effect of frequency. This round 2 were manufactured from Al6082-T6 circular bars

with the same diameter (25 mm) and from the same batch to avoid any material source bias.

In the next sub-chapter comparisons of the results obtained from the different campaigns are presented. The frequency effect will be mentioned, as the effect of different gauge sections (size effect).

Table 5.1: Fatigue test campaigns of Al6082-T6

Name of test campaign	Number of tests	Frequency	Gauge section
Smooth, Round 1	22	19.97 kHz	5 mm
Smooth, Round 2	21	19.97 kHz	5 mm
Rumul, M16 Round 1	7	114 Hz	7 mm
Rumul, M16 Round 2	15	114 Hz	7 mm
Rumul, M22 Round 1	6	129 Hz	10 mm
Rumul, M22 Round 2	15	129 Hz	10 mm
Flat	20	19.60 kHz	-

5.1.1 Fatigue S-N curve - Size Effect

To test the size effect on the fatigue life, tension-compression tests in the Rumul machine, with specimens with 7 mm and 10 mm of diameter were performed. Figure 5.1 portrays the fatigue life of these smooth specimens.

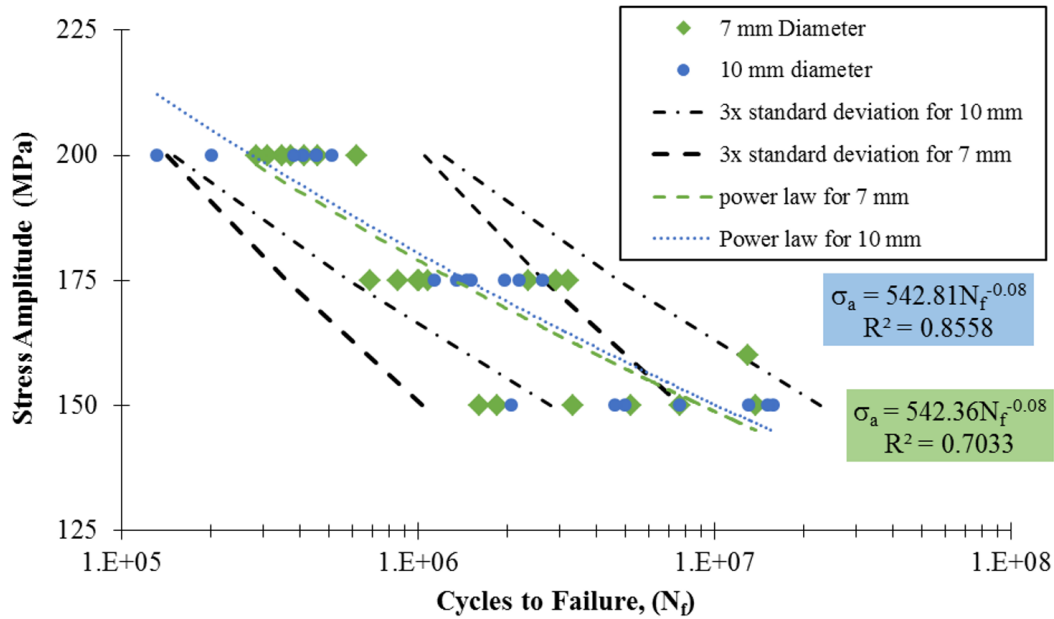


Figure 5.1: Comparison of fatigue life of specimens with 7 vs 10 mm of diameter

The black broken dash lines and the dash dot lines represent three standard deviation for the M16 and M22 threaded Rumul specimens respectively.

As shown in the Table 5.2 the specimens with 10 mm of diameter, compared with the ones with 7 mm have a cross section area of more than the double and 43 % more surface area.

Table 5.2: Rumul specimens size comparison

	Rumul M16	Rumul M22	% difference
Gauge diameter	7 mm	10 mm	+43 %
Cross section	38.48 mm ²	78.54 mm ²	+104 %

From the results obtained with these tests, and with the analysis of the figure 5.1 it can be concluded that, for this material, in contrary to what was expected from the literature, the diameter had no significant effect on the fatigue life of the specimens for the tested sizes. The campaigns shows an almost identical curve for the two size of specimens with 3 well defined stress levels compared. The runout value was set at 2E7 cycles in this tests which correspond to close to 2 days test duration, and this value was not reached in any test. The initially set value of 1E7 was reached with the specimens with 7 and 10 mm tested in the first campaigns and was then adjusted to allow the tests running in a finite life regime.

As the results obtained in these campaigns didn't show any significant different it will be considered that the size did not impact the results of the fatigue life for the sizes tested in this research.

5.1.2 Fatigue S-N curve - Frequency Effect

With the size comparison completed follows the analysis of the frequency effect on the results. The smooth specimens tested at 20 kHz have a different diameter (5 mm) compared to the specimens tested at Rumul but for what was established before there is no effect of the size. Figure 5.2 portrays the fatigue lives of the second campaign of smooth specimens tested at USF2000 and the smooth specimens tested at Rumul.

From the figure analysis, a significant difference can be seen in the results of fatigue life. The S-N curve of the specimens tested at 20 kHz shows a frequency effect on the fatigue life, and an increase in the cycles before failure.

The results from the comparison of the tests between the Rumul and Shimadzu

Smooth specimens is shown in the Table 5.3 where is seen a significant increase in the life of the specimens tested at 175 MPa and 150 MPa. The specimens tested at 20 kHz increased their fatigue life 4 times at 175 MPa and 6 times at 150 MPa.

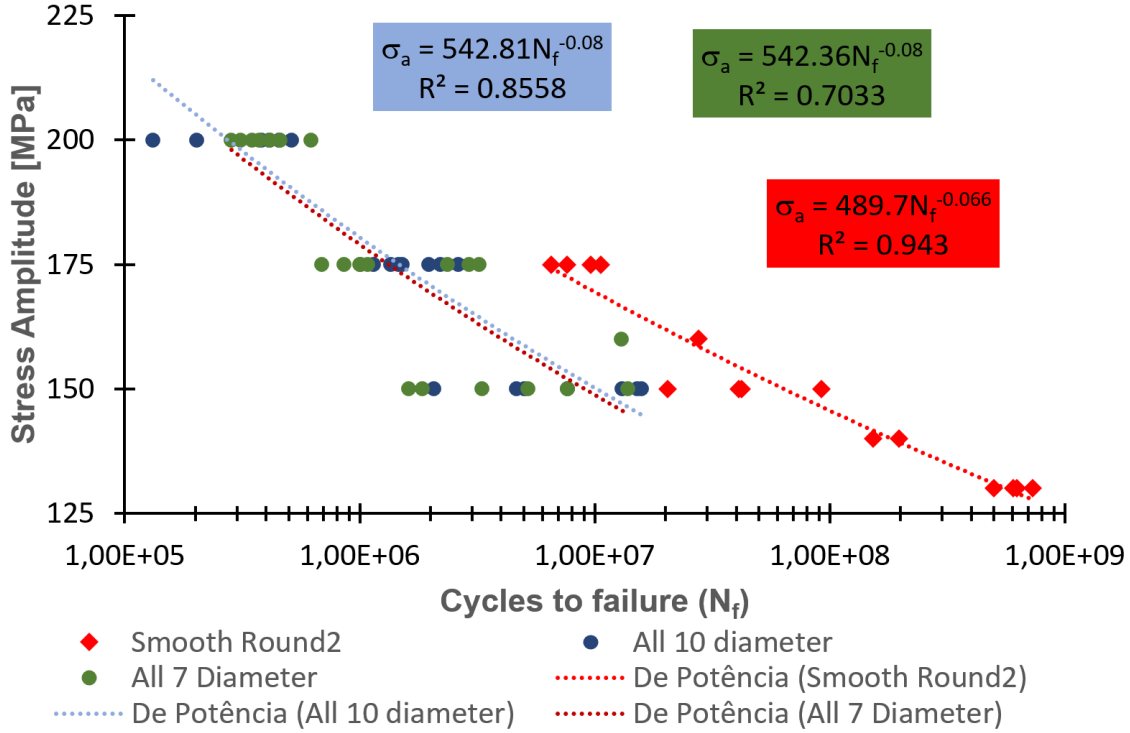


Figure 5.2: Comparison of fatigue life of specimens tested at different frequencies

Table 5.3: Life, diameter and frequency between tests

	100 Hz		20 kHz
	Rumul M16	Rumul M22	Smooth
Frequency	115 Hz	130 Hz	20 kHz
Diameter	7 mm	10 mm	5 mm
Expected life at 175 MPa	1.24E6		5.18E6
Expected life at 150 MPa	9.18E6		5.76E7

5.1.3 Fatigue S-N curve - Surface Roughness Effect

It is well known that the surface roughness can affect the fatigue life of the specimens. In order to test the effect of the surface finish in the fatigue life of Al6082-T6 specimens, 6 tests of smooth polished specimens were performed on the USF2000 machine and compared with the results obtained from specimens that have

not been polished (just turned). In the Figure 5.3 the test result is portrayed and a comparison can be done.

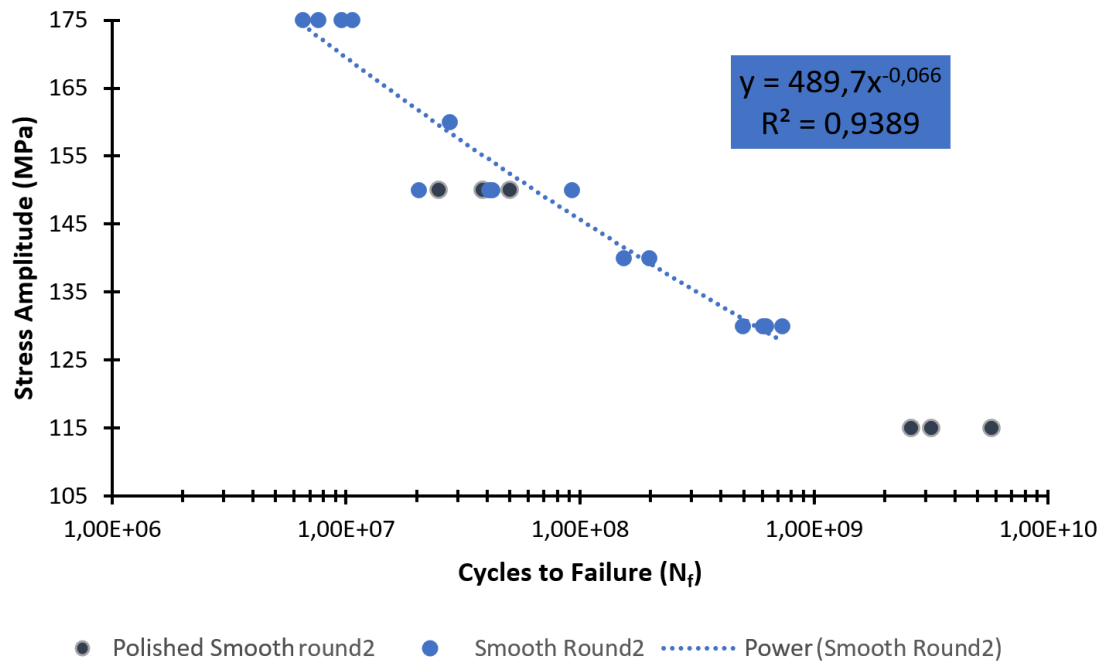


Figure 5.3: Comparison of fatigue life of Smooth polished specimens

From the results of this tests one can not verify that a better surface roughness improves the fatigue life of specimens with the Al6082-T6 Alloy.

In the Table 5.4, the results of the tests performed at 150 MPa are shown. From the average fatigue life can be seen that the results were actually opposite to the expected, the polished specimens with better surface roughness ended with lower mean fatigue life (less 27% in the number of cycles).

Table 5.4: Smooth Specimens tested at 150 MPa

Specimens without polishing		Polished specimens	
Specimen	Number of Cycles	Specimen	Number of Cycles
Sh2m	9.21E7	Sh16m	3.84E7
Sh6m	4.22E7	Sh17m	5.01E7
Sh11m	2.05E7	Sh18m	2.49E7
Average	5.16E7	Average	3.78E7

From the S-N curve resulting only from the results of specimens not polished, the expected life for tests performed at 115 MPa is $3.42E9$. If the results of the 3

polished specimens tested at 150 MPa are added to the curve the expected life for 115 MPa raises to 3.84E9, not so significant change. In the Table 5.5 the fatigue life of the specimens tested at 115 MPa is shown, also with the average life. The value for the average life is within the expected values being 12% less than the expected without the test Sh16m to Sh18m and being the same value if the results of these test are added.

Table 5.5: Polished Smooth Specimens tested at 115 MPa

Test number	Number of Cycles
Sh19m	5.75E9
Sh20m	2.60E9
Sh21m	3.17E9
Average	3.84E9

From the analysis of the results, the surface roughness seems not affecting the fatigue life of specimens of this aluminum alloy tested at the USF2000 machine. Figure 5.4 shows two specimens, one polished (specimen on the right) and the other one without polishing (specimen on the left). The surface aspect can be compared as well as the crack path.



Figure 5.4: Surface and crack path comparison for polished and not polished smooth specimens

5.1.4 Fatigue S-N curve - Smooth Specimens from different batches

As was said before there were performed two test campaigns at 20 kHz for the smooth specimens. The first campaign was performed with specimens obtained from circular bars with 50 mm of diameter and from each section were obtained 7 specimens. In the second campaign, the process for manufacturing the specimens was changed and they were obtained from circular bars with 25 mm of diameter. Figure 5.5 portrays the fatigue life of the two campaigns, also as a trendline of each campaign.

It can easily be seen results with a significant difference between the two campaigns. The specimens of the second campaign, for higher stresses, would have a longer fatigue life. In the Table 5.6 the fatigue life on the stress levels of 150 and 140 MPa is compared between the two campaigns. For these two levels the second campaign achieved results with significant higher life. The average number of cycles of the second campaign was 19.8 and 16.3 times higher at 150 and 140 MPa respectively, when compared with the first campaign.

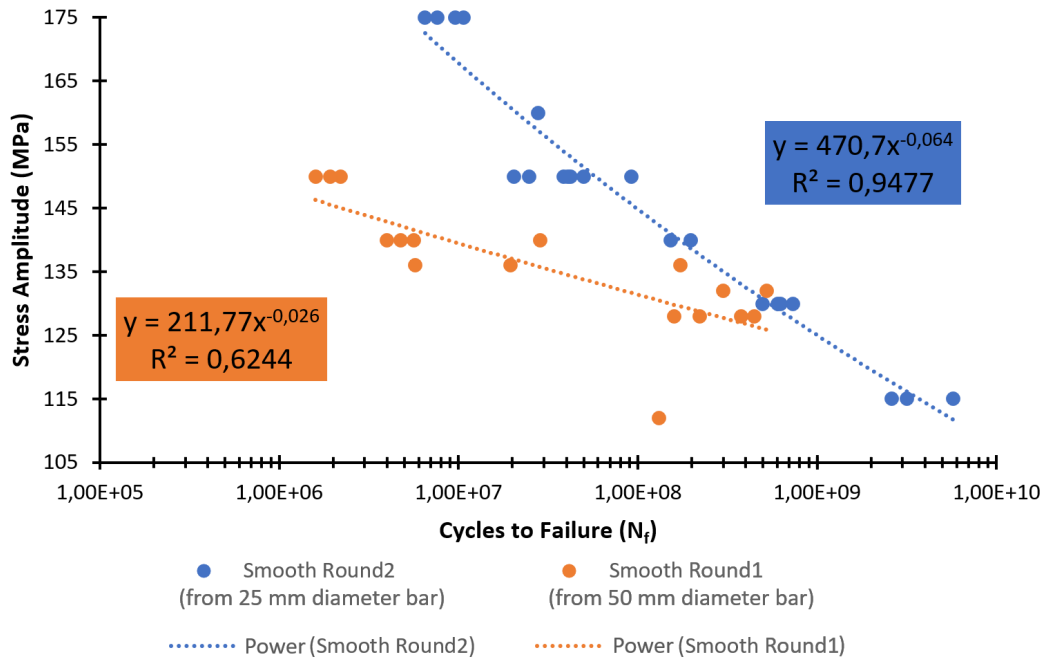


Figure 5.5: Fatigue life of two campaigns of smooth specimens (20 kHz)

Table 5.6: Campaign comparison of Smooth Specimens tested at 150 MPa and 140 MPa

	1st campaign	2nd campaign
	150 MPa	
Minimum	1.60E6	2.49E7
Maximum	2.20E6	5.01E7
Average	1.91E6	3.78E7
	140 MPa	
Minimum	3.98E6	1.53E8
Maximum	2.86E7	1.97E8
Average	1.08E7	1.75E8

When the stress applied lowers to 125 MPa, the fatigue life of both campaign intersect around $1E9$ cycles. This difference in the fatigue life of the two specimens can be justified with two reasons. Firstly, the material properties changes with the dimensions of the bar, and secondly the manufacturing process may induce residual stresses in the specimen which would affect their fatigue life.

Referring to the first option, bars with diameters up to 20 mm have 295 MPa of

tensile strength and 250 MPa of Yield strength. When the diameter raises to the range of 20 to 150 mm the tensile strength and Yield strength raises to 310 MPa and 260 MPa, respectively. But in the first campaign the specimens were obtained from a bar with a bigger diameter and the fatigue life presented is lower so the justification of the fatigue life being shorter on the first campaign due to different material properties is negated.

Relatively to residual stresses applied during the manufacturing process, the specimens of the different campaigns were produced in different workshops and with different cutting parameters, so this could be a reason for the discrepant results.

In both campaigns, the results obtained show a significant improvement in the performance of this alloy when compared with values from the literature. Multiple researchers ([32][33][34]) obtained fatigue lives of 1E7 cycles with stress amplitudes of 100 MPa but the results from this work show that for the regime of 1E7 cycles the stress applied was around 140 and 175 MPa for the campaign 1 and 2 respectively.

5.1.5 Fatigue S-N curve - Effect of lower stress levels and damage

In the first campaign of smooth specimens when a test was performed with low stress levels and achieved runout it was followed by a test at higher stress levels. It was noticed that contrary to what was expected (that the test at lower stress levels would damage the specimen and reduce its fatigue life) the specimen would be able to perform the same number of cycles before failure as a specimen without any test performed.

For example, in both the specimen Sh4m and Sh5m were performed a first test at 120 MPa. Both specimens achieved the 1E9 number of cycles defined as runout. After runout they were tested at 140 MPa and achieved 5.04E7 and 9.77E6 number of cycles respectively. Then the specimens Sh6m, Sh13m, Sh15m and Sh18m were tested at 140 MPa and only the Sh15m had a fatigue life longer than the prior tested specimens.

In the Table 5.7, the number of cycles of each specimen is shown also as an average of the life with and without prior tests at lower stress. Figure 5.6 complements the Table 5.7 with a visual representation of the life of the specimens.

Table 5.7: Smooth specimens with tests at lower stress

Specimens tested with previous runouts		New specimens	
Specimen	Number of cycles	Specimen	Number of cycles
Sh4m	5.04E7	Sh6m	4.77E6
Sh5m	9.77E6	Sh13m	5.63E6
		Sh15m	2.86E7
		Sh18m	3.98E6
Average	3.01E7		1.08E7

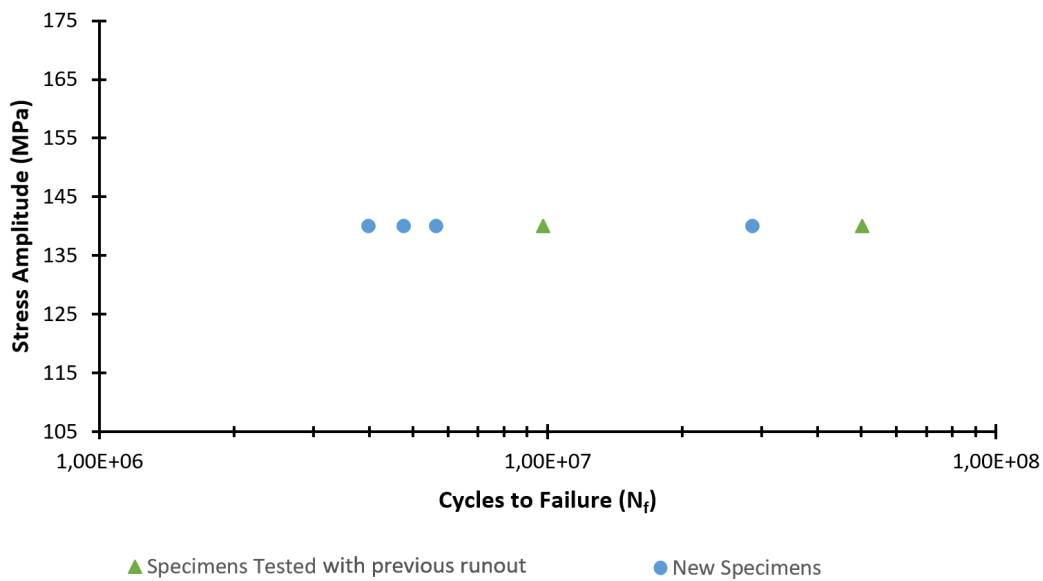


Figure 5.6: Fatigue life of tested and new specimens

5.1.6 Fatigue S-N curve - Flat Specimens Bending Life

Until now, all the tests compared were tensile-compression tests with stress ratio $R=-1$. There were also performed tests with specimens obtained from thin sheets of the aluminum alloy, but these were performed under bending. With a different loading is expected a different S-N curve. Figure 5.7 portrays the fatigue life of the second campaign of smooth specimens tested at USF2000 and the flat specimens, tested at the same frequency.

It can easily be noticed that the flat specimens that had been bend tested have a fatigue life shorter than the smooth specimens. For around 140 MPa the flat specimens have a fatigue life of about $1E7$ cycles while for the same stress amplitude

the smooth specimens lasted for 2E8 cycles, a 20x increase. From the observation of the two S-N curves, it can also be noticed that the Flat specimens curve is a lot steeper and the interception of the two curves occur at 192.4 MPa with a fatigue life estimation of 1.4E6 cycles.

From the analysis of the S-N curve for the flat specimens an horizontal asymptote and infinite life looks to appear around 95 MPa. The maximum number of cycles achieved without runout was 5E7 cycles at 100 MPa. With this same stress applied one of the specimens achieved runout with 8E9 cycles without crack propagation. With lower stress applied (92 MPa) the two tests performed ended with runouts of 8E9 and 1E10 cycles.

From all the tests performed the flat specimen shows a fatigue limit while the smooth specimens do not, even with test with failure around 5E9 cycles when tested at 115 MPa.

Other interesting fact is that for 150 MPa tests the Flat specimens show to have the same fatigue life as the specimens tested at Rumul.

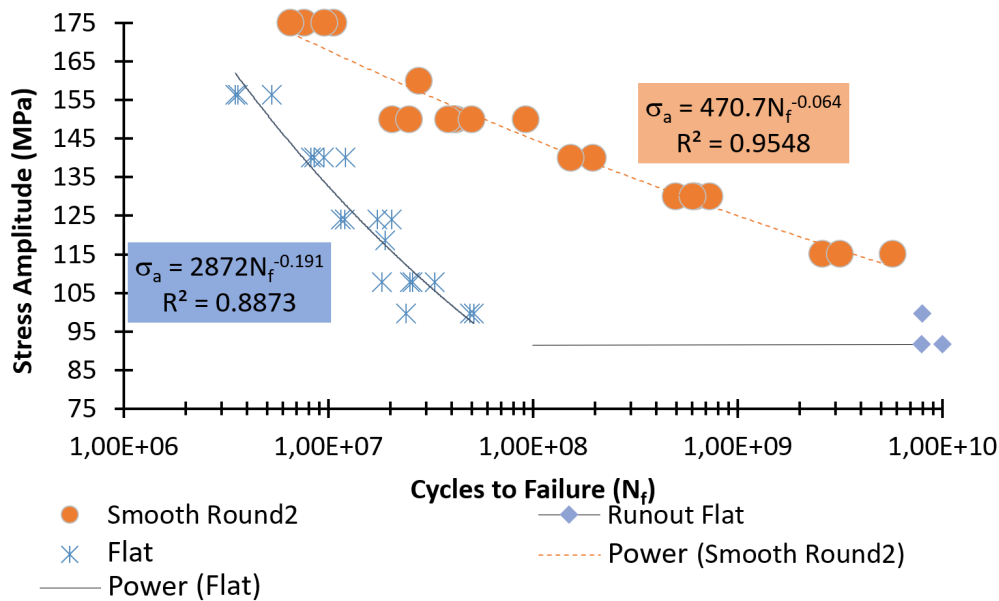


Figure 5.7: Comparison of fatigue life of Smooth vs Flat specimens

Figure 5.8 shows the temperature over the test time on the Sh6m smooth specimen test. The TBox value represents the ambient temperature. After a slight increase at the start of the test, there is a stabilization which is maintained until crack propagation begins, which is accompanied by a rapid rise in temperature until complete failure. Figure 5.9 shows a thermographic image at the instant of crack propagation where is visible the localized heat generation in the crack propagation.

5. Results

To better visualize this event, the video of the crack growth obtained by the thermographic camera is available at the following youtube link:

<https://www.youtube.com/watch?v=WPObNAAA4ZA>

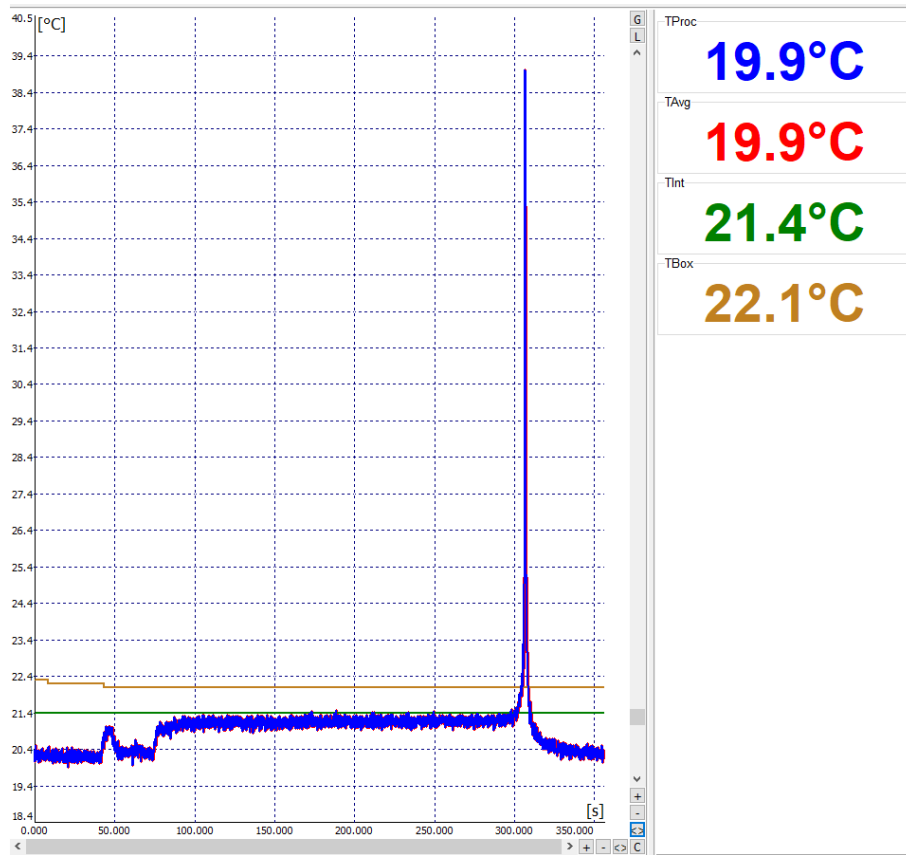


Figure 5.8: Temperature evolution on specimen Sh6m test

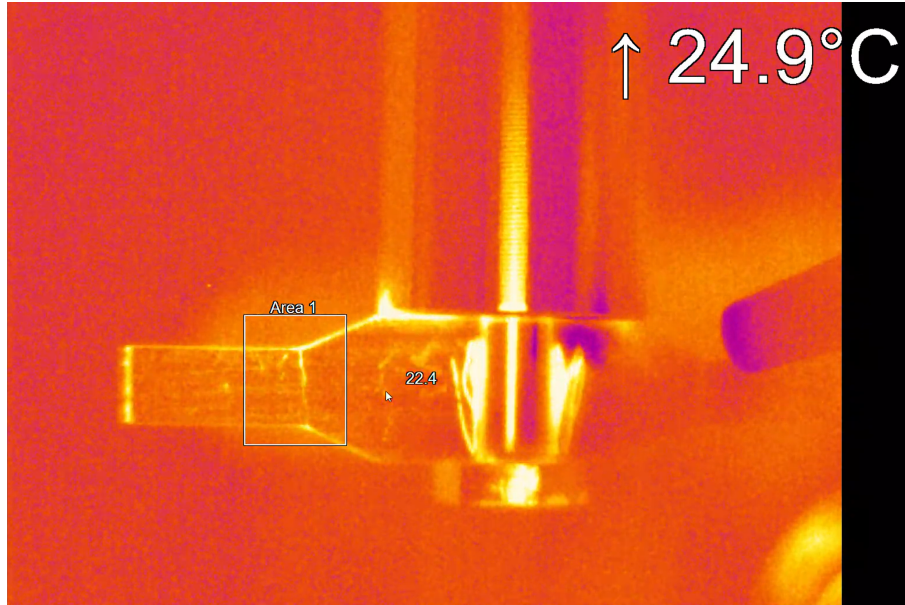


Figure 5.9: Thermographic image at the instant of crack propagation on specimen Flat1

5.2 Fatigue S-N curve - Flat specimens from casting components

An additional 36 tests were performed with Flat specimens obtained from cast components in AlSi10MnMg (Silafont-36) alloy, with bending loading with ratio $R=-1$. These 36 tests were distributed in 5 campaigns. In one of the campaigns, the specimens were in the as cast state while the other campaigns the specimens were submitted to thermal treatments (all the thermal treatments performed are T6 treatments).

Table 5.8 shows the designation of each campaign, the duration and temperature of the solubilization and of the aging. The campaigns 4 and 6 had the same thermal treatment and will be refereed as the same. The campaign 14 is the material without thermal treatment.

Table 5.8: Campaigns thermal treatments

Designation	Solubilization	Aging	Number of tests
4/6	15 mins at 520 °C	3 hours at 180 °C	14
7	30 mins at 490 °C		6
12	3 hours at 490 °C		7
14	-	-	9

5.2.1 Fatigue S-N curve - Effect of duration of Solubilization

Since the campaign 7 and 12 had thermal treatments that only differ in the duration of the solubilization (the temperature was the same, also as the parameters of the aging) their comparison can indicate the effect of the duration of solubilization in the fatigue life of this alloy. The campaign 7 had 30 minutes of solubilization while the campaign 12 had 6 times that duration, 3 hours, being a significant difference.

The graph of the Figure 5.10 shows the fatigue life of the specimens of campaign 7 and 12.

The results of these campaigns indicates that the duration of the solubilization does not affect the fatigue life of this material when subjected to a thermal treatment T6.

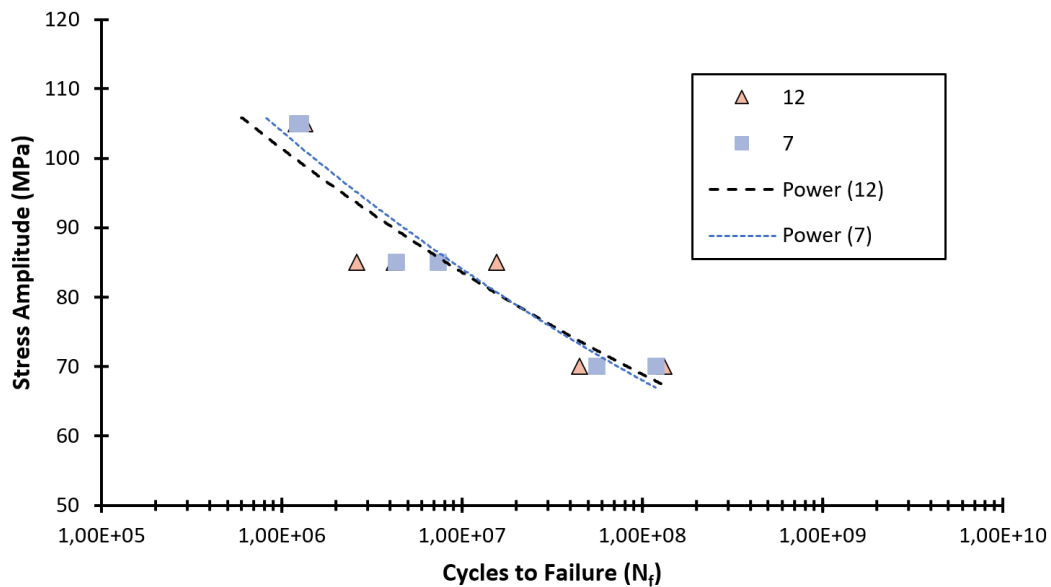


Figure 5.10: Fatigue life of specimens with different solubilization duration

5.2.2 Fatigue S-N curve - Effect of temperature of Solubilization

The thermal treatments of the campaign 6 and 7 had different duration (15 and 30 minutes respectively) but since the results analysed before indicate that the duration of the solubilization does not affect the fatigue life of this material. When these campaigns are compared, the effect of the temperature of solubilization can be investigated. From the campaign 7 to the campaign 6 there was an increase of 30 °C, from 490 to 520 °C.

The graph of the figure 5.11 shows the fatigue life of the specimens of campaign 7 and 6.

The results from campaign 6 show a fatigue limit with runouts at 55 MPa for 1E9 and 1E10 cycles. The results appear to overlap somewhat, and the difference falls within the margin of error/scatter band. The tendency line (power law) indicates a better performance from campaign 6 at higher stress tests and a better performance from campaign 7 at lower stress tests (70 MPa), but there was no tests done at 55 MPa with campaign 7 to confirm the appearance of a fatigue limit.

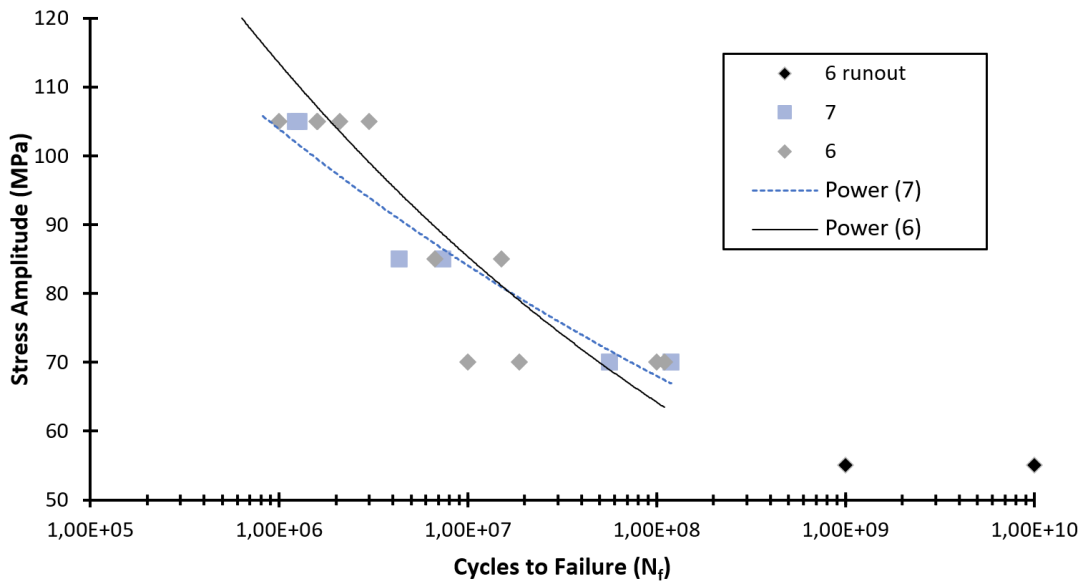


Figure 5.11: Fatigue life of specimens with different solubilization temperature

5.2.3 Fatigue S-N curve - Effect of T6 Thermal Treatment

The specimens of the campaign 14 were obtained from a component in the AlSi10MnMg (Silafont-36) alloy that was not subjected to a T6 thermal treatment. This campaign allows to obtain a baseline and compare the fatigue performance of

specimens with various thermal treatments when compared to the base material.

The graph of the figure 5.12 portraits all successful tests performed with the cast alloy.

From the analysis of the results displayed on the graph one can observe two aspects. First, the fatigue life of the base material at high stress tests (105 MPa) is shorter, with every tested specimen performing worse than the specimens of the campaigns with thermal treatments. In second, when tested with lower stress levels (70 MPa) the base material performs better than the specimens with T6 treatments, with two runouts of $1E9$ and $1E10$ cycles. With this, the specimens from the campaign 14 appear to have a fatigue limit at 70 MPa, higher value than the 55 MPa of the fatigue limit of the campaign 6.

These results indicate that if the goal is to use this alloy in the regime of the VHCF, beyond the Gigacycle, the tested T6 thermal treatments do not favour its performance, reducing the fatigue limit. The best option would be to use the base material.

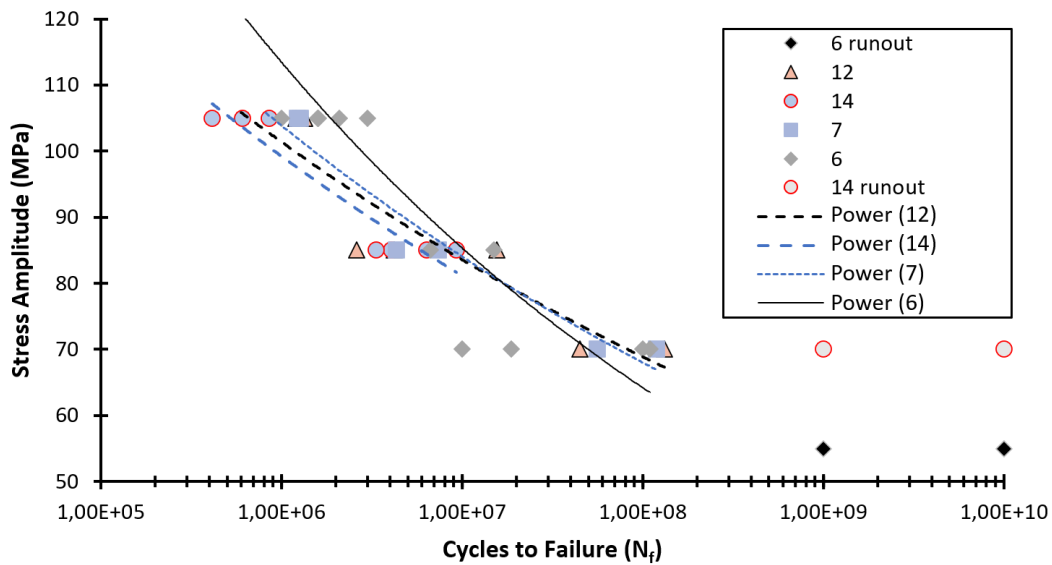


Figure 5.12: Fatigue life of specimens with and without T6 Thermal Treatment

Conclusions and Future Work

6.1 Conclusions

It is concluded that the procedure and geometry developed in this thesis are suitable for obtaining the S-N curve of high pressure die-casting aluminum alloys, using test samples with thin thicknesses.

It was possible to obtain and compare S-N curves for various alloys, with data falling within the VHCF and UHCF regime.

It was concluded that for the Al6082-T6 alloy, in the case of smooth specimens, the S-N curve is not influenced by the size for a variation of 43 percent in surface area and 104 percent in cross section. However, with regard to the effect of the test frequency, it is concluded that it does exist and overestimates the fatigue life of the material by around a decade when compared to the results obtained at frequencies 200 times lower.

It is concluded that for the Al6082-T6 alloy, slight improvements in surface finish obtained by polishing do not improve fatigue life.

It is concluded that for the Al6082-T6 alloy, initial low stress tests do not induce damage to the material, and that they could be even beneficial for increasing the life of the sample.

It can be concluded that for the Al6082-T6 alloy, bending stresses present an S-N curve that is different from the S-N curve for tension-compression tests, with $R=-1$. Despite a much steeper slope, this curve has a fatigue limit value around 92 MPa, with tests without failure up to $1E10$ cycles.

In the case of the AlSi10MnMg alloy, it was also possible to obtain the S-N curves of the heat treatment variants, which showed that thermal treatments do

not favor fatigue performance, reducing the value of stress of the fatigue limit. The best fatigue option would be to use the base material when lives over $1\text{E}7$ cycles are desired.

6.2 Future work

Regarding future work a few ideas are suggested.

Defining a test campaign to analyze the surface stresses in this material after long periods of low stress tests.

It is suggested to perform campaigns of fatigue tests with specimens obtained from deposition material. The verification of the geometry suitability of the flat specimen design with other materials other than aluminum alloys is also suggested. The formulation of this flat specimen geometry would be of high interest.

The fracture surface analysis of tested specimens is also one of the tasks to perform.

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