

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

**MECHANICAL AND MICROSTRUCTURAL
CHARACTERISATION OF THE SPOT WELDING
OF A PASSENGER RAIL VEHICLE**

FRANCISCA MARQUES DE SOUSA BAPTISTA



Master's Degree Dissertation in Material Engineering

Supervisor: Professor Manuel Vieira

September 13, 2024

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Abstract

The austenitic stainless steel type 301L is widely used across various industries due to its excellent corrosion resistance, mechanical strength, and weldability. These characteristics are crucial for the railway industry, which values comfort, safety, and durability in its locomotives, making 301L a common choice for the structure of railway carriages. This master's thesis investigates the suitability of 301L sheets for spot welding, with the aim of optimising this process to reduce time and costs and ensuring their suitability for the sidewalls of railway carriages.

To achieve this, the first phase involved characterising the available material by determining the *Vickers* microhardness, mechanical strength, chemical composition, and microstructure of the four sheets of 301L under study. A difference was detected between the mechanical properties of the High Tensile and Medium Tensile sheets, with the High Tensile reaching higher values than the Medium, probably due to post-rolling tempering heat treatments under different conditions, which may have led to these deviations. Additionally, a high percentage of martensite, around 30%, was detected, explainable by the phenomenon of Work Hardening, which accounts for the high values of hardness, between 403 and 564 HV, obtained for these sheets comparing to the values found in the literature, 241 HV, for the same steel in the annealed state.

Based on the initial characterisation, particularly the values obtained for the mechanical strength and thickness of each sheet, different combinations of electric current, electrode force, and weld cycles were tested to optimise the process for sheets of higher and lower mechanical strength. The best combination found for the equipment *SCIAKY C227SP* was as follows: for the hardest sheet, an electric current of 8.6 kA, with 15 welding cycles and 900 kg electrode force, and for the softest, the best results were obtained with an electric current of 7.6 kA, with 12 welding cycles and an electrode force of 614 kg.

The mechanical results indicate that the optimized parameters provide robust welding, with adequate mechanical properties and nugget size, and a homogeneous microstructure, minimizing defects and ensuring the durability of the welds.

Keywords: AISI 301L Stainless Steel Resistance Spot Welding, Microstructural Characterisation, Mechanical Properties, Transformation-Induced Martensite, Contact Resistance, Railway.

Resumo

Os aços inoxidáveis austeníticos tipo 301L são amplamente utilizados em diversas indústrias devido à sua excelente resistência à corrosão, resistência mecânica e soldabilidade. Estas características são cruciais para a indústria ferroviária, que valoriza o conforto, a segurança e a durabilidade das suas locomotivas, tornando estes materiais comuns na estrutura das carruagens ferroviárias. Esta dissertação de mestrado investiga a aptidão à Soldadura por Pontos das chapas de 301L, com o objetivo de otimizar este processo de ligação, reduzindo tempo e custos, e assegurando a sua adequação para as paredes laterais das carruagens ferroviárias.

Para tal, numa primeira fase, procedeu-se à caracterização do material disponível, determinando-se a microdureza *Vickers*, a resistência mecânica, a composição química e a microestrutura das quatro chapas de 301L em estudo. Detetou-se uma diferença entre as propriedades mecânicas das chapas *High Tensile* e *Medium Tensile*, com as *High Tensile* a atingirem valores superiores às *Medium*, provavelmente por terem sido sujeitas a um tratamento térmico de revenido pós-laminagem com diferentes condições. Para além disso, detetou-se uma elevada percentagem de martensite, cerca de 30%, explicável pelo fenómeno de Encruamento justificando assim, os valores elevados de dureza, entre 403 e 564 HV, destas chapas em comparação com os valores encontrados na literatura, 241 HV, para o mesmo aço no estado recozido.

Com base na caracterização inicial, em particular nos valores obtidos para a resistência mecânica e para a espessura de cada chapa, foram testadas diferentes combinações de corrente elétrica, pressão dos elétrodos e ciclos de soldadura para otimizar o processo nas chapas de maior e menor resistência mecânica. A melhor combinação encontrada para a chapa mais dura no equipamento *SCIACKY C227SP* foi uma corrente elétrica de 8,6 kA, com 15 ciclos de soldadura e carga de elétrodo de 900 kg, e para a mais macia, os melhores resultados foram obtidos com uma corrente elétrica de 7,6 kA, com 12 ciclos de soldadura e carga de elétrodo de 614 kg.

Os resultados mecânicos indicam que os parâmetros otimizados proporcionam uma soldadura robusta, com propriedades mecânicas e tamanho de *nugget* adequados, e microestrutura homogênea, minimizando defeitos e garantindo a durabilidade das soldaduras.

Keywords: Aço Inoxidável AISI 301L, Soldadura por Pontos, Caracterização Microestrutural, Propriedades Mecânicas, Martensite Induzida por Transformação, Resistência de Contato, Ferrovia.

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"Is it worth it? Everything is worth the effort
If the soul isn't small."
Fernando Pessoa.

Francisca

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*“Enquanto houver ventos e mar,
A gente não vai parar,
Enquanto houver ventos e mar.”*

Jorge Palma

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Abbreviations

AAS Atomic Absorption Spectrophotometry

ASSs Austenitic Stainless Steels

BM Base Material

CARG Compound Annual Growth Rate

CWASS Cold-worked Austenitic Stainless Steels

EDS Energy Dispersive Spectroscopy

HAZ Heat Affected Zones

OM Digital Optical Microscope

SEM Scanning Electron Microscopy

W Weldability

Chapter 1

Introduction

This dissertation was carried out as part of the Master's Program in Material Engineering at the Faculty of Engineering of the University of Porto. This chapter offers an initial overview of the dissertation's subject matter and outlines its primary objectives. In addition, it describes the structure of the document and summarizes its content.

1.1 Motivation

During the late 1960s and mid-1970s, SOREFAME, a Portuguese company founded by Engineer Ângelo Fortes, was the primary manufacturer of railway carriages in Portugal. This company produced almost all the railway equipment used then with complete independence. However, after the 25th of April 1974, the company declined and eventually closed its doors. Since then, Portugal has sought to source railway equipment from highly developed countries such as France and Germany [1].

To counteract this trend, the PRR (Recovery and Resilience Plan) "Producing Railway Rolling Stock in Portugal" was established. This initiative involves 13 entities, including FEUP (Faculty of Engineering of the University of Porto) and the company SERMEC (the project leader), aiming to bring together the most relevant entities in an integrated manner to develop a project with a strong component of innovation and productive investment. The goal is to realize the production of a new product: the manufacturing of railway rolling stock, comprising three types of carriages (vehicles, i.e., Box and Bogies, as well as interiors), thereby promoting technologically advanced production by companies. The main objective of this project is to contribute to the diversification and complexity of the production structure and the specialisation profile of the Portuguese economy [2].

1.2 Objectives

Within the scope of the previously described project, the initial phase will involve studying various manufacturing processes applied to the production of railway carriages to ensure their optimisation,

achieving the best results with minimal time and costs associated with constructing a full-scale prototype carriage. Spot welding, a commonly used process in the production of carriage walls, will be the focus of this master's dissertation, with the following main objectives:

- Reuse materials currently unused at the CP Entroncamento Maintenance Workshop, specifically stainless steel sheets type 301L, thus giving them a new lease of life and adding a more sustainable dimension to the project.
- Investigate whether the available materials for constructing the carriage are in good condition for use through mechanical and microstructural characterisation.
- Determine Spot Welding parameters aimed at reducing manufacturing time and costs for similar joints.
- Given that the existing standards for Spot Welding date back to the 1970s, assess whether the parameters presented in these standards can still be applied to the current technology.
- Optimise the Spot Welding process to ensure both safety requirements and weight reduction.

To achieve the aforementioned objectives, the Gantt chart, Figure 1.1, was developed to define the various tasks assigned within an estimated time frame. This approach enables the structuring of the action plan in a clear and effective manner.

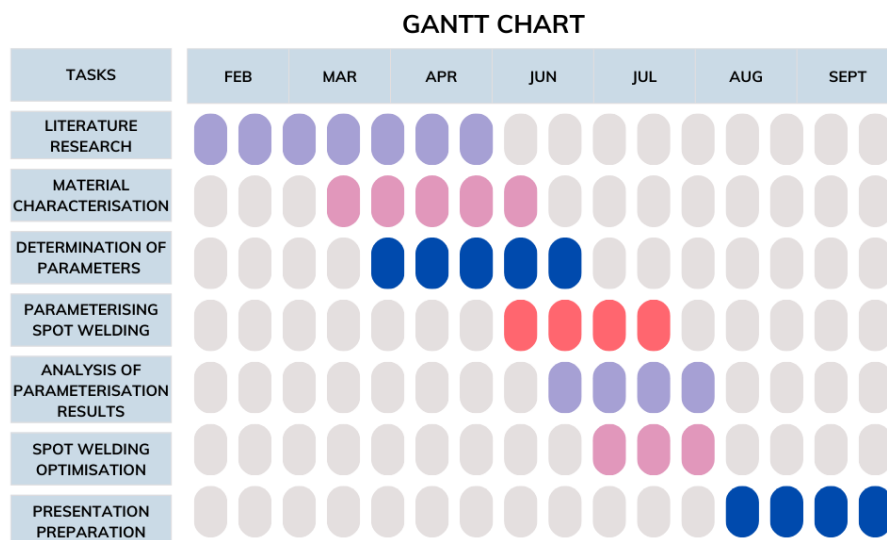


Figure 1.1: Dissertation's Gantt Chart.

1.3 Dissertation 's Structure

In addition to this chapter (Chapter 1), which provides a brief introduction to the topic of this dissertation, the thesis comprises four further chapters. Chapter 2 provides a brief overview of Spot Welding technology, focusing on its application in AISI 301L stainless steel. This chapter extensively explores key parameters to consider, challenges, applications, advantages, and disadvantages in various industries, notably highlighting the railway sector. Chapter 3 outlines the methodology adopted in this study to achieve the project objectives, subdivided into two topics: initial material characterisation and parameterization and implementation of Spot Welding. Chapter 4 presents the results and discussion of all activities carried out, including the mechanical and microstructural characterisation of 301L stainless steel sheets, and the parameterization of Spot Welding technology through mechanical testing and microstructural observation. Finally, Chapter 5 synthesizes the conclusions drawn from this study and suggests future work perspectives to complement and enrich the current research.

Chapter 2

Literature Review

Throughout this chapter, various topics related to the world of welding will be addressed, specifically focusing on Spot Welding with the aim of contextualizing and enlightening the most important aspects of this technology. The application of Spot Welding in AISI 301L stainless steels will be extensively explored, covering the key parameters to consider, the challenges, applications, advantages, and disadvantages across various industries, with particular emphasis on the railway sector.

2.1 Spot Welding Background

Welding is one of the techniques used to join two or more pieces of metal together. There are several methods for metal joining, namely mechanical fastening, adhesive joining, and welding. In welding, the base metal, comprising the two pieces to be joined, is liquefied along with filler metal (the use of which is optional in certain cases), forming a molten mixture. Upon solidification, this mixture constitutes a welded joint that connects the two pieces of base metal [3].

Welding can be further categorized according to the method used to melt the metal. When metal is melted through the heat generated from an electric arc, it is termed Arc Welding, which presently stands as the most prevalent welding technique. Conversely, if the heat necessary to melt the base metal is produced by the resistance of the workpieces to electric current and pressure is applied during the welding process, it falls under Resistance Welding, often conducted within workshop environments due to the immobility of the machinery involved [3]. There is a global trend of growth in this technology. According to *Grand View Research*, "the global welding equipment market size was valued at USD 19.72 billion in 2023 and is projected to grow at a Compound Annual Growth Rate (CARG) of 5.1% between 2024 and 2030." Figure 2.1 illustrates this growing trend [4]. As can be seen in Figure 2.1, Resistance Welding is one of the most popular and economical methods of joining. This technology emerged during the late 1800s and early 1900s, and the first recorded patent for Resistance Welding dates back to 1885 and belongs to Elihu Thomson [3]. It is a joint technology that requires the simultaneous application of heat and pressure to achieve a solid joint [5, 6]. This

process applies to all types of stainless steel if certain precautions are taken and the correct procedures are followed [6].

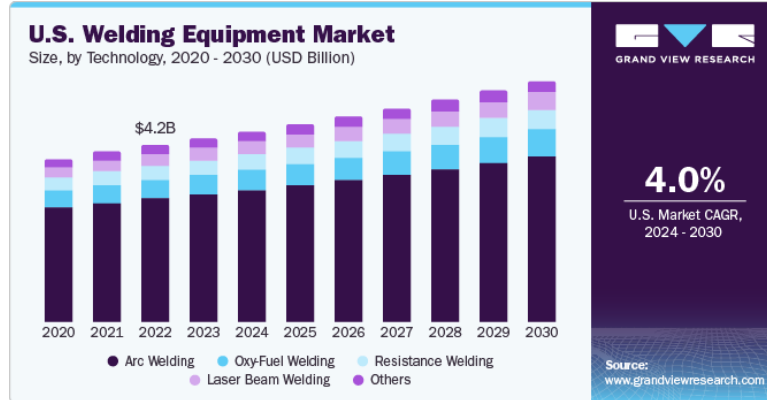


Figure 2.1: Welding Equipment sales forecast according to *Grand View Research* [4].

Spot Welding is the simplest method and works by contacting metallic electrodes to the sheet surfaces, whereby pressure and electric current are applied [6]. Resistance is determined by various factors, including resistivity and surface condition of the initial material, the dimensions, morphology, and composition of the electrodes, as well as the force exerted by the electrodes [5].

The electrodes are traversed by a current, generating sufficient heat at the interface between the sheets, leading to melting at the contact points [5]. This phenomenon, also known as contact resistance, occurs when two surfaces make contact, causing microscopic roughness and limited metal-to-metal bridges due to the breakage of the oxide layer under pressure. The welding current passes through these bridges, increasing the current density and generating heat, leading to melting. The molten metal forms new bridges, directing current toward them until the entire surface is molten [7]. The heat generated depends on the current and the duration of its passage, as well as the resistance at the interface [5].

The two electrodes apply pressure, also known as welding force, compressing the material interfaces of the work parts into a weld nugget as the material melts due to the applied heat [6]. A weld nugget is formed and an autogenous weld (without filler material) is achieved between sheets [5]. The dimensions and morphology of the welds are predominantly determined by the dimensions and contour of the electrodes. The Welding Cycle includes Squeeze time, Hold time, Weld Heat time, and Off time [6]. The basic principles of the technique are illustrated in Figure 2.2 [8].

2.1.1 Parameters and Variables of the Process

Each welding process is characterised by its specific parameters. Only by setting these parameters correctly can the desired output be achieved. However, if one parameter is set incorrectly, it can also

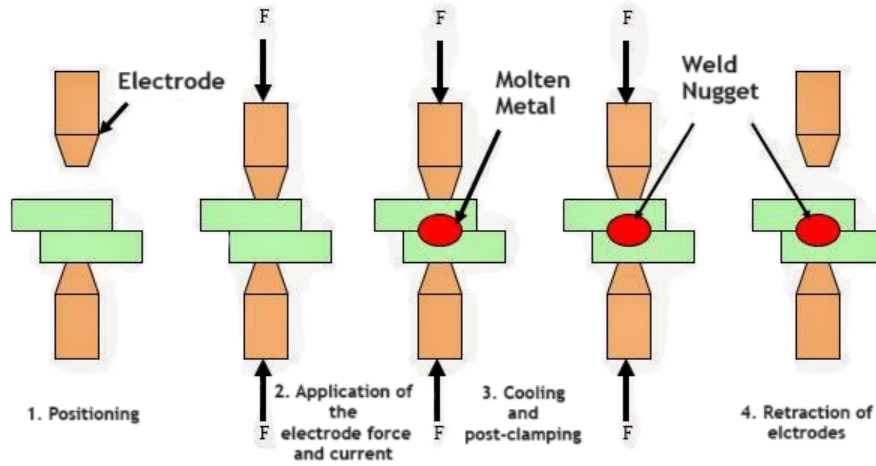


Figure 2.2: Example of Spot Welding operation (Adapted from [8]).

affect others. Consequently, determining the appropriate parameters for Spot Welding becomes a highly complex issue. Some of these parameters include:

Current Intensity - The rate of heat generation at the joint is directly proportional to the square of the current intensity, expressed by the following formula 2.1:

$$P = RI^2 \quad (2.1)$$

where:

P : Power in a circuit

R : Resistance of the conductor

I : Current through the conductor

Consequently, increasing the current intensity results in a higher heat generation rate [7].

Electrical Resistance - Electrical resistance is a fundamental physical property crucial for the effectiveness of the welding process. When resistance is excessively high, insufficient current may flow, leading to inadequate heat generation. On the other hand, if the resistance is too low, insufficient heat may also result due to inadequate power dissipation [9].

Surface Properties of the Joint - The surfaces in contact between the electrodes must be free of contaminants and possess low resistance to ensure they do not overheat [9].

Chemical Composition of the Materials to Join - The chemical composition of the materials

being joined influences not only their electrical resistivity but also their thermal conductivity. It is essential for the heat generated locally to effectively overcome the heat dissipated through conduction [9].

Electrode Force - Pressure is essential for maintaining contact between the joint surfaces throughout the entire process. It facilitates the flow of current and promotes surface adhesion by breaking down the oxides present in these areas [9].

Pressure Application Time - The duration of pressure application directly influences the total energy transferred to the joint. Longer application times result in greater energy transfer for the same current density. However, excessive time may lead to the displacement of liquid material from the joint, potentially compromising mechanical strength [9].

Material, Shape, and Degradation Level of the Electrodes - The higher maintenance cost associated with Spot Welding is attributed to dressing or replacing the electrodes [5]. The electrode should not only facilitate the conduction of electrical current to the workpiece as provide mechanical support to constrain the workpiece and enable the transfer of heat away from the workpiece. Moreover, the materials utilized in electrode construction must endure substantial loads at elevated temperatures while preserving sufficient electrical and thermal conductivity properties [7]. Depending on the material to be welded, the choice of electrode may fall into one of the following three groups:

-Group A: copper-based alloys.

1. Class 1: 99% Copper, 1% Cadmium, conductivity of 92% IACS, for aluminium and magnesium alloys, brasses, and bronzes.

2. Class 2: 99.2% Copper, 0.8% Chromium, conductivity of 82% IACS, for most materials.

-Group B: refractory metals and their composites, for high electrical conductivity metals (gold, copper, among others).

-Group C: specialty materials such as precipitation-hardened copper alloys [9].

In general, copper electrodes, known for their conductivity, are employed in welding applications involving resistive materials such as nickel or stainless steel. Resistive molybdenum electrodes are used in the welding of conductive metals such as gold and copper [7].

The lifespan of an electrode is defined by the number of spot welds that can be performed while ensuring a minimum diameter of the weld nugget. Factors such as high welding currents, surface finish, and electrode forces contribute to shortened electrode life. To prolong electrode life, replaceable caps can be used on electrode tips. Efficient electrode water cooling is essential to maintain tip life, where larger diameter electrodes offer increased heat dissipation. Also, the profile of the electrode

tip significantly impacts both tip life and weld quality. Common tip shapes include truncated, flat, domed, or cylindrical, with truncated cones and domes being the most used [5]. Some of the different types of tips available in the industry are presented in Figure 2.3 [10].

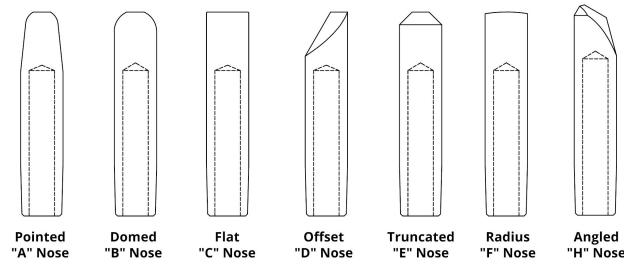


Figure 2.3: Example of electrode tip shapes available on the market [10].

The diameter of the electrode contact area is also an important criterion to consider. If the area is too large, the weld will be unstable. If it is too small the weld created will be too weak [7].

There are several variables related to welding duration that, when modified, allow different materials and thicknesses to be welded, and different types of welds to be obtained, including:

Squeeze time is the interval between applying electrode force and initiating current flow during welding. It's crucial for achieving optimal electrode force and preventing issues like electrode wear and arcing. While extending squeeze time improves weld quality, it increases cost per weld due to reduced welding efficiency [11].

Welding time is the duration of active current flow through the metal pieces. Factors to consider include minimizing weld time to prevent issues like melt-through and warping, ensuring adequate nugget size for thick sheet welding, and adjusting weld time to compensate for equipment limitations [11].

Holding time allows the weld nugget to solidify after welding, starting once welding time ends. Excessive holding time can accelerate electrode wear and lead to brittle welds, particularly with high-carbon content steels. Balancing holding time is important for the effectiveness of weld quality and electrode longevity [11]. Figure 2.4 shows a schematic of a basic welding circuit [12].

The most utilized power sources in Spot Welding machines include:

- Single phase AC units.
- Single phase DC units.
- Secondary side rectified three-phase DC units.
- Secondary side rectified inverter units.

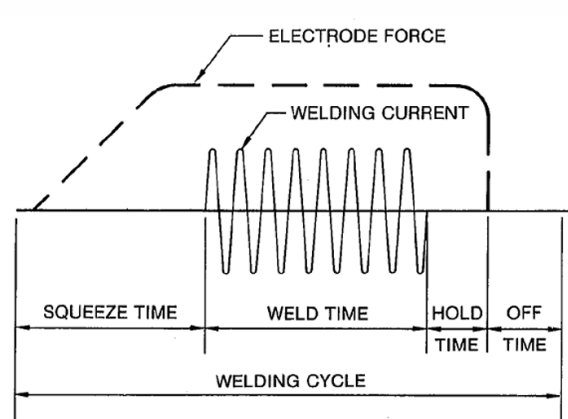


Figure 2.4: Basic Welding Circuit [12]).

Among Spot Welding machine options, single-phase AC units are the simplest and most cost-effective but lack energy efficiency. Single-phase DC units offer higher efficiency due to current rectification, improving welding quality despite added weight. Three-phase DC machines deliver high current levels suitable for thicker materials but are bulkier. Inverter-based machines further enhance efficiency and power output by rectifying AC, storing energy, and employing switches at medium frequencies. Transitioning to DC with inverters reduces costs, enhances quality, and enables the welding of new materials, expanding a company's capabilities [13, 14].

2.1.2 The Weldability

The Weldability (W) of a material reflects its weld capacity. It depends on the material's resistivity, thermal conductivity, and melting temperature [9]. The following formula 2.2 represents the method to calculate this property [9]:

$$W = \frac{\rho}{TK} \times 100 \quad (2.2)$$

where:

W : Weldability

ρ : Resistivity

T : Melting Temperature

K : Thermal conductivity

If W is below 0.25, the weldability is considered weak; between 0.25 and 0.75 is fair; between 0.75 and 2 is good, and above 2 the weldability is excellent. Metals characterised by high resistance

to current flow, low thermal conductivity, and a relatively low melting temperature, such as ferrous metals, are conducive to easy welding [9].

2.1.3 Applications, Advantages and Disadvantages

Spot Welding is commonly used for joining thin metals, and is primarily employed in automobile manufacturing, where a typical car features over 1000 spot welds across its body panels. Moreover, resistance Spot Welding finds widespread application across various industries, including aerospace, rail, manufacturing, electronics, construction, and battery production [11]. The circular graphs shown in Figure 2.5 (a) and (b) display the main industries where this technology is used and their main applications globally in 2022, respectively, according to *Transparency Market Research* [15].

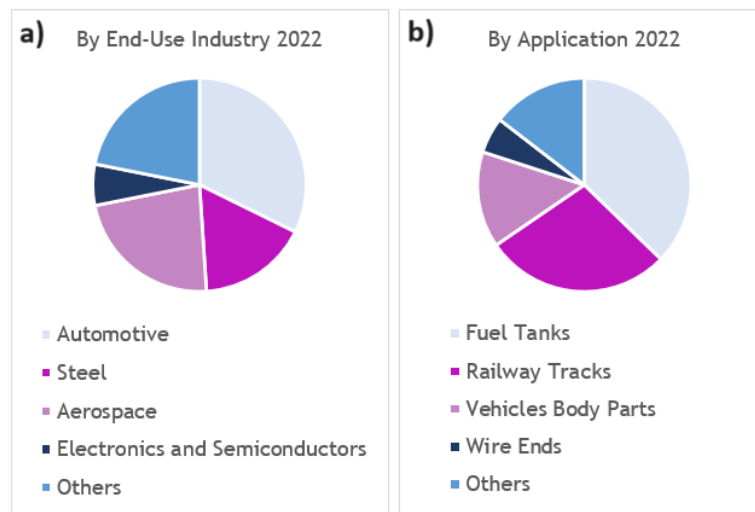


Figure 2.5: Distribution of Spot Welding Applications by End-use Industry (a) and by Product (b) in 2022 (Adapted from [15]).

Table 2.1 shows a schematic of some of the advantages and disadvantages of this technology [11].

2.2 An overview of Stainless Steel- AISI 301L

During the mid-1800s, French researchers endeavoured to develop a highly corrosion-resistant material. They achieved this goal by blending chromium and nickel with carbon, iron, and additional elements, resulting in the creation of a novel metal known as chromium-nickel steel. Subsequently, due to its exceptional corrosion resistance, this alloy acquired the name stainless steel [16].

AISI type 301 Stainless steel is an austenitic steel, characterised by its nominal composition comprising 17% chromium and 7% nickel. In Figure 2.6, is presented the family of Austenitic Stainless Steels (ASSs) [17].

Table 2.1: Schematic of the advantages versus disadvantages of Spot Welding technology [11].

Advantages	Disadvantages
Fast delivery of high energy to a localized spot.	Inaccessible sides of the metal make spot welding impractical.
Relatively simple to execute, reducing the skill level required from operators.	The welding output typically involves low voltages, making spot weld quality susceptible to fluctuations.
Capable of welding any conductive metal.	Hardening of the weld nugget and surrounding material may occur, potentially leading to cracks.
Ideal for achieving proper weld strength with thin metal (up to 2 mm) without burning through.	Depending on the type and thickness of the metal, frequent repairs may be necessary to maintain weld quality and integrity.
Electrodes dissipate heat away from the spot weld, addressing thermal conductivity issues.	The welding process can alter the chemical and physical properties of the workpiece metal, compromising corrosion resistance, particularly in stainless steel.

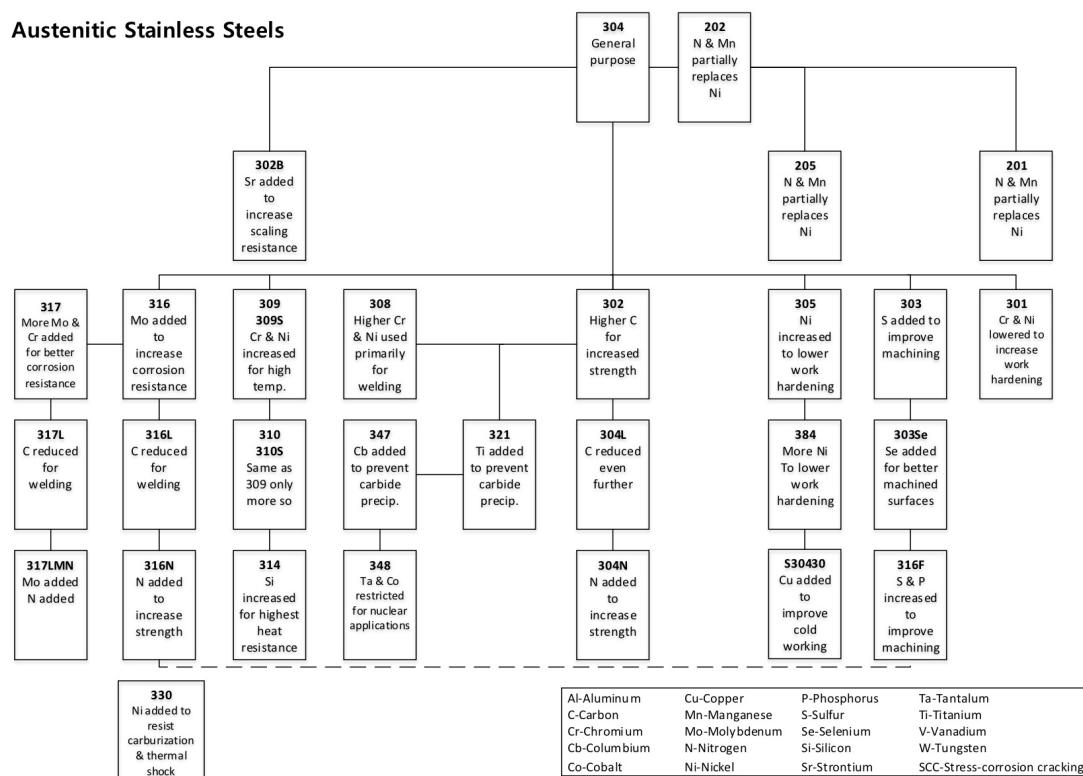


Figure 2.6: Austenitic Stainless Steel Family [17].

Grade 301L stainless steel is a low carbon variant, making it ideal for enhanced ductility and welding heavy sections. Unlike grade 301, welds in grade 301L do not require annealing to achieve maximum corrosion resistance. Its chemical composition is presented in 2.2 [18].

Table 2.2: Chemical Composition of stainless steel grade 301L [18].

Grade		C	Mn	Si	P	S	Cr	Ni	N
301L	min. (%)	-	-	-	-	-	16.0	6.0	-
	max. (%)	0.03	2.0	1.0	0.045	0.030	18.0	8.0	0.20

301L stainless steel offers high strength across different conditions or tempers, along with notable resistance to atmospheric corrosion. Additionally, its visually appealing bright surface renders it highly suitable for decorative structural applications [19]. Its physical properties are presented in Table 2.3 [20].

Table 2.3: AISI 301L Stainless Steel's physical properties [20].

Physical Properties	Reference Values
Density (g/cm ³)	7.90
Melting Range (°C)	1399-1421
Modulus of Elasticity in Tension (GPa)	193

The main advantage of Type 301L lies in its remarkable resistance to various forms of corrosion. This resistance stems from the presence of chromium and nickel within the alloy, affording it exceptional durability against corrosive environments, including those containing chlorides, sulfuric acid, and other corrosive substances. Consequently, it is well-suited for applications such as chemical processing equipment, and food-grade applications [21]. Lower carbon content leads to reduced chromium carbide precipitation, resulting in decreased corrosion at weld lines, including less intergranular corrosion, sensitization, and weld decay [22].

Moreover, the alloy's high strength and hardness render it highly suitable for diverse applications, as it can endure significant levels of stress and wear, although it is not as strong as type 301. This property makes it particularly well-suited for components subject to constant wear and tear. Additionally, its malleability facilitates shaping into intricate forms and sizes, making it an excellent choice for parts requiring precise fitting within a confined space [21]. Due to these properties, it is used in the production of springs, medical devices, and automotive exhaust systems, aircraft structural parts, trailer bodies, architectural applications (roof drainage/door frames), among others [19, 21]. The mechanical properties of austenitic stainless steels exhibit some degree of variation depending on directionality. Notably, there exists an asymmetry in the tensile and compressive 0.2% Proof Strength,

particularly pronounced in the longitudinal orientation [23]. Table 2.4 shows some of the mechanical properties of the AISI Type 301L stainless steels [18].

Table 2.4: AISI 301L Stainless Steel's mechanical properties [18].

Mechanical Properties	Reference Values
Hardness, Brinell	241
Tensile Strength, Ultimate (MPa)	550
Tensile Strength, Yield (MPa)	220
Elongation at Break (%)	45
Modulus of Elasticity (GPa)	193

Furthermore, Type 301L stainless steel proves to be cost-effective despite its initial higher cost compared to alternative alloys. Its robustness and longevity justify the investment, especially when considering its comparative affordability for various applications, particularly those requiring frequent utilisation [21].

At temperatures up to 810°C, 301L stainless steel exhibits excellent oxidation and scaling resistance, as well as strong creep strength, making it an ideal choice for high-temperature applications like furnace parts or turbine blades. However, if the temperature exceeds 871°C, immediate rapid cooling is necessary to prevent damage from overheating [22]. Table 2.5 presents 301L thermal and electrical properties [22].

Table 2.5: AISI 301L Stainless Steel's thermal and electrical properties [22].

Thermal Properties	Temperature Range (°C)	Reference Values
Mean Coefficient	0-100	16.9
of Thermal Expansion	0-315	17.2
($\mu\text{m}/\text{m}/^\circ\text{C}$)	0-538	18.2
Thermal Conductivity	at 100	16.2
(W/m.K)	at 500	21.4
Specific Heat	0-100	500
(J/kg.K)		
Electrical Properties	Reference Value	
Electrical Resistivity	695	
($\text{n}\Omega\cdot\text{m}$)		

As can be observed in Table 2.5, the coefficient of thermal expansion increases with increasing temperature range, and therefore, when welding 301L steels it is necessary to take certain precautions in the design of fixtures and parts to avoid this problem. The use of water cooling of the parts can reduce expansion and control distortion [6].

301L stainless steel materials can be purchased in different hardness conditions. However, its mechanical properties will differ according to its manufacturing conditions. These differences can be seen in Table 2.6 [20].

Table 2.6: Tensile Strength, 0.2% Yield Strength and Elongation of 301L stainless steel according to different heat treatment conditions [20].

Condition	Tensile Strength, Min. (MPa)	0.2% Yield Strength, Min. (MPa)	Elongation (50 mm), Min. (%)
Annealed	550	220	45
¼ Hard	870	530	30
½ Hard	1104	770	22
¾ Hard	1307	1031	16
Full Hard	1426	1265	12

The higher the level of hardening of this steel, the better its tensile and yield strength, but at the expense of its ductility.

2.2.1 Deformation Induced Martensitic Transformation

There are several mechanisms used to strengthen ASSs, including Work Hardening, Nitrogen Alloying, and Grain Refining. Currently, Work Hardening is the primary method employed in industrial production lines to enhance strength. However, a drawback of this method is the rapid decrease in strength of the Heat Affected Zones (HAZ) after welding. Nonetheless, it is widely acknowledged that Grain Refinement is the only method capable of improving strength without compromising ductility [24].

Transformation-Induced Plasticity (TRIP) stands as one of the most effective methods for improving strength-ductility balance. Beyond just mitigating plastic damage by delaying strain localization, the TRIP process introduces strain gradients at phase boundaries to sustain strain continuity. Cold deformation is harnessed to bolster strength and hardness through strain hardening, alongside the concurrent formation of strain-induced martensite from metastable austenite. Consequently, the steel exhibits both high strength and enhanced plasticity due to strain hardening as well as the formation of strain-induced martensite during cold deformation (TRIP effect) [25]. There are various steels that can exhibit this effect, some with chemical composition and processing specifically designed to maximise it. However, there is a class of stainless steels called Metastable ASSs, which also exhibit this effect and steel 301L has a composition that falls into this class [26]. Metastable grades exhibit higher tensile strength and better formability than stable Austenitic grades. Metastable ASSs find application in various structural uses, such as railway and automotive structural components, due to the need for weight reduction and crash safety in automobiles and coaches [27].

As previously mentioned, austenite in metastable stainless steel is prone to deformation-induced martensitic transformation owing to its comparatively lower Ni equivalents [27]. Fundamentally, the theory of spontaneous martensitic transformation applies to deformation-induced martensitic transformation. Bain proposed a theory outlining the transformation of face-centered cubic (FCC) γ -austenite into body-centered cubic (BCC) α' -martensite or body-centered tetragonal (HCP) ϵ -martensite through cooperative atomic movement [28]. In the case of steels, the transformation takes place from γ -austenite to α' -martensite. The transformation from austenite γ to α' -martensite hinges on various factors like alloy composition, stacking fault energy, degree of deformation, plastic strain, strain rate, grain size, and temperature [27]. This transformation results in martensitic phases that induce volume changes compared to the parent austenite, with α' -martensite leading to a volume expansion of 1-4%. Moreover, α' -martensite tends to nucleate at dislocation pile-ups, and martensite growth is halted at high-angle grain boundaries or at other martensite plates, as represented in Figure 2.7 [28]. Typically, annealing cycles are subsequently employed to achieve desired properties in all tempers except high temper (HT), where the steel is produced in an as-cold rolled condition [25].



Figure 2.7: Schematic of the growth of α' -martensite plates [28].

2.3 Spot Welding of Austenitic Stainless Steel

During the welding process of stainless steel, numerous microstructural transformations occur in the vicinity of the joint because of elevated temperatures. The influence of these transformations on mechanical and corrosion resistance is contingent upon factors such as thickness, alloy composition, and joint configuration. The primary objective of welding is to generate a joint possessing properties equivalent to or superior to those of the base metal, thus compensating for any microstructural alterations. There are three distinct regions: 1) the weld joint, 2) HAZ wherein solid-state transformations take place, and 3) the base metal subjected to moderate or negligible heating [6]. These three zones are delineated in Figure 2.8 [6].

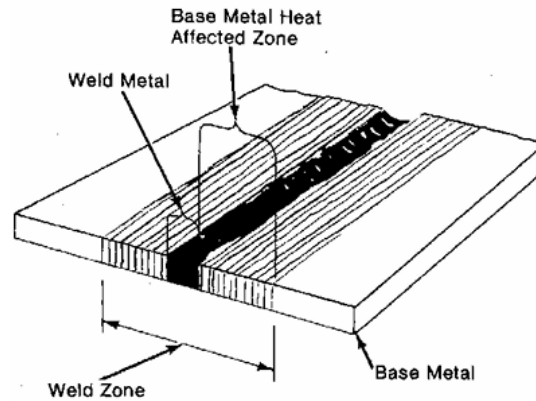


Figure 2.8: Schematic of a welded joint [6].

In contrast to mild steel, austenitic stainless steels present several characteristics that demand heightened attention during welding procedures. Notably, their lower melting temperature necessitates less heat for metal fusion, while their elevated electrical resistance mandates a reduced welding current compared to mild steel. As illustrated in Table 2.5, these steels exhibit a notably low coefficient of thermal conductivity, resulting in heat concentration within a localized area. Moreover, their coefficient of thermal expansion surpasses that of mild steel by 50%, thus necessitating enhanced measures for distortion control [6].

2.3.1 Common problems with Austenitic Stainless Steels

The two main goals in creating a welded joint in austenitic steels are twofold: to maintain corrosion resistance and to mitigate the formation of cracks.

A characteristic of austenitic stainless steels is their susceptibility to chromium carbide precipitation along grain boundaries when exposed to temperatures ranging from 426 to 899°C. Alongside temperature, the elevated carbon content and duration of exposure at specific temperatures may exacerbate the precipitation of these carbides. The interplay of these three factors is depicted in Figure 2.9 [29]. This precipitation diminishes the corrosion resistance of the metal, as chromium, instead of being present in a protective oxide form, manifests as a carbide. Moreover, precipitation along grain boundaries can sensitize these regions, potentially leading to intergranular corrosion [29].

One way to restore corrosion resistance is to apply an annealing heat treatment above the sensitization range followed by fast cooling. Another reason why heat treatment is usually applied after welding is Stress-Corrosion Cracking. This phenomenon occurs due to the accumulation of residual stress in areas close to the joint [6, 29].

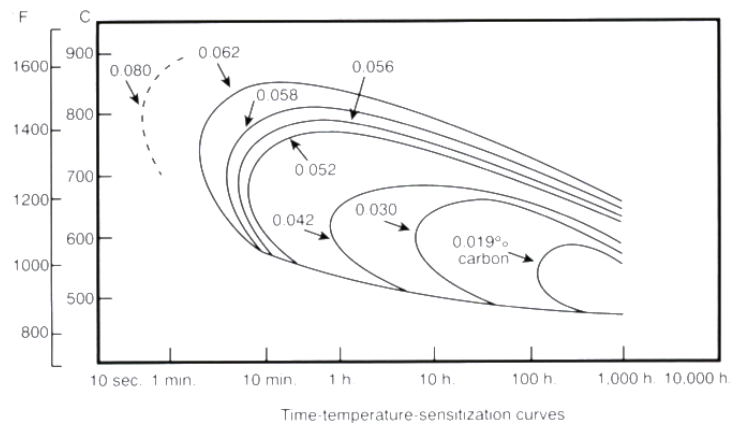


Figure 2.9: Effect of Carbon Content on carbide precipitation [29].

Cracking in welded austenitic stainless steel can manifest in the weld metal during or immediately following the welding process, as well as in the base metal near the joint. The microstructure of the welded metal significantly influences its susceptibility to microcracking. A metal with a wholly austenitic microstructure is notably more prone to microcracking compared to another metal, containing some delta or free ferrite within an austenitic matrix. Ferrite can mitigate issues such as hot cracking in type 308 steels, although even a small amount of it in a type 316 weld deposit can pose serious corrosion challenges in the chemical processing industry. Depending on the application, ferrite may yield beneficial or undesirable effects [6].

The Schaeffler diagram, developed between 1942 and 1949, Figure 2.10, facilitates the prediction of stainless-steel microstructure based on its chemical composition, offering valuable insights into preventing microcrack formation [30].

Later in 1973, the DeLong Diagram (Figure 2.11) was developed, offering a more precise interpretation of the role of nitrogen, and enabling more accurate calculations in this regard [30].

There is another problem that may occur when spot welding steel. The shunting effect is recognized as a phenomenon whereby the welding current intended for a new weld is diverted by existing welds in the vicinity. It is crucial to pre-determine the welding current necessary for creating shunt welds. A parallel electrical path is created from the existing weld (referred to as a shunt weld), resulting in a reduction of welding current flowing to the new weld (referred to as a shunted weld), as illustrated in Figure 2.12 [31]. The inadequate generation of heat due to shunting negatively impacts the strength and nugget diameter of the shunted weld. This, combined with poor fit-up issues introduced by existing welds, decreases the weldability range and contributes to expulsion, which is the forceful ejection of molten metal from the weld. To mitigate the shunting effect in stainless steel,

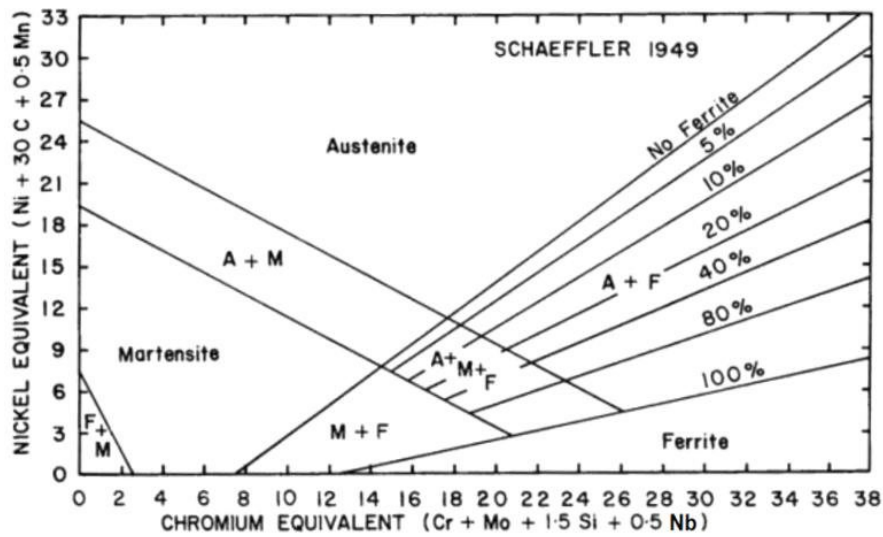


Figure 2.10: Schaeffler Diagram for predicting the amount of ferrite and austenite in the resulting microstructure of a steel [30].

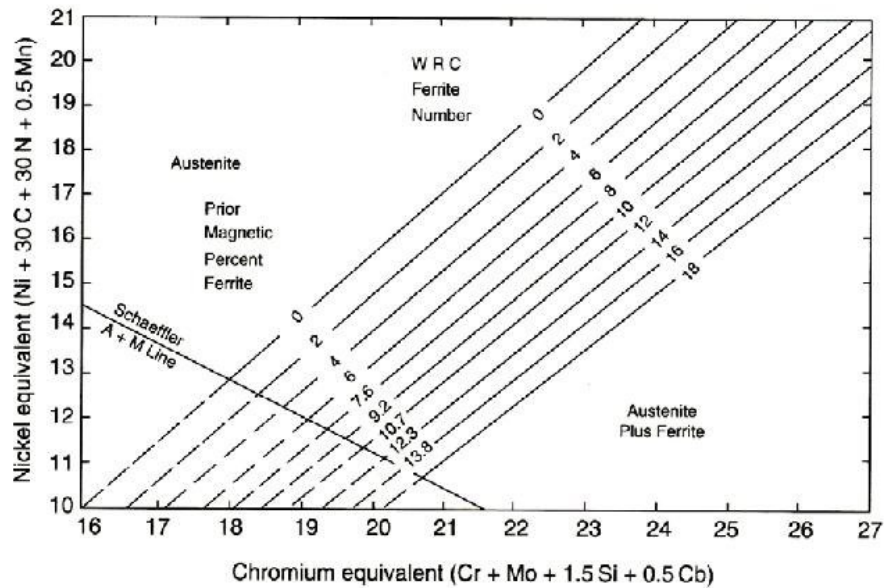


Figure 2.11: DeLong Diagram for stainless steel weld metal [30].

a higher welding current may be assigned to compensate for the heat input required for the shunted weld. However, this approach can lead to an increase in the thermal expansion of the sheets and electrodes. Alternatively, a current control system can be implemented based on electrode displacement [31].

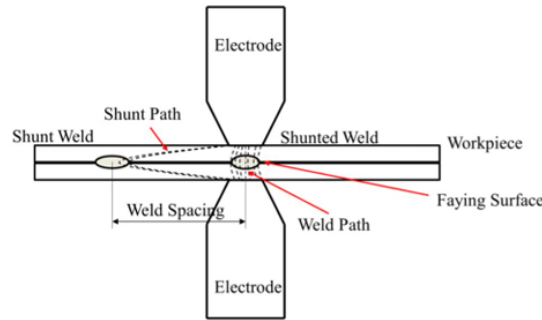


Figure 2.12: Schematic diagram of Shunt Effect in Spot Welding [31].

2.4 Welding Procedures

In general, Preheating Treatment in Austenitic Stainless Steel is not very impactful because no structural changes occur in either the joint or the HAZ and can lead to increased precipitation of carbides at the grain boundaries which, as previously discussed, could sensitize the steel. In the case of crack-sensitive austenitic weld metal (containing little or no ferrite), it is important to minimize the amount of stress imposed during cooling. To do this, the restraint on the base metal during welding and deposit or fuse relatively narrow beads is minimized [6].

In the case of Spot Welding, when the HAZ overlaps, it becomes imperative to factor in the mechanical material properties within that region. This includes considerations such as residual stresses, reductions in strength, and decreases in hardness. To mitigate angular deformation and the accumulation of stress, the determination of the minimum distance between two joints is contingent upon the thickness of the components being joined and the clamping configuration of the assembly [32]. The spacing between welds denotes the centre-to-centre distance between neighbouring spots, with its minimum value being dependent on factors including the Thickness, Electrical Conductivity, Surface Cleanliness of the metal being welded, as well as the Diameter of the melting core. Table 2.7 delineates an example of recommended minimum spacing between welds [23].

Table 2.7: Minimum recommended spacing between welds for stainless steel and superalloys according the thickness of the thinnest plate [23].

Thickness of the thinnest plate (mm)	0.5	0.8	1.0	1.2	1.5	2.0	2.5	3.0	3.5	4.0
Minimum Point Distance (mm)	8	10	10	12	12	14	26	18	20	22

In the design process of a Spot Welding structure, careful consideration must be given to the accessibility of the electrode, ensuring its ability to adequately reach the welding area of the component.

Furthermore, various factors such as Edge Distance, Overlap Amount, Assembly Clearance, and Weld Strength must be meticulously taken into consideration. The minimum value of the Edge Distance depends on the type of metal being welded, its thickness, and the prevailing welding conditions. A reduced value may be applicable for high-yield strength metals, thin sheets, or when robust welding conditions are implemented. Table 2.8 provides minimum parameters for the design of the Spot spacing and Distance from the edge in dependency on the thickness of the thinnest plate for Resistance Spot Welding according to EN 15085-3:2022 [32].

Table 2.8: Spot spacing, distance from edge according the thickness of the thinnest plate from EN 15085-3:2022 [32].

Plate thickness (mm)	1	1.25	1.5	1.75	2	2.5	3
Spot spacing (mm)	25	35	35	35	40	50	50
Distance from edge (mm)	≥ 10	≥ 10	≥ 10	≥ 10	≥ 15	≥ 15	≥ 15

Table 2.9 presents the minimum overlap in millimeters for single and double row solder joints according to the thickness of the thinnest sheet [23].

Table 2.9: Minimum recommended overlap amount for joints of stainless steel and superalloys according the thickness of the thinnest plate [23].

Thickness of the thinnest plate (mm)	0.5	0.8	1.0	1.2	1.5	2.0	2.5	3.0	3.5	4.0
Minimum overlap of single row solder joints (mm)	6	7	8	9	10	12	14	16	18	20
Minimum overlap of double row solder joints (mm)	14	16	18	20	22	26	30	34	38	40

Typically, the determination of Spot Welding process parameters relies upon considerations of the material composition and thickness of the workpiece, guided by the welding conditions table specific to the material in question. Initially, the shape and dimensions of the electrode end face are established. Subsequently, electrode pressure and welding duration are tentatively chosen, followed by the adjustment of welding current for welding samples across varying current levels. Upon confirming compliance with the specified molten core diameter requirements, electrode pressure, welding duration, and current are further refined within an appropriate range. Sequentially, sample welding and inspection procedures are conducted until the weld quality aligns with the stipulated criteria outlined in the technical specifications [23].

2.4.1 The influence of different elements on the welding of Stainless Steel

There are several factors that must be taken into consideration during welding, namely:

i) The influence of elements in the weld environment:

Oxygen- the resistance of stainless steel to adverse phenomena such as corrosion and oxidation is primarily due to the formation of chromium oxide on the steel surface. However, despite its advantages, this oxide can be a hindrance in applications such as brazing and welding. In the case of welding, as the temperature increases, more Oxygen from the air reacts with Chromium, forming a viscous slag-like layer on top of the weld. This coating protects the weld from contact with the atmosphere; however, it represents a significant loss of Chromium and must be removed at the end of the process [6].

Hydrogen- may be the cause of porosity in stainless steel. Generally, the amount of residual Hydrogen present in the composition of these steels is within acceptable limits; however, there may be other sources that could lead to porosity in the joint [6].

Copper/Lead- traces of Copper or Lead can lead to embrittlement and cracking of the joint; therefore, ensuring the cleanliness of the HAZ is crucial [6].

ii) The influence of alloying elements on weldability:

Chromium is by far the element that has the greatest impact on the weldability of steel due to the formation of oxide slag. However, other elements also affect the steel's weldability. For example, Silicon can promote the formation of oxide slag because it has a high affinity for Oxygen. On the other hand, certain residual elements such as Phosphorus, Selenium, and Sulphur can have both positive and negative impacts. They are added to stainless steels to impart free-machining characteristics but can impair weldability to some extent, such as causing porosity and cracking [6].

iii) The influence of alloying elements on weld structure:

The metallurgy of stainless steels is contingent upon both the rate of solidification and, more significantly, their chemical composition. Steels belonging to the 300 series may either consist entirely of austenite or feature ferrite within an austenitic matrix. The integrity of the weld or its freedom from crack defects predominantly hinges on the presence of ferrite. Hence, there is a huge interest in understanding the impact of elements on the formation of ferrite and austenite. Furthermore, certain elements serve as stabilizers of austenite, which is pivotal for the resilience of the joint. Chromium and Molybdenum play dual roles; they act as stabilizers of austenite while also serving as strong ferrite formers. Nickel, Carbon, and Nitrogen also have dual roles; they act as strong stabilizers and formers of austenite. Silicon and Niobium function as ferrite formers. On the other hand, Manganese acts as a weak former and a strong stabilizer of austenite [6].

2.5 Austenitic Stainless Steels in Passenger Railcars

The structures of Cold-worked Austenitic Stainless Steels (CWASS) were utilized in railway passenger cars manufactured in the mid-1930s. The adoption of stainless steel in the fabrication of passenger railcars marked a remarkable achievement in engineering, attributed to the innovative thinking of Edward Gowan Budd (1870–1946), the founder of the *Edward G. Budd Manufacturing Company* located in Philadelphia, Pennsylvania. His company was pioneering in producing all-steel automobile bodies and wheels crafted from sheet steel and was among the first to employ Resistance Spot Welding techniques. During a trip to Europe in 1930, Edward Budd conceived the idea of incorporating stainless steel into railway car design and manufacturing. This concept gave birth to the *Zephyr* trains, representing a significant departure from traditional passenger railcar design. The introduction of the *Zephyr* trains brought about notable advancements in railway travel, marked by reduced train weight enabling the pioneering use of a diesel-electric propulsion unit [33].

The initial stainless steel railcars were crafted from an austenitic "18-8" alloy closely resembling 301 (1.4310) steel in chemical composition. This steel, characterised by a relatively high carbon content, exhibited the phenomenon of sensitization within the HAZ of welds, leading to subsequent intergranular corrosion. To mitigate this issue, Budd's experts devised the 'Shotweld' short-time Spot Welding process, necessitated by the imperative to limit dwell time within the critical temperature range. Presently, the grades most commonly employed in railcars are 301 L/LN, with the side skin sheets typically fashioned from 1/4 hard. These materials offer heightened strength, with the 1/4 hard strength level deemed sufficient for structural integrity, particularly given stress analyses of the skin based on buckling and shear considerations. Spot Welding emerges as one of the primary joining technologies for these structures, with precise procedures implemented, including the application of shielding gas. Stringent quality standards govern spot welds, mandating the absence of nugget expulsion, shallow and uniform indentation, and prohibition of surface discoloration visible to users. Specific criteria dictate nugget strength, diameter, penetration, and the absence of discontinuities, applicable to both welding procedure qualification and production welds [33]. A typical stainless steel car body structure is presented in Figure 2.13 [33].

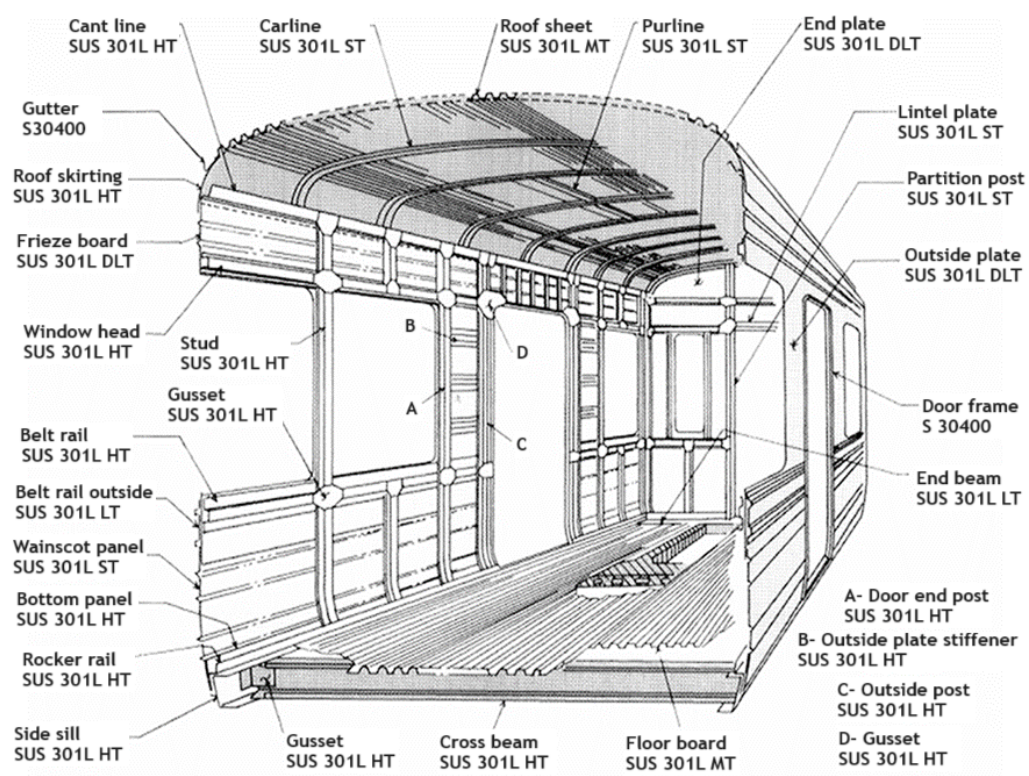


Figure 2.13: – Example of a typical stainless steel car body structure (Adapted from [33]).

Chapter 3

Methodology

The following Subchapters will present the methodology used to characterise the sheet material in order to gather enough information to optimise Spot Welding. The Figure 3.1 summarises the methodology and the main objectives of each stage.

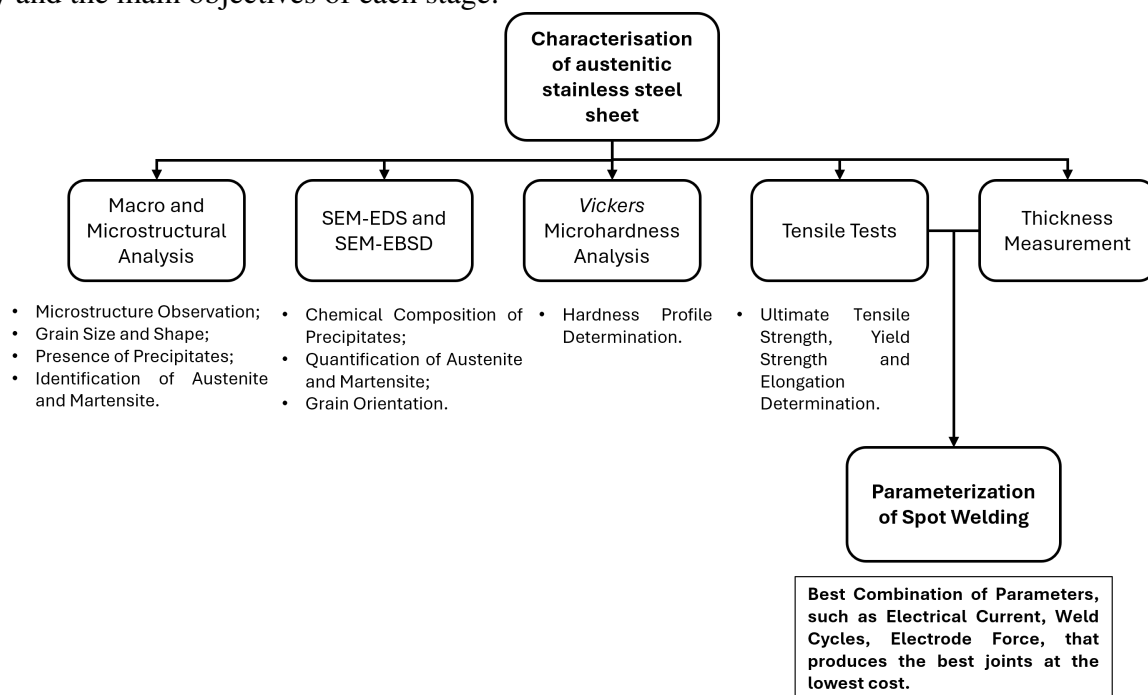


Figure 3.1: Overview of the experimental procedure.

3.1 Chemical, Macro and Microstructural Characterisation

For the macro and microstructural analysis of the sheets supplied by the CP- Comboios de Portugal (one of the co-operating identities in this project), three samples were cut from each sheet using a guillotine. All sheets were analysed using Atomic Absorption Spectrophotometry (AAS) in order to determine their chemical composition.

Subsequently, all the samples were cold mounted with a mixture of epoxy resin and hardener, two from the cross-section to determine the direction of rolling and a third from one of the surfaces of each sheet to observe its microstructure. Table 3.1 shows the designation given to each sample according to the location analysed and the sheet that gave rise to it. Afterwards, they were ground and polished using silicon carbide abrasive paper according to the following sequence, 180, 320, 600, 1000, and 4000 mesh and finished with a 1µm diamond suspension. All stages were carried out until mirror-like samples were obtained with no scratches visible to the naked eye.

Table 3.1: Designation of each sample according to its sheet of origin and its place of collection.

Designation of each Sheet	Surface	Cross Section 1	Cross Section 2	Thickness (mm)
11954010 HT AISI 301L	Sample 1	Sample 1L	Sample 1C	1.20
11954020 HT AISI 301L	Sample 2	Sample 2L	Sample 2C	1.50
11954040 HT AISI 301L	Sample 3	Sample 3L	Sample 3C	2.28
11954240 MT AISI 301L	Sample 4	Sample 4L	Sample 4C	1.50

In the cross-sections of the sheets, several common features were observed using the *Leica DVM6* Digital Optical Microscope (OM) through the software *LeicaLas*, namely parallel white stripes that crossed the cross-section from one end to the other, indicated in Figure 3.2 for Sample 3L with a red arrow.

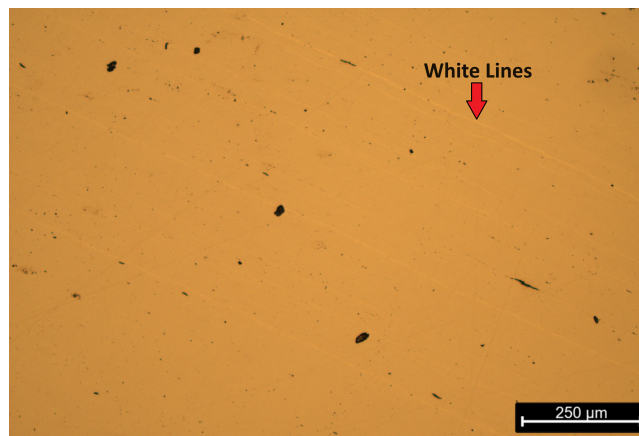


Figure 3.2: OM image of the surface of Sample 3L with the white lines (in red).

In addition, the alignment of predominantly elongated or extremely rounded precipitates was also observed. Different examples of these precipitates can be seen in Figures 3.3 (a) and (b), obtained by Scanning Electron Microscopy (SEM) for Samples 3L and 4, respectively.

SEM technology was used to determine the nature of these precipitates. The following samples were analysed post-polishing. Because they had not been chemically attacked to reveal their microstructure, the white stripes could not be identified in this first SEM analysis. Figure 3.4 (a) shows

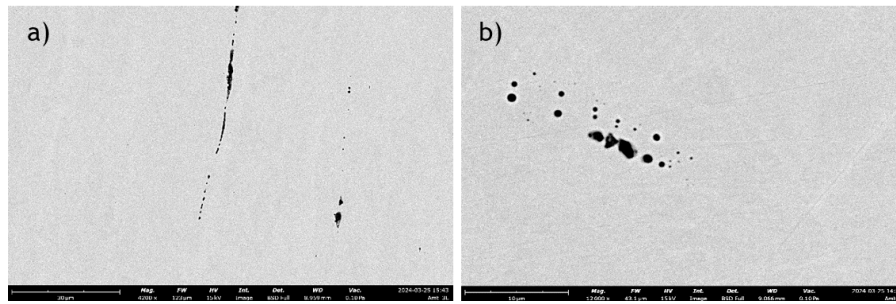


Figure 3.3: Examples of the carbides visible in Samples 3L (a) and 4 (b) by SEM.

an example of an alignment of precipitates visible in Sample 1L and (b) approximates one of these elongated-looking precipitates that will be the subject of an SEM-Energy Dispersive Spectroscopy (EDS) elemental analysis with *Thermo Scientific™ ChemiSEM™ Technology* using a BSD detector.

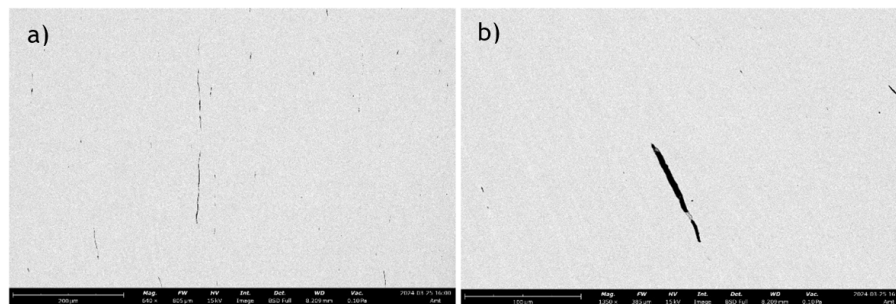


Figure 3.4: Example of an alignment of precipitates visible in Sample 1L (a) and an approximation of one of these precipitates (b) by SEM.

In Figure 3.5 (a), the SEM-EDS analysis points are represented by the blue targets and point 2, the target of the following elemental analysis, is marked in (b).

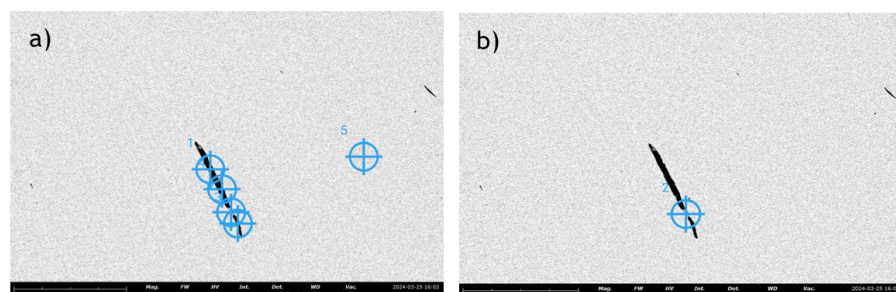


Figure 3.5: The SEM-EDS analysis points in Sample 1L are represented by the blue targets in (a) and the target of the following elemental analysis, point 2, is represented by a blue target in (b).

For each analysis, a spectrum was generated with the chemical elements identified by SEM-EDS analysis. Figure 3.6 shows the spectrum obtained for point 2.

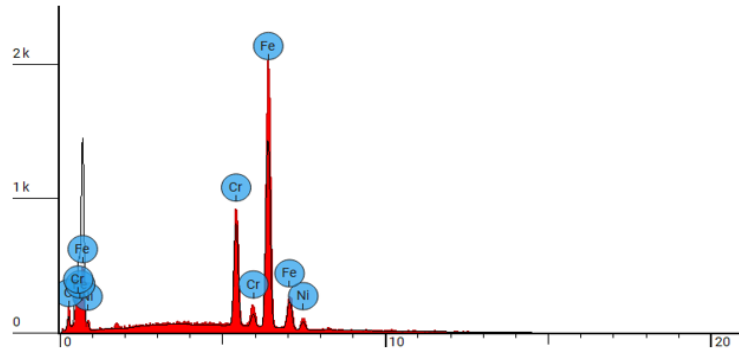


Figure 3.6: Energy Spectrum obtained by SEM-EDS of point 2 of Sample 1L.

In addition to this information, the SEM-EDS analysis also provides a table, Table 3.2, with the elements and their weight and atomic concentration present at the place analysed.

Table 3.2: Weight and Atomic Concentration (%) for each element present at point 2 of Sample 1L from SEM-EDS analysis.

Element Number	Element Symbol	Element Name	Atomic Concentration (%)	Weight Concentration (%)
6	C	Carbon	8.987	2.106
24	Cr	Chromium	20.065	20.361
26	Fe	Iron	67.182	73.220
28	Ni	Nickel	3.766	4.313

This methodology was repeated for all the points identified in Figure 3.5 and also for other precipitates identified in Samples 3L and 4.

For the Microstructural Analysis, after polishing the samples, each one was chemically attacked. Given that this is stainless steel whose main attribute is its corrosion resistance, obtaining good quality microstructures through a chemical attack (whose operating principle is precisely to cause localized and controlled corrosion to reveal the microstructure) was a very time-consuming process and the results obtained were somewhat less than expected. For the following analyses, an electrolytic attack was chosen as it is much more efficient. The Aqua Regia's Reagent, Modified Aqua Regia's Reagent, Villela's Reagent and finally, the Marble's Reagent were tested. The composition of this last attack consisted of 4 g of CuSO_4 , 20 mL HCl and 20 mL of H_2O , for 20 seconds, and then was stopped in ethyl alcohol [34]. An electrolytic attack of 10% oxalic acid at a voltage of 6V for 40 seconds was also tested on Samples 1 and 3 [35], which proved to be much more efficient than the previous one. The

samples were cleaned under running water, dried with compressed air, and observed under a *Leica DVM6 OM* to see the microstructure of each one. In addition, Sample 3L, after being attacked, was observed again in SEM to determine the chemical composition of the white lines observed previously.

Later, a more comprehensive analysis was conducted using SEM with Electron Backscatter Diffraction (EBSD) to aid in Phase Identification on the *FEI QUANTA 400 FEG ESEM/ EDAX PEGASUS X4M* Equipment at the Centre for Materials of the University of Porto (CEMUP). To do this, Sample 3 was finished with colloidal silica. This analysis was carried out to ascertain the existence of the martensitic phase in the material studied and to understand the martensite-austenite relationship in the hardest sample, resulting in Phase Maps and an Inverse Pole Figure (IPF) Map for Sample 3.

3.2 Microhardness Characterisation

Vickers Microhardness Tests were carried out on the equipment *FALCON 400 micro/macro-Vickers Hardness Tester (INNOVATEST)* with an applied load of 25 gf for 10 seconds for each cross-sectioned sample, according to EN ISO 6507-1:2005 standard [36, 37]. Graphs were obtained, such as the one shown in Figure 3.7, with the distribution of microhardness along the XY axis for each sample by measuring the diagonals d_1 and d_2 of each indentation, shown in Figure 3.8. In total, eight indentations were made for each long and short section to obtain statically significant results.

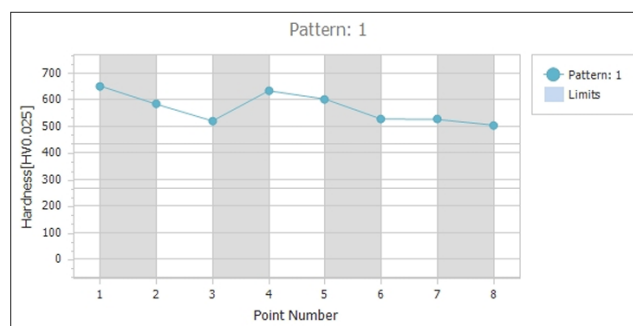


Figure 3.7: *Vickers* Microhardness Distribution Profile obtained for Sample 3C.

Later, microhardness profiles were carried out, with an applied load of 10 gf for 10 seconds, along the width of each long cross-sectioned sample, with approximately 100 μm between indentations, to analyse whether there were hardness gradients from the surface to the interior of each sheet. Figure 3.9 shows a microhardness profile carried out on the Sample 2L.

3.3 Tensile Tests

In order to determine the mechanical strength of the sheets for later selecting the welding parameters (which depend on the thickness and mechanical strength of each sheet), three test specimens of Sheets

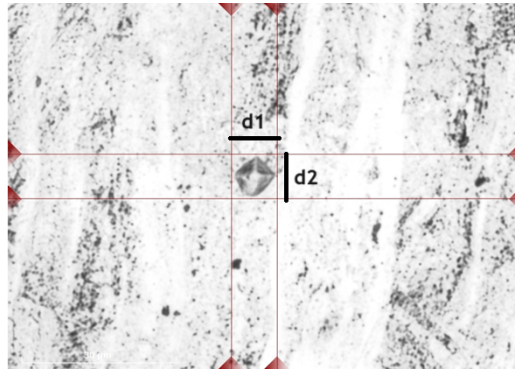


Figure 3.8: Example of an indentation generated for Sample 3C with diagonals d_1 and d_2 identified.

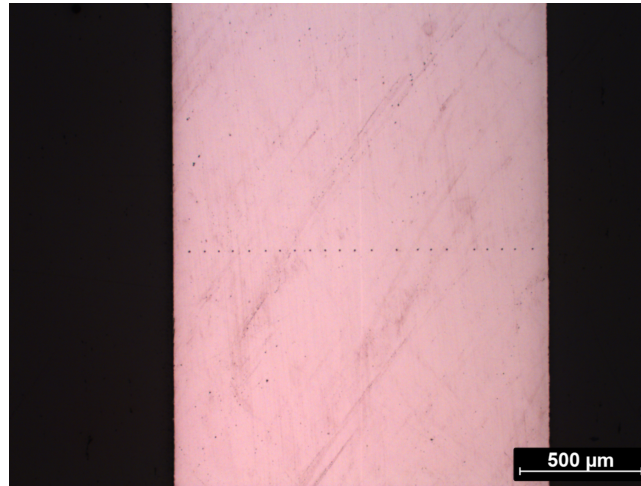


Figure 3.9: Example of a microhardness profile for Sample 2L.

3 and 4 were fabricated in accordance with the NP EN 10002-1 Standard [38]. The dimensions are presented in Table 3.3, obtained using a caliper. The selection criterion for the sheets was hardness; that is, the hardest and the softest sheets were selected for the tests.

The tensile test was conducted using the *Autograph AG-X Plus* Equipment with a maximum load of 250 kN and a grip advancement speed of approximately 10 mm/minute.

3.4 Parameterization of Spot Welding

To conduct a preliminary screening of the parameters to identify those yielding the best results, small sheets were cut from Sheets 1, 2, 3, and 4, measuring 30x20 mm, ensuring a distance of 15 mm between the welding point and the edges of the sheet, according to 15085-3:2022 Standard [32]. The *MP500 Equipment from Motofil*, with a maximum current of 80 A, available at the Department of

Table 3.3: Dimensions of samples 1, 2, and 3 of Sheets 3 and 4.

	Length of reduced section (mm)	Average Thickness (mm)	Standard deviation	Average Width (mm)	Standard deviation	Cross Sectional Area (mm ²)
<i>Sheet 3</i>						
Sample 1	50	2.21	0.005	12.45	0.012	27.5
Sample 2	50	2.21	0.000	12.46	0.005	27.5
Sample 3	50	2.22	0.005	12.44	0.008	27.6
<i>Sheet 4</i>						
Sample 1	50	1.45	0.010	12.47	0.006	18.1
Sample 2	50	1.44	0.005	12.49	0.012	17.9
Sample 3	50	1.45	0.005	12.46	0.005	18.0

Metallurgical and Materials Engineering, was utilised. The controllable parameters on this equipment were the electric current and the duration in seconds. The minimum current applied to join two sheets was approximately 13 A, as the equipment could not achieve higher values. The joining of sheets from Sheet 2 was studied with current application intervals of 2, 4, and 6 seconds, resulting in a total of 3 joints for each selected time. Additionally, a joint was achieved with a current intensity of approximately 40 A; however, to avoid damaging the equipment, only one joint was made under this condition with a 2-second application. Subsequently, tensile stress was applied to the ten joints made, and the maximum force values were recorded using the *Autograph AG-X Plus equipment* with a grip advancement speed of approximately 10 mm/minute.

Spot Welding tests were conducted again, this time using equipment provided by the company IETA, which allowed for the control of various variables. The objective was to identify which parameters presented in the literature lead to the best results. Based on previous studies and tables provided for Spot Welding Equipment, including the table for the equipment used, the parameters listed in Tables 3.4 and 3.5 were defined according to the thickness and mechanical strength of the tested material [6, 39, 40]. The parameters studied were the electric current and welding cycles, and eight joints were made with the sheets from Sheet 3. All sheets were cleaned and degreased before welding.

Table 3.4: Applied Electrical Currents (kA) for Joints 1, 2, 3 and 4.

<i>Electric Current w/ 12 cycles</i>				
	Joint 1	Joint 2	Joint 3	Joint 4
Electric Current (kA)	10	11	12	13

The tests were conducted using *TECNA's DC Three-Phase Resistance Welder*, and the remaining parameters were established under Program 4 of the equipment due to the company's experience with

Table 3.5: Applied Weld Cycles for Joints 5, 6, 7 and 8.

<i>Weld Cycles w/ 12kA</i>				
	Joint 5	Joint 6	Joint 7	Joint 8
Weld Cycles	12	13	14	15

this program. According to this program, the type of current is DC, the applied pressure is 0.65 MPa, with an Electrode Squeeze Time of 96 ms, a Forge Delay of 14 ms until the application of pressure by the electrodes, a single pulse of electric current, and a Hold Time of approximately 70 ms. The shape of the copper electrode was truncated and due to the absence of a second electrode tip, it was replaced with a copper base.

The welded joints were cut in half to examine the potential presence of porosity within the joint, using an abrasive disc. The samples were cold-mounted, and the polishing steps described in previous chapters were followed. The joints were then observed using the *Leica DVM6* Digital Microscope. After that, the size of the nugget was measured for all samples.

On a third attempt, the available equipment at CP Entroncamento Maintenance Workshop, *SCI-AKY C227SP* with AC current and a power of 50 Hz, was tested. The equipment had two copper electrodes with a truncated shape and a diameter of 19 mm.

To perform Tensile-Shear Tests and microstructure evaluation, Sheets 3 and 4 were cut into specimens with the dimensions presented in Figure 3.10 according to their thickness [41]. According to the EN ISO 15614-12 Standard, to validate a condition, eleven specimens of that condition are required to be tested by Tensile-Shear test and two for macrosection evaluation [42]. However, since this is not the final equipment to be optimized, the number of specimens was reduced to three for the tensile tests and to one for the microstructural analysis.

Based on the previous experience and after a discussion with on-site engineers specializing in the subject, it was concluded that, with this equipment, the current intensity specified in the standard is excessive for the material, and therefore, these values were adjusted accordingly, and new parameters were selected, shown in the Table 3.6, for Sheets 3 and 4. All specimens were cleaned and degreased before welding in an acetone bath except for one pair to study the impact of the lack of cleaning on the resistance of the spot. The joints were produced without heating or cooling cycles.

Subsequently, Tensile-Shear tests were carried out following the EN ISO 15614-12 Standard, totalling two tests per condition from Table 3.6. The samples for observing the macro and microstructure in OM and SEM were cold-mounted and underwent the same procedure described in Subchapter 3.1. Images were also taken using the Stereo Microscope *STEMI 2000-C* from *Leica* equipment to

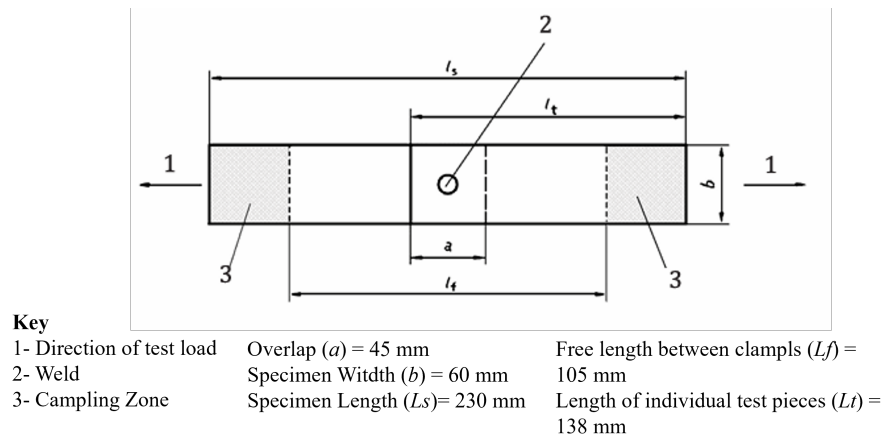


Figure 3.10: Tensile shear test specimen (Adapted from [41]).

Table 3.6: Values of Welding Current (kA), Weld Time Cycles, and Electrode Force (kg) for Sheets 3 and 4.

	Welding Current (kA)	Weld Time Cycles (50 per sec)	Electrode Force (kg)	Condition
Sheet 3 11954040 HT	7.6	10	900	(a)
	7.6	12	900	(b)
	8.6	12	900	(c)
	8.6	15	900	(d)
	9.0	12	900	(e)
	10.4	12	900	(f)
Sheet 4	7.6	12	614	(g) and (dirty)
11954240 MT	8.6	12	614	(h)

measure the size of the nugget for each condition. The samples selected for this purpose were those corresponding to the conditions (c), (d), (h), (dirty) and (j).

Vickers microhardness tests were also carried out, following the same procedures described in the Subchapter 3.2, in order to obtain microhardness profiles, with an applied load of 10 gf for 10 seconds, to study the differences in hardness between the base material, the HAZ and the nugget in each sample.

Chapter 4

Results and Discussion

The following Chapter will present the data resulting from the characterisation of the material under study as well as the results obtained through the Spot Welding parameterization.

4.1 Material Characterisation

In order to characterise the material under study, various technologies were applied, namely SEM-EDS Analysis, Microstructure Analysis, *Vickers* Microhardness Tests, SEM-EBSD Analysis and Tensile Tests. The results of which will be presented and discussed in the following sub-chapters. Furthermore, after AAS was concluded that all of them were of 301L nature, contrary to the initial assumption that two would be of 301 nature and the other two of 301L nature. The analysis results can be found in Appendix A.

4.1.1 SEM-EDS Analysis

In Figure 4.1, the various target locations for SEM-EDS analysis of Sample 1L are depicted. Table 4.1 summarizes the results obtained through spectrum analysis for Points 1, 2, 3, 4 and 5.

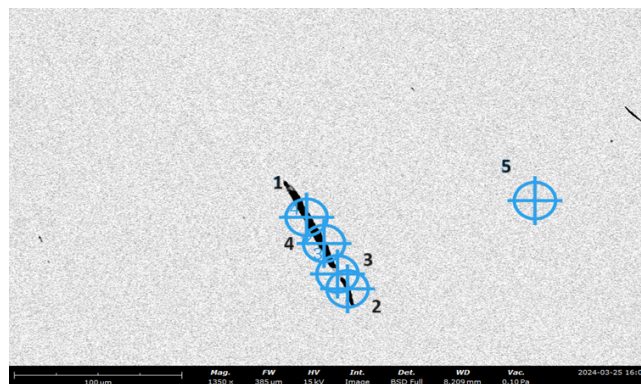


Figure 4.1: SEM image of Sample 1L with the analysed points.

Table 4.1: Percentage in Weight Concentration of each element at each point analysed for Sample 1L.

Element Name	Weight Concentration (%)				
	Point 1	Point 2	Point 3	Point 4	Point 5
Carbon	7.1	2.1	10.1	28.2	4.9
Oxygen	48.5	-	13.9	7.1	-
Fluorine	2.0	-	-	-	-
Aluminium	0.9	-	0.9	0.5	-
Silicon	35.3	-	9.3	16.4	0.6
Chlorine	-	-	0.9	1.5	-
Potassium	-	-	-	0.8	-
Chromium	2.7	20.4	14.2	10.6	16.3
Manganese	-	-	-	-	1.5
Iron	3.6	73.2	48.5	34.9	71.9
Nickel	-	4.3	1.4	-	4.8

From the analysis of Table 4.1, it is evident that significant quantities of Silicon (Si) and Oxygen (O) are present, as identified for Points 1, 3, and 4. Despite Si being a constituent of the chemical composition of type 301L stainless steel, the observed content, approximately 36%, significantly exceeds the typical 1% observed for this steel. This could potentially be attributed to contamination of Sheet 1 during the manufacturing process [43]. This Si content could be concerning since this element increases susceptibility to hot cracking both in the weld metal and the HAZ. However, given that it is associated with an oxygen peak, it is inferred that it is mostly in the form of oxide and therefore should not present any risk to the performance of the steel [44].

A similar explanation could apply to the analyses depicted in Points 1, 3, and 4, as they also identify the presence of Aluminium (Al), albeit to a lesser extent compared to Si. Al also forms very stable oxides, as, for example, alumina, which is often used in furnace linings [45]. In Point 4, elevated levels of Carbon (C) and Chromium (Cr) are identified, potentially combined in the form of chromium carbides, which could result from the sensitization phenomenon of the steel [6]. However, these C values are excessively high compared to those observed in the chemical composition of this alloy. This may be because there are some limitations of the equipment itself, which generally has difficulties in identifying Carbon, Nitrogen, and Oxygen, for example. Point 5 was a control conducted to compare the composition of the base material with the composition of the inclusions found, which also emphasises the difficulty in correctly determining the carbon value, which should not exceed 0.030%.

In Figure 4.2, the various target locations for SEM-EDS analysis of Sample 3L are depicted. Table 4.2 summarizes the results obtained through spectrum analysis for Points 1, 2, 3, 4, 5 and 6.

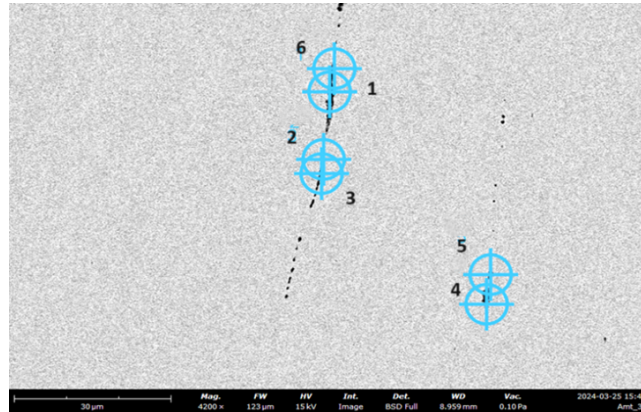


Figure 4.2: SEM image of Sample 3L with the analysed points.

Table 4.2: Percentage in Weight Concentration of each element at each point analysed for Sample 3L.

Element Name	Weight Concentration (%)					
	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6
Boron	-	-	-	13.8	-	-
Carbon	19.5	17.3	16.9	18.1	16.6	17.3
Nitrogen	-	-	-	1.3	-	-
Oxygen	11.1	5.8	9.3	6.8	31.7	5.7
Magnesium	-	-	-	-	0.9	-
Aluminium	1.7	0.8	2.3	-	7.6	1.1
Silicon	3.6	1.7	2.9	-	1.1	2.0
Calcium	1.6	0.9	2.0	-	0.6	1.3
Titanium	0.7	-	-	-	3.2	-
Chromium	14.7	11.9	10.7	11.1	14.7	13.0
Manganese	2.3	2.5	2.6	-	14.0	-
Iron	42.7	53.7	48.0	45.0	9.7	54.8
Nickel	2.0	5.4	5.3	3.9	-	4.8

In Sample 3L, in addition to identifying silicon oxides, the presence of Al and Titanium (Ti) elements was observed at some locations during the analysis. Al, as previously mentioned, is commonly found in furnace compositions in the form of oxide. However, it is often added to the metal bath, along with Ti, to act as a deoxidizing element and prevent the formation of oxides that would compromise the mechanical performance and corrosion resistance of stainless steels [46]. Additionally, Ti forms Titanium Carbides (TiC), which enhance resistance to Intergranular Corrosion by preventing the precipitation of chromium carbides [47]. In Point 4, a peak of the Boron (B) element is identified, which could be attributed to the presence of boron carbides that typically contribute to the improve-

ment of the mechanical properties of the metal. B is normally added to the metal bath because it works as a grain refiner [48]. The high Calcium content could potentially be explained by probable contamination from cleaning products, for example, from Sheet 3 since it is not a common element in the composition of steels.

In Figure 4.3, the various target locations for SEM-EDS analysis of Sample 4 are depicted. Table 4.3 summarizes the results obtained through spectrum analysis for Points 1, 2 and 3.

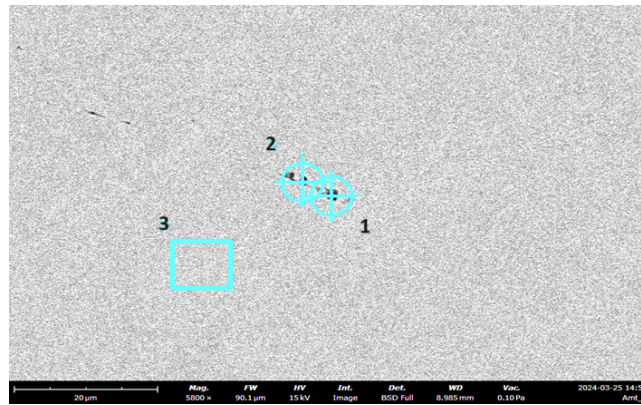


Figure 4.3: SEM image of Sample 4 with the analysed points.

Table 4.3: Percentage in Weight Concentration of each element at each point analysed for Sample 4.

Element Name	Weight Concentration (%)		
	Point 1	Point 2	Point 3
Carbon	11.3	9.3	-
Oxygen	27.4	17.4	-
Aluminium	1.3	1.0	-
Silicon	-	-	0.7
Sulphur	3.1	5.7	-
Titanium	9.7	5.6	-
Chromium	17.8	16.6	17.5
Manganese	19.7	17.1	-
Iron	9.7	26.1	74.3
Nickel	-	1.2	7.5

This analysis revealed, in addition to the previously identified precipitates, a concerning level of Sulphur (S) element, approximately 5.7% at some analysed locations. Sulphur is typically present in stainless steels at levels below 0.030%, as higher concentrations can induce brittleness, reduce steel weldability, and diminish resistance to pitting corrosion. During the solidification process, S can react with Iron (Fe) to form Iron Sulphide (FeS) at grain boundaries with an acicular shape similar to a

needle. The formation of FeS can introduce areas of brittleness in the material, which are more prone to cracking and can lead to hot cracking in the steel. Conversely, when the steel has a lower S content, it may create challenges in weldability and decrease the machinability of the metal. Generally, to prevent FeS formation, Manganese (Mn) content is increased to form Manganese Sulphide (MnS) inclusions, more rounded, which prevent severe hot tearing during rolling or forging. This could explain why the Mn content identified in points 1 and 2 is significantly higher, almost ten times more than the 2% observed in the base metal [49].

After the chemical etching, Sample 3L was subjected to a new SEM-EDS evaluation to understand the chemical composition of the White Lines identified in the OM image of Figure 3.2. Figure 4.4 shows the microstructure of Sample 3L, and the SEM-EDS analysis target locations are indicated by the blue targets. Table 4.4 shows the results for Sample 3L of the points identified in the image.

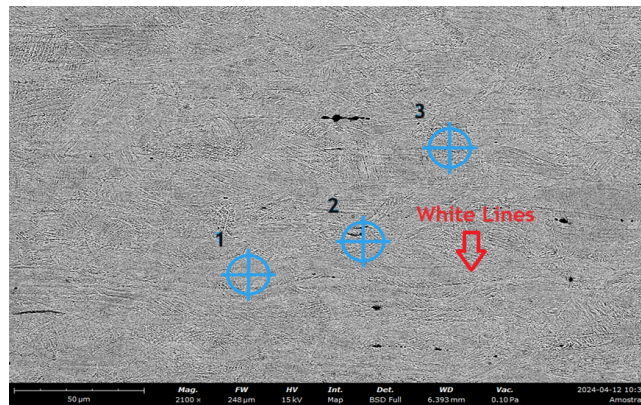


Figure 4.4: SEM image of Sample 3L after chemical etching with the analysed points of the white lines (in red).

Table 4.4: Percentage in Weight Concentration of each element at each point analysed for Sample 3L.

Element Name	Weight Concentration (%)		
	Point 1	Point 2	Point 3
Carbon	4.3	4.3	5.7
Silicon	0.6	0.6	0.6
Chromium	17.9	17.0	17.0
Iron	72.1	71.8	70.7
Nickel	5.1	6.3	6.0

The white lines identified and analysed were found to have the same composition as the base metal (note that the high percentage of carbon in this steel may be related to the limitations of the SEM-EDS technology itself, as previously mentioned). It can therefore be seen that their white appearance, which remained even after chemical etching, is probably due to the high deformation caused by

the cold rolling process and not to differences in chemical composition in these regions. Probably, the deformation introduced caused the appearance of lines orientated in the direction of the rolling process because they were slightly deep, were not attacked by the chemical attack, and therefore always maintained their whitish appearance.

4.1.2 Microstructural Analysis

Samples 1, 2, 3, and 4 were observed through an OM, and the obtained images were all very similar. In Figure 4.5, the microstructure obtained through electrolytic attack for Sample 3 is presented with lower magnification to reveal an overall view of the grain distribution and shape.

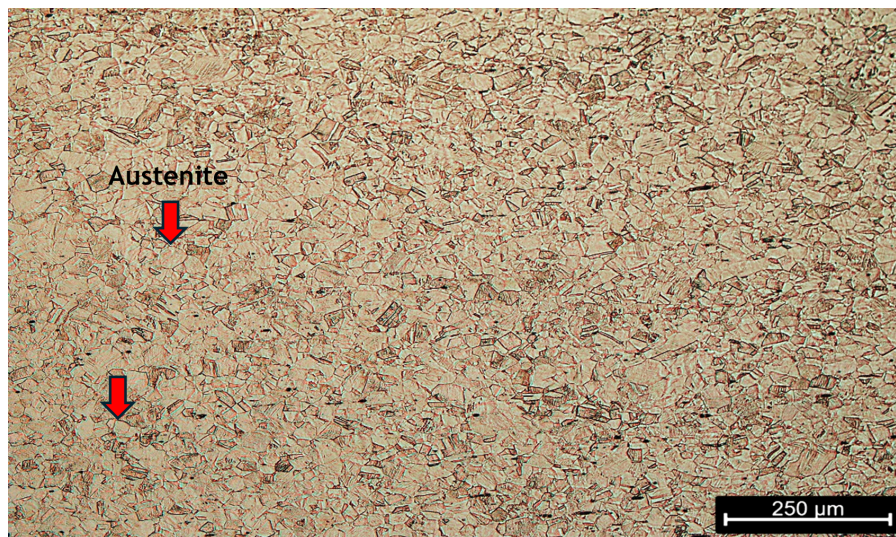


Figure 4.5: Microstructure of Sample 3, obtained by OM through electrolytic attack with 10% oxalic acid, with indication of the austenitic phase.

In the previous figure, the austenitic phase was identified, indicated by red arrows, through comparison with the literature. Figure 4.6 served as a reference (obtained by other authors) for the identification of the phases [50]. The protruding grains observed in the image correspond to the austenitic phase, while the darker phase in the form of needles is martensitic [50].

After the sample's observation, it was noted that they all exhibit precipitates, appearing darker in colour, as indicated by the blue arrows in Figure 4.7, which depicts the microstructure obtained for Sample 3 with higher magnification compared to Figure 4.6.

In Figure 4.7, grains with a darker shade are indicated by red arrows. This appearance may have two possible justifications, either the orientation of this grain differs from the surrounding grains, meaning the crystallographic phases are distinct, resulting in a darker shade, or the transformation of austenite into martensite may have occurred. This transformation is since stainless steel type 301L

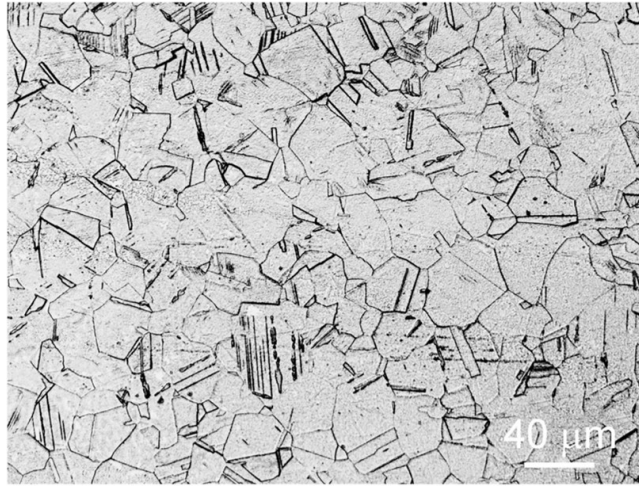


Figure 4.6: Optical image for the as-received 301 stainless steel [50].

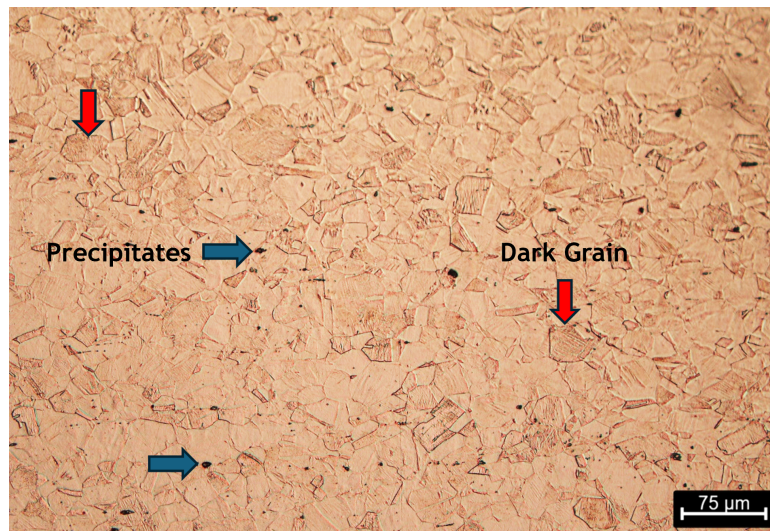


Figure 4.7: Microstructure of Sample 3, obtained through electrolytic attack with 10% oxalic acid by OM, with indication of precipitates (in blue) and dark grains (in red).

is metastable, and therefore, during the cold rolling process, the transformation of austenite into martensite may have occurred, a phenomenon known as Strain Hardening. Strain Hardening involves some distortion at the interface between austenite and martensite due to shear stresses. The shear at the interface occurs by either slip or twinning, resulting in grains with a darker appearance [28]. To ascertain whether it is indeed a martensitic phase, microhardness tests were conducted, the results of which will be presented and discussed later in this study.

In general, the grain size is identical, and the grain shape is mostly equiaxial. Since all samples

originate from metal sheets that underwent the rolling process, one would expect the grains to have a more elongated shape. This apparent contradiction may be explained by the fact that during the sheet manufacturing process, several stages of hot rolling are applied before a final stage of cold rolling which not only allows dimensional control but is also the stage that allows the desired properties to be achieved for the sheet. During hot rolling, the grains recrystallise, which is why they have an equiaxial rather than elongated appearance. This process is also accompanied by the formation of twins, identified with red arrows in Figure 4.8, obtained by a chemical attack with Marble's reagent, in all observed microstructures.

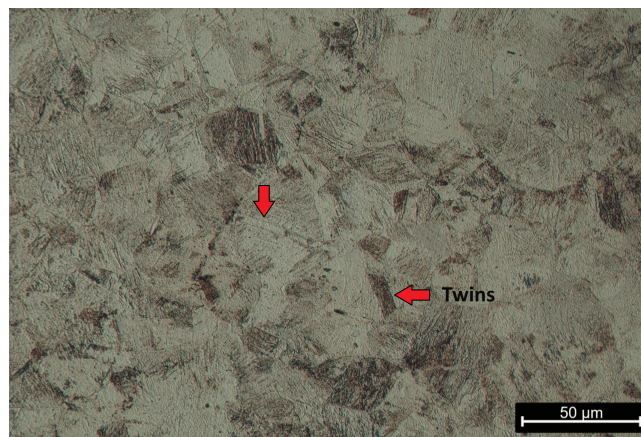


Figure 4.8: Microstructure of Sample 3 obtained through chemical attack with Marble's reagent by OM with indication of the crystalline twinning defect.

Twin boundaries are a type of crystal defect that can occur during solidification, plastic deformation, recrystallization, or grain growth and may be either deformation twins or annealing twins [51].

In the images obtained for the cross-sections of each sheet, the microstructure was challenging to observe because it was underneath whitish deformation lines, identified in Figure 4.9 by the red arrows. These white lines may indicate the direction of deformation resulting from the cold rolling process and observed in all samples.

4.1.3 Vickers Microhardness Analysis

The cross-section samples were then analysed for microhardness to validate whether what was inferred from the analysis in Figure 3 was true, whether the grains with a deformed appearance corresponded to the martensitic phase in the form of small needles or if they were grains with different crystallographic orientations. The results of the *Vickers* microhardness analysis are shown in Table 4.5.

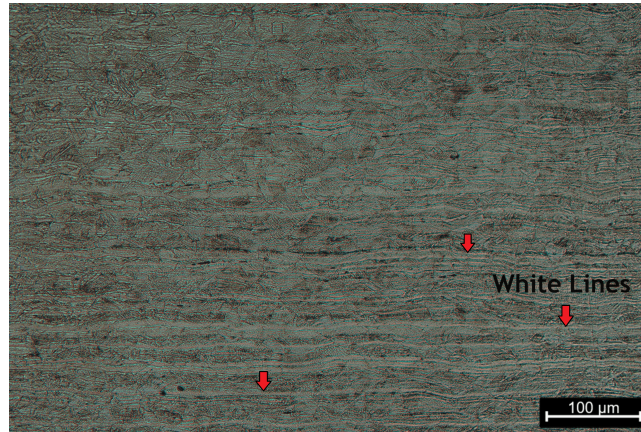


Figure 4.9: Microstructure of Sample 3L, obtained through chemical attack with Marble's reagent by OM, with indication of deformation lines

Table 4.5: *Vickers* microhardness values [HV 0.025] obtained for Samples 1L, 1C, 2L, 2C, 3L, 3C, 4L, and 4C.

Measurement Index	Sample 1L	Sample 1C	Sample 2L	Sample 2C	Sample 3L	Sample 3C	Sample 4L	Sample 4C
[HV 0.025]								
1	517	588	446	448	499	653	446	385
2	633	524	492	468	549	584	429	353
3	488	495	510	552	611	521	398	368
4	575	469	573	427	497	634	405	356
5	462	432	392	416	568	604	361	353
6	479	468	480	436	601	528	464	484
7	511	486	426	445	573	526	374	497
8	535	547	483	486	578	505	425	346
Mean Value	525	501	475	460	560	569	413	393
Standard deviation	53	46	52	41	40	53	33	57

First of all, the hardness values between the sheets vary significantly, with the sheet corresponding to Sample 3, the 11954040 HT sheet, having the highest hardness, with around 564 HV, and the 11954240 MT sheet corresponding to Sample 4, the softest with around 403 HV. This divergence can be explained by the differences in the tempering applied to the sheets. While the last sheet was a Medium-Tensile (MT) sheet, corresponding to the 1/4 hard temper, the others were High-Tensile (HT) sheets, corresponding to 1/2 hard conditions produced by controlled amounts of cold rolling [52].

It was also noted that there are some differences in the *Vickers* hardness values obtained in the samples themselves, with differences of up to 181 HV in the case of Sample 2L, which points to the presence of different phases in the same sheet. In addition to this, can be also observed the increase in hardness caused by cold rolling, since all the samples show values that are much higher than those found in the literature for austenitic stainless steels, around 241 HV [53]. This increase leads to the assumption made earlier, that cold rolling caused the formation of α' -martensite from austenite which typically increases the value of microhardness from 220 to 610 HV due to the applied cold rolling [54]. This conjecture is supported by the fact that the expected *Vickers* hardness values for this phase vary between 525 and 616 HV, values that are in line with the values in Table 4.5 [55]. The observed carbides could also account for this increase; however, every effort was made to avoid data collection in these regions so as not to influence the results.

The results of the *Vickers* microhardness analysis along the profiles of Samples 1L, 2L, 3L and 4L are shown in Table 4.6.

Table 4.6: *Vickers* microhardness values [HV 0.01] along the profiles of Samples 1L, 2L, 3L and 4L.

Measurement Index	Sample 1L	Sample 2L	Sample 3L	Sample 4L
[HV 0.01]				
1	548	450	636	368
2	514	534	641	401
3	457	465	576	363
4	507	576	589	383
5	590	498	577	388
6	570	422	617	363
7	485	466	625	381
8	567	492	660	413
9	451	426	605	360
Mean Value	521	481	614	380
Standard deviation	45	45	26	17

Given that during rolling, mechanical force is applied to the surface of the metal, one would expect to observe a hardness gradient from the surface to the interior in the samples from the cross-section of each sheet, corresponding to a transformation of austenite into martensite predominantly at the surface compared to the interior. However, this was not observed, leading to the conclusion that the transformation of austenite into martensite is randomly distributed throughout the thickness of each sheet. These results also reinforce the analysis conducted in Table 4.5; Sheet 3 exhibits the highest hardness, while Sheet 4 is the softest.

4.1.4 SEM-EBSD Analysis

Through SEM-EBSD analysis of Sample 3, it was possible to conduct a point-by-point analysis, as depicted in Figure 4.10, and to index each point to identify the corresponding phase at the analysed location.

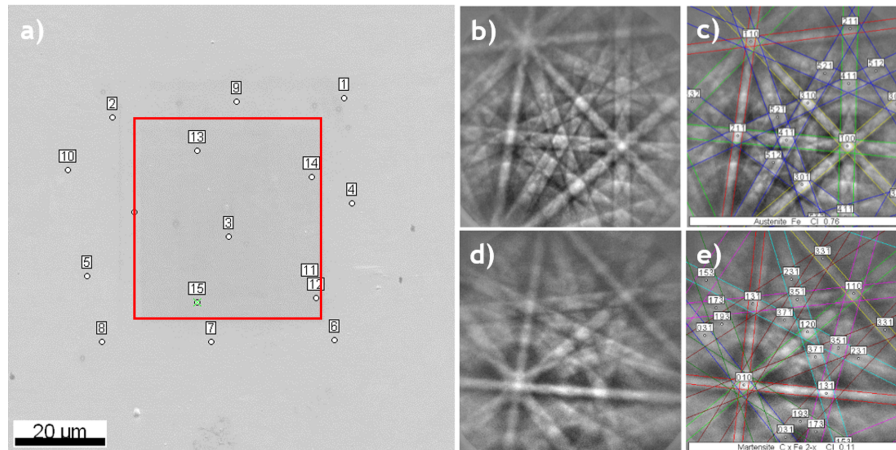


Figure 4.10: SEM image of Sample 3 (a), Kikuchi Patterns obtained for points 13 (b) and 15 (d) and respective indexing (c) and (e).

Figure 4.10 (a) displays the different points targeted for analysis. Figures 4.10 (b) and (d) show identified Kikuchi Patterns for points 13 and 15, respectively, while Figures 4.10 (c) and (e) correspond to the indexing of each pattern, respectively. The indexing presented in Figure 4.10 (c) resulted in the identification of the austenitic phase for point 13, and in Figure 4.10 (e), the identified phase was martensitic for point 15. In reality, what this analysis identifies is a body-centred cubic (bcc) structure that can be associated with ferrite or martensite since they have very close lattice parameters. However, based on the results obtained in the previous microhardness analysis, it was defined that the bcc structure corresponds to the martensitic phase.

The inner area of the red rectangle in Figure 4.10 (a), containing points 3, 11, 12, 13, 14, and 15, underwent scanning analysis resulting in a Phase Map, Figure 4.11, and an IPF Map, Figure 4.12.

In 4.11, it was possible to identify the presence of two distinct phases, the austenitic phase (in red) and the martensitic phase (in green), with a percentage of austenite of approximately 70% and martensite of 30%. This result validates the previous findings; in the OM analysis, darker grains were observed, and in the *Vickers* microhardness analysis, hardness values significantly higher than those typically observed for the austenitic phase were obtained. This Phase Map leads to the conclusion that during the cold rolling process, approximately 30% of the austenite transformed into martensite, thus corroborating the previously conducted microstructural and microhardness analyses. Furthermore,

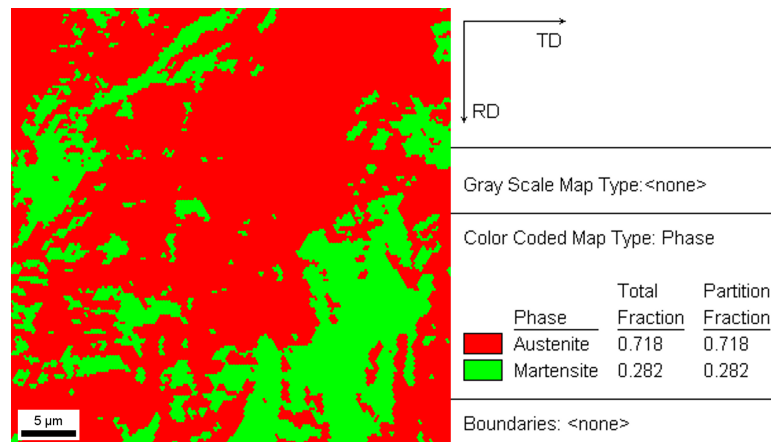


Figure 4.11: Phase Map obtained by SEM-EBSD where the austenitic (in red) and martensitic (in green) phases are identified.

this result aligns with the phase composition prediction provided by the Schaeffler Diagram for the chemical composition of 301L stainless steel [6].

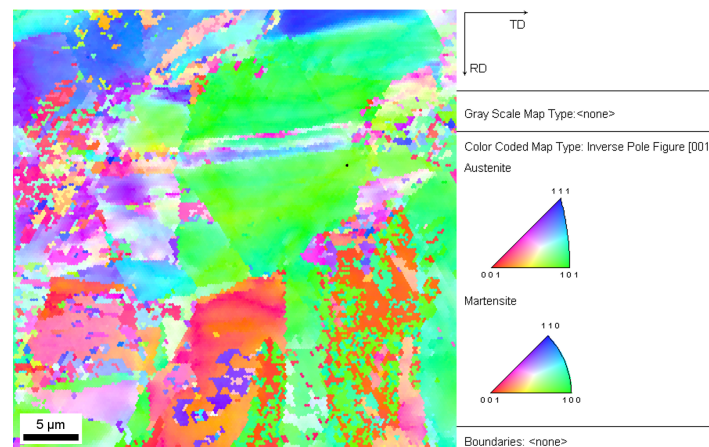


Figure 4.12: The IPF Map obtained by SEM-EBSD identifies the orientation of each grain according to the austenitic and martensitic phases.

In 4.12, it is possible to observe the different orientations of each grain. Given that two distinct phases are present, identifying a predominant orientation becomes a rather complex process, as the same colour may correspond to different orientations according to each phase. It is noticeable that within some grains, there is colour variation, indicating the presence of deformation. This result was expected since the transformation of austenite into martensite involves some distortion due to shear stresses. Noticing that, in order to obtain an analysis with greater statistical weight, at least eight more fields should have been analysed. However, due to a shortage of time (since SEM-EBSD analysis is

a very time-consuming process), it was only possible to analyse two fields whose results were in agreement with each other.

4.1.5 Mechanical Resistance Analysis

Through the tensile tests, the following tensile curves were obtained, Figures 4.13 and 4.14, for Sheets 3 and 4, respectively.

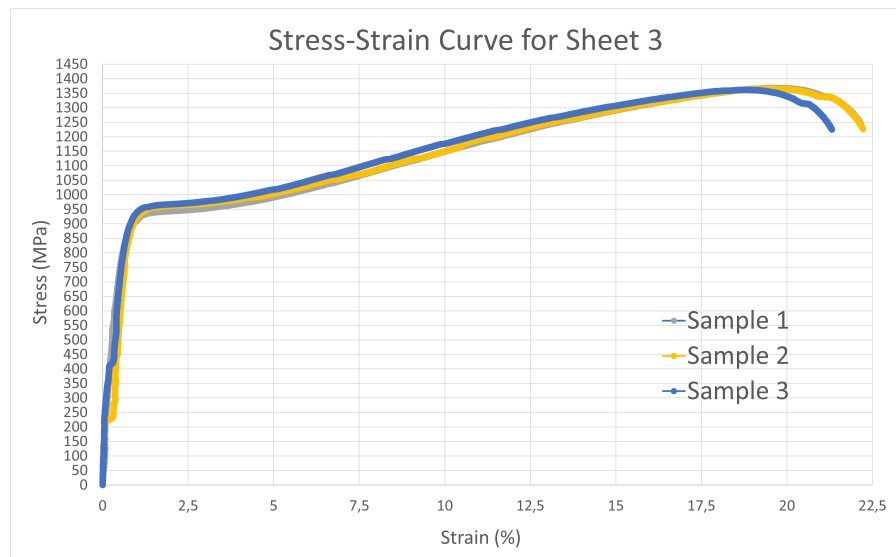


Figure 4.13: Stress-strain curve obtained for Sheet 3.

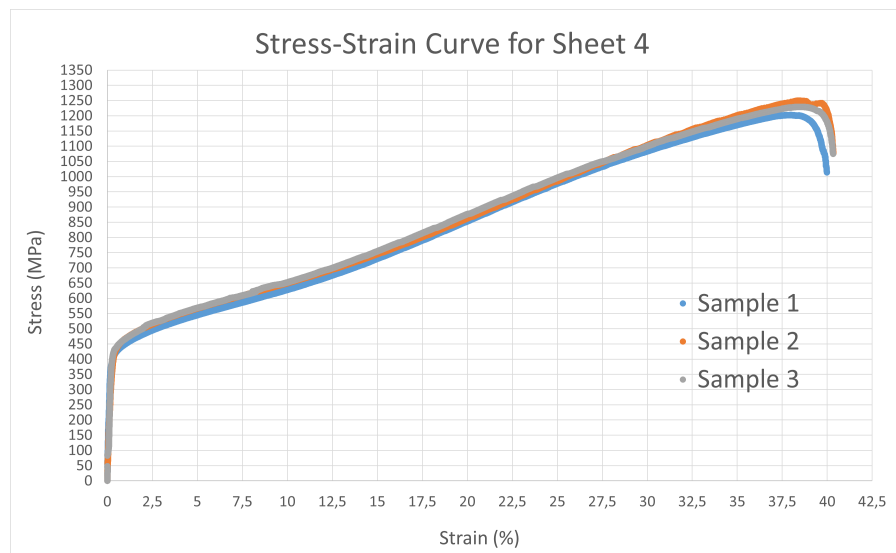


Figure 4.14: Stress-strain curve obtained for Sheet 4.

Through the analysis of the tensile curves, it is possible to observe that, in general, the samples from Sheet 3 exhibit higher mechanical strength than the samples from Sheet 4, but significantly

lower elongation, as the curves are shorter. The data obtained from the test are summarised in Table 4.7.

Table 4.7: Ultimate Tensile Strength (MPa), Yield Strength (MPa) and Elongation (%) for Sheets 3 and 4.

	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)
<i>Sheet 3</i>			
Sample 1	1130	875	25
Sample 2	1129	925	25
Sample 3	1135	900	24
<i>Sheet 4</i>			
Sample 1	826	415	49
Sample 2	852	435	50
Sample 3	841	440	50

The values obtained for both Ultimate Tensile Strength (UTS) and Yield Strength (YS) for Sheet 3 are higher than those obtained for Sheet 4, with a difference of up to 309 MPa for UTS and up to 415 MPa for YS. In terms of ductility, Sheet 4 exhibits twice the elongation compared to Sheet 3. These data are consistent with the values found in the literature and the microhardness analysis conducted in Chapter 4.1.3 [19]. The difference in strength between the sheets can be explained by the same reasons highlighted in that analysis, due to the possible higher amount of martensite in Sheet 3 and the fact that it is High Tensile, whereas Sheet 4 is Medium Tensile. The obtained values are more or less in line with those presented in Table 2.6, except for the significantly higher ductility values. This is ultimately advantageous, as it does not compromise the material's strength. Along with measuring of each sheet's thickness, the mechanical strength constituted the selection factor for the Spot Welding parameters. With this information, it was possible to select the values for weld current, weld time, and electrode force used in the following subchapter.

4.2 Parameterization of Spot Welding

In the first analysis carried out on the equipment *MP500* from *Motofil*, the maximum force values obtained for the sheets from Sheet 2 ranged between 5000 and 7000 N for all the studied times, making it impossible to identify a more favourable period for the joining of the sheets. The joint achieved through the application of a current of 40 A reached a maximum force of approximately 10037 N, and thus, yielded the best result. The diameters of the nuggets averaged around 4 mm for all the welds performed.

Spot Welding was conducted again, but this time using a different piece of equipment, the TECNA DC Three-Phase Resistance Welder. All joints generally, exhibited a depression at the weld point, as observed in Figure 4.15. This depression is undesirable and should be avoided in future tests.

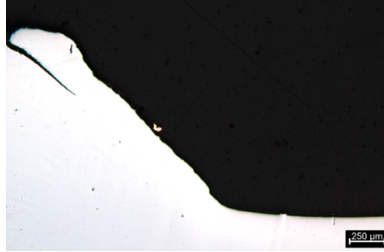


Figure 4.15: Example of the depression observed in OM from Joint 5.

One possible reason for the existence of this depression might be related to the fact that there is only one electrode tip applying all the pressure and introducing electric current into the sheets, as this depression is only observed on the side of the tip. The pressure exerted by the electrodes could also be one of the causes of this depression, as it was not possible for the equipment to control this variable and the pressure applied was twice that recommended in the literature [56]. All the nuggets were measured and they all complied with the relation $3.5\sqrt{t}$ indicated by the ISO 18278-2:2016 Standard [57].

Figures 4.16 (a) and (b) are OM images showing the welded joint of Joints 2 and 4, respectively, see Table 3.4. These images show a considerable amount of porosity in Joint 4 compared to Joint 2. This difference in porosity may be related to the fact that the value of the electric current applied in Joint 4 was excessively high, thus causing the appearance of large pores. According to the EN 15085-3:2022 Standard, these types of porosities are not acceptable in welded joints [32]. Therefore, the current applied in Joint 2, 11 kA, produces the best connections as it exhibits less porosity compared to the others.

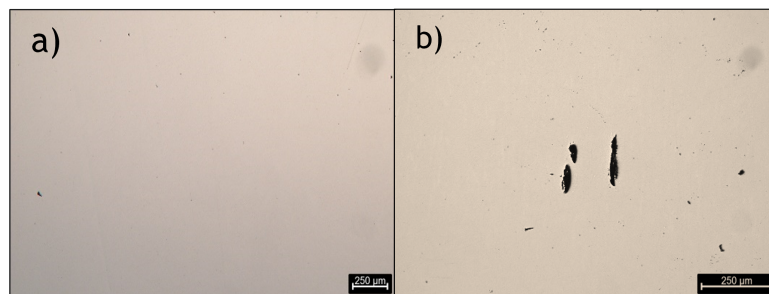


Figure 4.16: OM images obtained from the centre of the welded spot for Joints 2 (a) and 4 (b).

Figures 4.17 (a) and (b) show the joints obtained for 12 and 14 cycles, respectively, see Table 3.5. Based on the obtained images, it was concluded that the most advantageous number of cycles is 12.

For higher cycle numbers, large-sized porosities were observed, as shown in Figure 4.17 (b) for 14 cycles. Additionally, using fewer cycles consumes less energy, thereby reducing electricity costs. The presence of porosity in Figure 4.17 (a) might be related to the application of a current of 12 kA since this type of porosity was observed for currents higher than 11 kA. However, it should be noted that material expulsion occurred in all the joints made, and although this is accepted in the automotive industry, in the railway industry, such a phenomenon results in the joint being rejected.

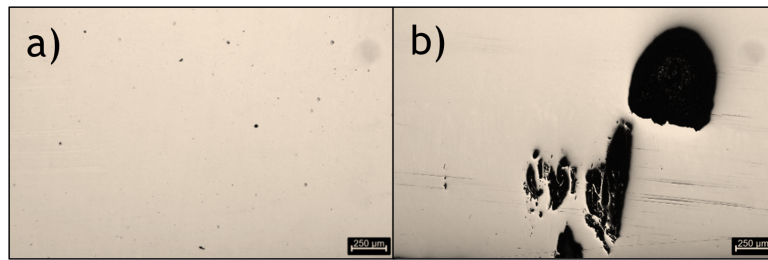


Figure 4.17: OM images obtained from the centre of the welded spot for Joints 5 (a) and 7 (b).

Regarding the third attempt (welding conditions resumed in Table 3.6), in general, all the joints exhibited a slight indentation and some even showed material expulsion, as shown in Figure 4.18 (a) and (b), respectively. However, the observed indentations were much less pronounced than the joints previously analyzed. Although not accepted in the railway sector, these indentations tend to disappear with consecutive spot welding due to the Shunt Effect [31]. This information is quite significant, as an increase in indentation depth leads to a decrease in the energy absorption capacity of the joint [58].

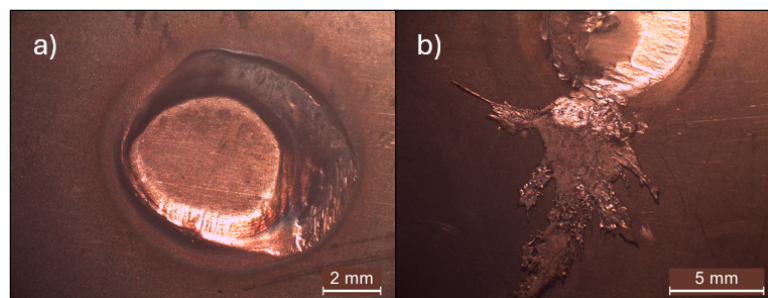


Figure 4.18: Examples of an indentation with some depth (a) and a material expulsion (b), obtained by stereo microscope.

Table 4.8 summarises the results obtained in the Tensile-Shear Test for all the conditions applied with *SCIARY C227SP* equipment.

Upon an initial review, the achieved Shear Strength values are consistent with those found in the consulted literature, approximately 12160 N for specimens from Sheet 4 and 26526 N for specimens from Sheet 3, yielding better results for the softer sheet [6, 39, 40]. This deduction is supported by

Table 4.8: Minimum and Maximum Shear Strength (N), Failure Mode, and existence of Expulsion for all the studied conditions.

Condition	Min. Tensile Shear Strength (N)	Max. Tensile Shear Strength (N)	Failure Mode	Expulsion?
(a)	22661	22857	Interfacial	No
(b)	22776	23601	Interfacial	No
(c)	24381	24655	Interfacial	No
(d)	25441	26102	Interfacial	No
(e)	24776	25432	Interfacial	Yes
(f)	23539	23786	Interfacial	Yes
(g)	14821	15873	Pull-out	No
(dirty)	13911	14907	Interfacial	No
(h)	15394	15868	Interfacial	Yes

the fact that the softer sheet had Shear Strength values all above the value found in the literature, as opposed to the harder sheet, whose values were slightly below the value found in the literature. Furthermore, all the results comply with the minimum values presented in the EN 15085-3:2022 Standard, which is a very positive aspect [32]. The Shear Strength values among the tests do not diverge significantly, and it was observed that for Sheet 3, the condition yielding the best results was condition (d), while for Sheet 4, the best results were obtained with the parameters of condition (g), since material projection is not permitted during Spot Welding. It was concluded that increasing the number of cycles with the same current, condition (c) to (d), also increases the Shear Strength without jeopardising the integrity of the joint. In addition, it was found that the values given in the standard are out of date since conditions (e) and (f), which are closer to the values given in the standard, 12 kA of electric current, showed expulsion of material, which is not permitted. It was also possible to observe the impact of sheet cleaning on the value of the Shear Strength. Compared to condition (g), whose parameters are the same, a difference of approximately 1000 N was obtained from the dirty sheets to the clean sheets, thus reinforcing the need and importance of cleaning the sheets before welding.

Regarding the Failure Mode, condition (g) was the only one that failed in the nugget pull-out mode (failure occurs via complete or partial nugget withdrawal from one sheet), which provides higher peak loads and energy absorption levels than spot welds that fail in the interfacial fracture mode (failure occurs via crack propagation through the fusion zone), thus serving as a good indicator of whether the joint has been properly executed or not [58]. The failure mode again emphasised the relevance of cleaning the sheets, since the failure mode of condition (dirty) was interfacial and not pull-out as observed in condition (g). Figures 4.19 show the difference between pull-out failure (a) and interfacial failure (b).

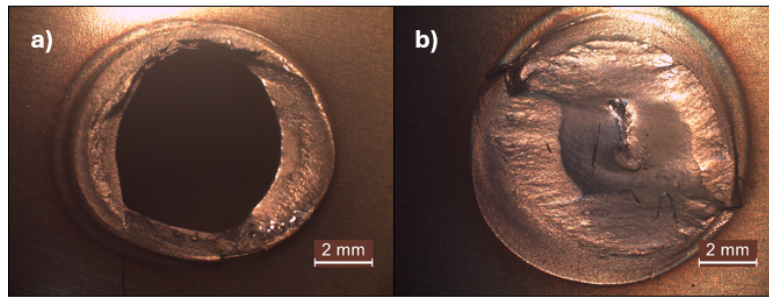


Figure 4.19: Example of a pull-out (a) and an interfacial (b) failure, obtained by stereo microscope.

For the microstructural analysis, conditions (d) and (g) were selected as they presented the best results from the previous test for Sheets 3 and 4, respectively. Condition (c) was chosen to study the impact of the number of cycles on the joint made compared to (d), condition (h) because material expulsion occurred, and condition (dirty) to compare with (g) and ascertain whether the cleaning of the sheets had any impact on the microstructure of the welded joint.

Figures 4.20 (a) and (b) show the nuggets obtained for Sheet 3 under conditions (c) and (d), respectively, and Figures 4.21 (a), (b), and (c) present the nuggets obtained for Sheet 4 under conditions (g), (dirty), and (h), respectively, obtained by stereo microscope. Note that when determining the size of each nugget, the largest size was taken into account.

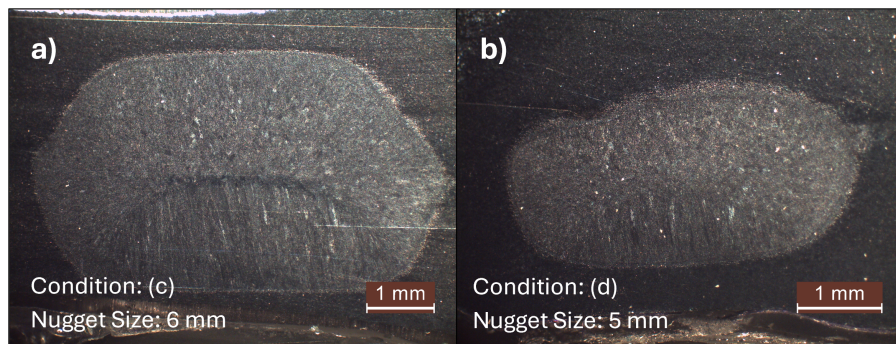


Figure 4.20: Nugget size for conditions (c) in (a) and (d) in (b), obtained by stereo microscope.

All the nuggets complied with the relation $3.5\sqrt{t}$ indicated by the ISO 18278-2:2016 Standard, except for condition (h) [57]. The effect of excessive electric current on the welded joint is quite evident in Figure 4.21 (c), where the nugget size reveals that it is significantly below (more than half) the tabulated value for this thickness.

About the microstructure, Figure 4.22 provides a brief overview of the microstructure of the samples, as they were all quite similar. Figure 4.22 (a) presents an image obtained using a stereo microscope of the joint according to condition (c), where three zones are identified: the Base Material

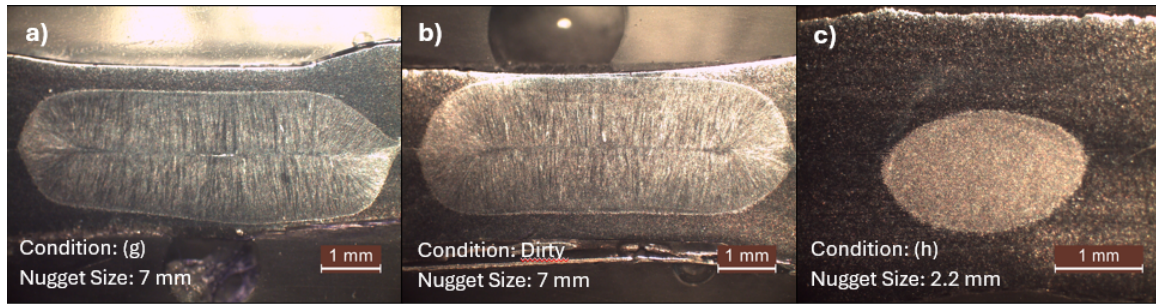


Figure 4.21: Nugget size for conditions (g) in (a), (dirty) in (b), and (h) in (c), obtained by stereo microscope.

(BM), HAZ, and the Nugget. In (b), the microstructure obtained by OM according to condition (g) after electrolytic etching is shown. In (c), an SEM image of the HAZ of condition (g) with higher magnification is presented, while images (d) and (e) show the microstructure of the BM and the Nugget, respectively.

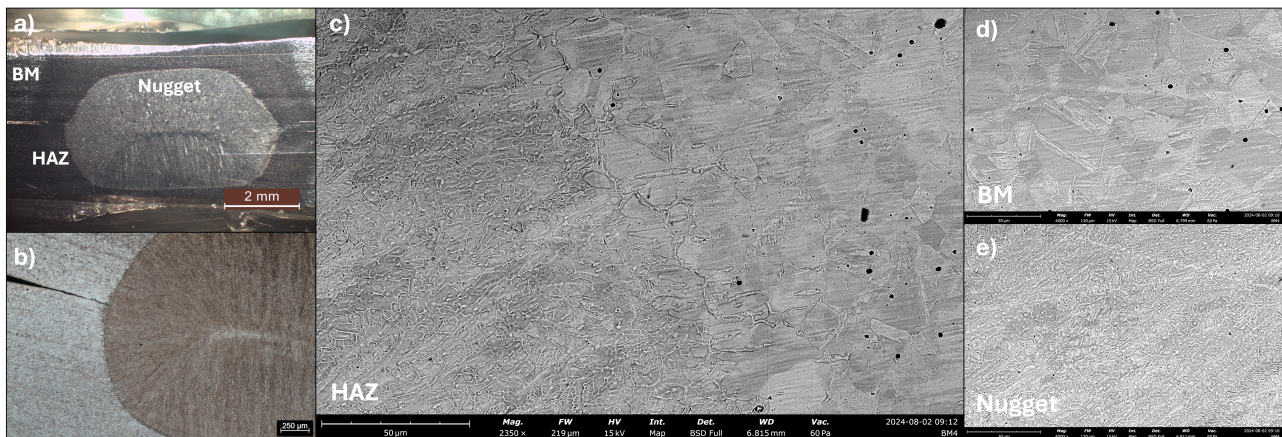


Figure 4.22: Image obtained by stereo microscope of the welded joint (a), microstructure obtained by OM of the welded joint (b), microstructures obtained by SEM of the HAZ (c), the BM (d) and the Nugget (e).

From the analysis of the microstructure images of all the samples, it was possible to identify a dendritic microstructure, as shown in (e), in all the nuggets. According to the literature, these dendrites are composed of austenitic and delta-ferritic phases, with columnar grains making a radial distribution from the nugget edge to the central interface, which has arisen due to the very high cooling rates in the Spot Welding process [58, 59]. No porosities were observed in the centre of the nuggets, representing a significant improvement compared to the previous experiment. Regarding the HAZ, in (c), it was noted that there was a predominance of austenitic grains in this region, as the grains did not appear as dark. This can be explained by the phenomenon of grain recrystallization in this region due

to the high temperature generated during Spot Welding. However, grain growth was not observed in this region, as the size and shape of the grain are quite similar to those of the BM (d), which exhibits a microstructure very close to the initial material.

The microhardness values resulting from the *Vickers* Microhardness Analysis are presented in Table 4.9 for all conditions.

Table 4.9: *Vickers* microhardness values [HV 0.01] for BM, HAZ and Nugget of conditions (c), (d), (g), (dirty) and (h).

Condition	HV [0.01]					
	Min. in BM	Max. in BM	Min. in HAZ	Max. in HAZ	Min. in Nugget	Max. in Nugget
(c)	521	634	329	493	329	359
(d)	549	611	310	477	312	338
(g)	374	464	302	350	363	388
(dirty)	361	446	306	324	319	333
(h)	346	484	303	318	311	331

The analysis of Table 4.9 reveals a significant decrease in hardness values from the BM to the HAZ and the Nugget across all conditions, with the reduction being more pronounced in conditions (c) and (d). This decrease in hardness from the BM to the Nugget can be attributed to the loss of the Strain Hardening effect caused by the high temperatures applied during welding [58]. The elevated temperatures lead to a reduction in the martensitic phase, which is a key contributor to the hardness of the Nugget.

Similarly, the reduction in microhardness within the HAZ is also due to the high temperatures, as the HAZ is located close to the Nugget and is therefore similarly affected by thermal exposure. This thermal exposure results in the loss of cold deformation effects. This deduction is supported by previous microstructural analyses, which observed a reduction in the dark grains associated with the martensitic phase.

Furthermore, the microhardness values obtained for the Nuggets are consistent across all conditions, indicating that regardless of the initial hardness of each sheet, the microstructure formed at the fusion spot is a dendritic structure likely composed of delta-ferrite and austenite, with a microhardness ranging between 311 and 388 HV. This explains the more pronounced decrease in hardness in conditions (c) and (d), as these conditions have higher BM microhardness values. It is also noteworthy that the cleaning of the sheets does not appear to have influenced the hardness of the bond.

Chapter 5

Conclusions

In conclusion, this study enabled a comprehensive characterisation of the 301L stainless steel available at the CP Entroncamento Maintenance Workshop, specifically in terms of *Vickers* microhardness, obtaining values between 403 and 564 HV for the softest sheet, sheet 4, and the hardest sheet, sheet 3, respectively. These results, which are above the tabulated value for this steel (approximately 220 HV according to the consulted literature), prompted a more detailed analysis of the material. From the microstructural analysis combined with SEM-EBSD analysis, the presence of martensite was identified, explaining the increased hardness of the material. This martensitic phase resulted from the Strain Hardening effect during the cold rolling of the sheets. Furthermore, the sheets were characterised mechanically, and ultimate strength values between 826 and 1135 MPa were obtained, in accordance with the values presented in the literature. This information, along with the measurement of the thickness of each sheet, was crucial for defining the parameters for Spot Welding.

Regarding Spot Welding technology, this work proved to be of paramount importance for a deeper understanding of this technology and its applicability in joining 301L sheets. Three different pieces of equipment were studied, with the most interesting results for this thesis being obtained from the last equipment tested, *SCIAKY C227SP*. It was found that cleaning the sheets has a significant effect on the quality of the joint, as uncleaned sheets exhibited a lower shear strength value and an interfacial failure mode compared to clean sheets welded with the same parameters. Good results were achieved in terms of both shear strength and nugget size for the following conditions: for sheet 3 (harder and more resistant), the best combination was an electric current of 8.6 kA, with 15 welding cycles and 900 kg electrode force, obtaining a shear strength between 25441 and 26102 N and a nugget size of about 5 mm. For sheet 4, the softest, the best results were obtained with an electric current of 7.6 kA, with 12 welding cycles and an electrode force of 614 kg, achieving shear strength values ranging from 14821 to 15873 N and a nugget size of about 7 mm. This latter optimisation was superior to

the previous one, as it was the only one to exhibit the pull-out failure mode. It is noteworthy that the parameters adopted for the conditions were adjusted from the standard values due to dialogue with people experienced in Spot Welding, thus pointing to the need for updating the values indicated by the standards. A decrease in microhardness was also observed in all samples studied after welding, inferred to be due to a softening effect due to the application of high temperatures during welding. Furthermore, a dendritic structure probably composed of delta-ferrite and austenite was observed in all nuggets due to high post-welding cooling rates.

For future work, it is suggested to repeat this Spot Welding parameterization procedure for the new SERMEC equipment, where at least eleven Tensile-Shear tests and the microstructure analysis of two samples (in addition to the other tests presented in the standard) should be carried out for each condition to validate the parameterization performed. A review of the parameters presented in the Spot Welding standards may be pertinent, as the values are outdated compared to current technology, and the development of an accredited document with new parameters will certainly be crucial for the Railway Industry. Additionally, studies on the heating and cooling cycles of welding are suggested to ascertain the importance of these cycles in improving the mechanical properties of the sheets and their impact on the percentage of martensite.

In summary, the results obtained not only confirm the effectiveness of 301L stainless steel for railway applications but also highlight the importance of updated parameters and optimised techniques to ensure safety and efficiency in Spot Welding.

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Appendix A

AAS Analysis Results

Elements	% by weight		Elements	% by weight	
	Sheet 1	Uncertainty		Sheet 2	Uncertainty
C	0,026	0,003	C	0,023	0,003
Si	0,441	0,053	Si	0,492	0,059
Mn	1,33	0,16	Mn	1,26	0,15
P	0,024	0,003	P	0,026	0,003
S	0,005	0,001	S	<0,001	
Cr	16,9	2,0	Cr	17,0	2,0
Mo	0,158	0,021	Mo	0,133	0,017
Ni	6,21	0,75	Ni	6,15	0,74
Al	<0,01		Al	<0,01	
Cu	0,125	0,015	Cu	0,144	0,017
Nb	<0,008		Nb	<0,008	
Ti	0,002	0,0003	Ti	<0,002	
V	0,064	0,008	V	0,075	0,009
W	<0,01		W	<0,01	
Sn	<0,002		Sn	0,007	0,001
As	<0,05		As	<0,05	
Mg	*4		Mg	*4	
Fe ⁺³	*2		Fe ⁺³	*2	

Figure A.1: Chemical Composition of Sheets 1 and 2 obtained by AAS.

Elements	% by weight		Elements	% by weight	
	Sheet 3	Uncertainty		Sheet 4	Uncertainty
C	0,026	0,003	C	0,030	0,004
Si	0,449	0,054	Si	0,457	0,055
Mn	1,39	0,17	Mn	1,41	0,17
P	0,023	0,003	P	0,026	0,003
S	0,003	0,000	S	0,005	0,001
Cr	17,0	2,0	Cr	17,0	2,0
Mo	0,224	0,029	Mo	0,231	0,030
Ni	6,38	0,77	Ni	6,23	0,75
Al	<0,01		Al	<0,01	
Cu	0,092	0,011	Cu	0,095	0,011
Nb	<0,008		Nb	<0,008	
Ti	0,004	0,0006	Ti	0,002	0,0004
V	0,066	0,008	V	0,061	0,007
W	<0,01		W	<0,01	
Sn	0,005	0,001	Sn	0,006	0,001
As	<0,05		As	<0,05	
Mg	*4		Mg	*4	
Fe ⁺³	*2		Fe ⁺³	*2	

Figure A.2: Chemical Composition of Sheets 3 and 4 obtained by AAS.