Study of the mechanical and microstructural behavior of laser-welded AISI 441 ferritic and SAE 304 austenitic steel sheets

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ABSTRACT

Stainless steels are widely used in industries due to their high resistance to corrosion. In many of these applications, it is essential to resort to welding processes, which can impact the mechanical, thermal and metallurgical properties of the material. The present study aims to analyze and compare the mechanical properties of hardness and microstructure in the welded region of AISI 441 ferritic and SAE 304 austenitic stainless steels submitted to the laser welding process with a parameter of 1500W - 4.0m/min for 441 and 2000W - 4.0m /min to 304, no shielding gas. For this, laboratory tests were carried out, including metallography, hardness, and non-destructive testing (penetrant liquid). The results obtained made it possible to identify that laser welding without gas protection is effective for joining alloys 304 (austenitic) and alloys 441 (ferritic).

INTRODUCTION

Austenitic stainless steels are a type of steel that belong to the Fe-Cr-Ni system and are formed when austenite is stabilized at room temperature. These steels have a crystal structure known as face-centered cubic (FCC), which means they do not exhibit a temperature at which a ductile-to-brittletransition occurs. (PADILHA e GUEDES, 1994).
Ferritic stainless steels are a type of steel that belong to the Fe-Cr system and have ferrite as the predominant phase in their structure. Unlike austenitic stainless steel, they have a body-centered cubic (BCC) crystal structure and may contain martensite at lower chromium levels. These steels are magnetic and cannot be hardened through heat treatment or precipitation. (KOU,2003).

Within materials engineering, the study of techniques and consumables for welding ferritic stainless steels with austenitic stainless steels stands out. The objective is to combine the high stress corrosion resistance and good thermal conductivity of ferritic stainless steels (which, in general, have limited weldability) with the good weldability exhibited by austenitic stainless steels (but which are usually susceptible to stress corrosion). (PINTO, 2006)

There is a significant focus on studying techniques and consumables for welding ferritic stainless steels with austenitic stainless steels. The aim is to combine the desirable characteristics of these two types of steel to obtain a final material with superior properties.(PINTO, 2006)

Ferritic stainless steels are known for their high stress corrosion resistance and good thermal conductivity. However, they often have limited weldability, making them more challenging to weld compared to other materials. On the other hand, austenitic stainless steels exhibit good weldability but are more susceptible to stress corrosion.(PINTO, 2006)

The welding of ferritic stainless steels with austenitic stainless steels seeks to overcome these limitations. Specific welding techniques and consumables are investigated to achieve a welded joint with suitable properties. These studies may involve selecting appropriate welding parameters, developing specific welding alloys, and applying post-weld heat treatment techniques.(PINTO, 2006)

The main goal is to leverage the stress corrosion resistance of ferritic stainless steels while maintaining the good weldability provided by austenitic stainless steels. This allows to produce a welded material with balanced properties that are resistant to stress corrosion and, at the same time, can be welded without issues.(PINTO, 2006)

These studies and advancements in the welding of ferritic stainless steels with austenitic stainless steels are of great importance in various industries such as the chemical, petrochemical, food, and medical equipment industries, where corrosion resistance and weldability are fundamental requirements for proper material performance. (PINTO, 2006).

Welding is the method of combining two or more parts in order to maintain the mechanical and chemical properties of the material, as well as its continuity. The term "soldering" refers to the process of joining parts together, while the term "soldering" refers to the end result or product of the procedure. (INFOSOLDA,2021).

Laser welding has significant advantages over other welding processes in terms of speed, accuracy and low energy consumption. It is particularly suitable for applications that require the welding of thin materials or materials of varying thickness, such as in the automotive and aerospace industries. Additionally, laser welding can be used on a wide variety of materials, including metals, plastics, ceramics and composites. Pre-engineered laser welding systems can be quickly installed and configured to meet specific application needs, reducing downtime and increasing productivity. (AVENTA, 2018).

Laser welding is particularly suited to sheet metal applications. Sheet metal parts are usually very thin, requiring less heat to enter the drivetrain. It is also often used in applications where high aesthetic qualities are important, such as appliances, pictures or panels. (AVENTA, 2018).

However, laser welding still has some limitations, we can mention the low efficiency, approximately below 10%, the difficulty of changing the focal point, the low power of the device, which limits the thickness, problems with the reflectivity of certain materials and along with close fit tolerances. (INFOSOLDA, 2013).

To avoid these problems, it is essential to have an in-depth knowledge of the possible complications that materials can present during welding, as well as the material, design and welding procedure factors that affect them and their influence on the behavior of the structure in service. soldier. (MODENESI, 2011).

MATERIALS AND METHODS

METALLOGRAPHY

Metallography is, in fact, a crucial analysis to understand the structure and morphology of metals. This test provides essential information about the composition of the alloy, as well as the processing and fabrication steps of the material. In addition, Metallography can also provide a prediction of the chemical and mechanical properties of the material being applied. By examining the microscopic structure of the metal, it is possible to identify features such as grains, inclusions, present phases and possible defects, allowing a more accurate assessment of material properties and assisting in the development of welding processes, heat treatments and selection of suitable materials for different industrial applications. (C2LAB, 2022).

When applying a chemical attack on the sample, a selective reaction occurs with the constituents of the alloy or metal, revealing its microstructural characteristics. This reaction can be viewed macrographically, that is, with the naked eye, or micrographically, using optical or electron microscopes. (C2LAB, 2022).

For the metallography test to take place, it is necessary to prepare the samples.

The first step is to cut the steel plate, in our case a 127V Electric Micro Grinder, from the Dremel brand, was used. After this procedure, hot embedding took place to facilitate the transit of small parts. For the embedding, bakelite in black powder, from the Micron brand, transparent Bakelite, ATM embedding, OPAL X - PRESS and fastening clips for the piece, in order to keep the samples stable at the time of embedding, was used.

Due to the degree of perfection required to complete the sample Ideally prepared for metallography, every preparation step is essential. Carefully executed, it is one of the most time-consuming processes in the preparation process, Metallographic samples.(ROHDE, 2010).

The purpose of this operation is to remove scratches and surface traces. There are two sanding processes: manual (wet or dry) and automatic. (ROHDE, 2010). To carry out the sanding of the experiments, use the Qpol 250 A1-ECO brand automatic polishing sander - and in this way progressive sanding was carried out changing direction (90°) until previous sanding marks have disappeared.

The post-grinding operation aims to obtain a polished surface finish without marks, for which abrasives such as diamond paste or aluminum oxide are used. Before polishing, the sample surface must be cleaned so that it is free of wear marks, solvents, dust and other substances. The cleaning operation can simply be washed off with water, however, it is recommended to use a liquid with a low boiling point (ethanol, freon liquid, etc.), which can dry quickly.(ROHDE, 2010). In our tests, diamond paste was used.

After completing the sample preparation, it is necessary to carry out the chemical attack, whose objective is to allow the identification (visualization) of the contours of the grains and of the different phases of the microstructure. (ROHDE, 2010). Contact the acidic reagent with the surface of the workpiece for a certain period of time. Reagents will corrodesurfaces. The choice of reagents depends on the material and macrostructural composition to be compared in the micrometallographic analysis, as these are stainless steel plates, an electrolytic attack with oxalic acid was used.

Microscopic examination with magnification obviously requires not only special care but also very precise and highly specialized equipment.

To analyze the microstructure of the specimens, it was necessary to use an optical microscope Olympus BX41M.

HARDNESS TEST

A typical method for evaluating hardness involves applying pressure from a specifically dimensioned and weighted object, known as an indenter, onto the surface of the material under test. The hardness value is then determined by measuring either the depth of penetration of the indenter or the size of the impression it leaves behind.(STRUERS ENSURING CERTAINTY, 2023).

There are several hardness tests that focus on measuring the depth of indenter penetration. These include the Rockwell test, Instrumented Indentation Testing, and Ball Indentation Hardness.(STRUERS ENSURING CERTAINTY, 2023).

Alternatively, there are hardness tests that assess the size of the impression left by the indenter. Examples of such tests are the Vickers, Knoop, and Brinell tests.(STRUERS ENSURING CERTAINTY, 2023).

Each of these methods provides valuable insights into the hardness characteristics of the tested material, allowing for an accurate assessment of its mechanical properties. (STRUERS ENSURING CERTAINTY, 2023).

The choice of hardness test should be based on the microstructure, particularly the homogeneity, of the material being tested, as well as factors such as the material type, part size, and condition. (STRUERS ENSURING CERTAINTY, 2023).

In all hardness tests, it is crucial that the indented region represents the overall microstructure of the material, unless the goal is to identify different constituents within the microstructure. Therefore, if a material has a coarse and heterogeneous microstructure, a larger impression size is needed compared to a homogeneous material.(STRUERS ENSURING CERTAINTY, 2023).

There are four main hardness tests, each offering unique advantages and having specific requirements. Various standards exist for these tests, providing detailed procedures and guidelines for their application.(STRUERS ENSURING CERTAINTY, 2023).

When selecting a hardness test method, several important considerations should be taken into account, including:

1. The type of material to be tested for hardness.

2. Whether compliance with a specific standard is required.

3. The approximate hardness range of the material.

4. The homogeneity or heterogeneity of the material's microstructure.

5. The size of the part being tested.

6. The need for sample mounting.

7. The number of samples to be tested. The desired level of accuracy for the hardness measurement. Considering these factors will help determine the most suitable hardness test method and ensure accurate and meaningful results.

The Vickers hardness test is a versatile method used for assessing the hardness of all solid materials, including metallic materials. The hardness value obtained from this test is denoted as Vickers Hardness (HV). (STRUERS ENSURING CERTAINTY, 2023).

Key characteristics of the Vickers hardness test include:

1. Measurement of diagonal lengths: The test involves introducing a diamond pyramid-shaped indenter into the material under a specified load. The resulting indentation takes the form of a square-based pyramid. The diagonals of this indentation are measured optically.

2. Calculation of hardness value: The Vickers hardness value is determined by applying a formula or referring to a conversion table based on the measured diagonal lengths of

the indentation. This value represents the material's resistance to indentation and deformation.

3. Applicability to various materials: The Vickers hardness test is suitable for hardness testing of all solid materials, making it widely applicable in different industries and materials science research. It is commonly used for metallic materials but can also be applied to ceramics, composites, and other solid materials.

4. Wide range of applications: The Vickers hardness test finds applications in various fields, including quality control, material characterization, and research. It provides valuable insights into material properties, such as strength, wear resistance, and structural integrity.

5. Sub-group for hardness testing of welds: The Vickers hardness test includes a sub-group dedicated to assessing the hardness of welds. This is particularly important in welding quality control, as hardness variations within the weld area can indicate potential issues with the welding process.

Overall, the Vickers hardness test is a versatile and widely used method for evaluating the hardness of solid materials, including metallic materials. Its ability to provide accurate measurements and its broad applicability make it valuable in a wide range of industries and research disciplines.(STRUERS ENSURING CERTAINTY, 2023).

To carry out the hardness test, the same specimens used in metallography were used, being thus placed in a QATM hardness tester, model QNESS 60 A+EVO, with a load of 0.5 HV.

Based on the ISO 13919-1 standard, 26 points were performed on the piece to determine the hardness of the material. There were 4 points in stainless steel, 24 points in the Abnormal Transformation Zone and finally, 6 points where laser welding was performed.

LIQUID PENETRANT TESTING

Liquid or dye penetrant testing (PT) is a non-destructive method used for testing materials. This technique utilizes capillary forces to identify and make visible surface cracks or pores. It is highly effective in detecting flaws that extend to the surface, including cracks, laps, and porosity.

Liquid or dye penetrant testing (PT) relies on the penetration of liquid penetrant into visible surface irregularities. However, it is important to note that penetrant testing is not suitable for highly porous materials. The dye penetrant method is primarily utilized for identifying surface defects, such as surface cracks, pores, lack of fusion, and intergranular corrosion. This testing technique is commonly employed on both welds and parent materials to ensure their integrity.

It is important to differentiate between dye penetrant testing and fluorescent penetrant testing, as they have distinct characteristics. Both methods focus on examining the near-surface area of a test piece. The process begins with pre-cleaning the surface, followed by the application of the penetrant onto the test piece. Through the capillary effect, the penetrant seeps into fine cracks or pores. Subsequently, the excess penetrant is carefully removed from the surface, and a developer is applied. This developer helps draw out thedye penetrant from the cracks and pores, creating indicationsthat can be evaluated.

Dye penetrant testing typically employs a red dye penetrant, allowing for testing in daylight. On the other hand, fluorescent penetrant testing utilizes a fluorescent test agent, which is easier to assess in darkness or under UV light.

Liquid penetrant testing is a versatile method that can be applied to both metallic and non-metallic materials, as long as they are non-porous and clean. However, it is important to note that it is unsuitable for surfaces that are dirty or excessively rough. Surface cleaning plays a crucial role in the effectiveness of penetrant testing. The method can be executed manually, semi-automatically, or fully automated, depending on the specific requirements.

In the case of continuous-operation production lines, where specimens undergo a series of cleaning, dipping, washing, and drying cycles, penetrant inspections are commonly performed.

As a degreaser, penetrant and developer, we use the Metal-Chek brand, which is a leading company in the market for non-destructive tests using Penetrant Liquid methods, among others.

The figure 1 shows the sequence of materials used in test penetrating liquid

Figure 1. Surface cleaning (degreasing) (a); Penetrant liquid (b); Developer (c).

Liquid penetrant testing typically follows a six-stage process:

1. Surface cleaning: This involves the removal of contaminants such as grease and dirt from the surface of the test specimen.

2. Application of penetrant liquid: The penetrant liquid is applied to the cleaned surface using methods like dipping, spraying, or brushing. The penetrant infiltrates any surface discontinuities, such as cracks or pores, by capillary action.

3. Removal of excess penetrant: After a suitable dwell time, the excess penetrant is removed from the surface. This can be achieved through the use of solvents or water, depending on the type of penetrant used.

4. Application of developer: A developer is applied to the surface to draw out the penetrant from any discontinuities. The developer helps create a visible indication of the flaws.

5. Inspection of the test surface: The test surface is inspected for indications using visual examination or tools such as a television camera. The indications are evaluated to determine the presence and characteristics of any defects.

6. Post-inspection cleaning: After the inspection, the test surface is cleaned, and additional measures like applying

7. anti-corrosion solutions may be undertaken to preserve the integrity of the specimen.

RESULTS AND DISCUSSIONS

METALLOGRAPHY

Figure 2 shows the metallography performed using a microscope with a 50x magnification lens.

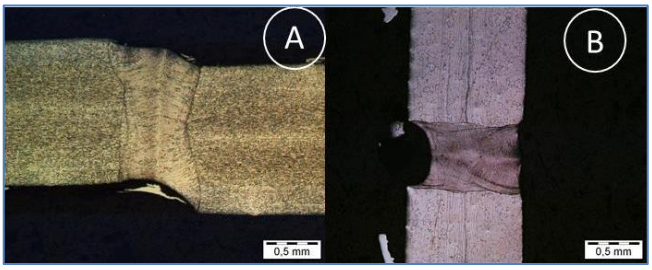

Figure 2. Metallography of austenitic steel 304 (A); Metallographyof ferritic steel 441 (B).

Figure 3 illustrates the metallography performed using lenses with a magnification of 100x.

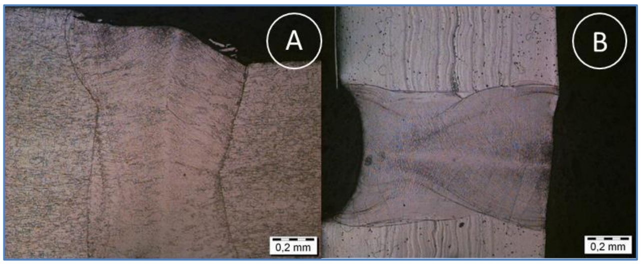

Figure 3. Metallography of austenitic steel 304 (A); Metallography of ferritic steel 441(B).

And figure 4 shows the metallography conducted using lenses with a magnification of 200x.

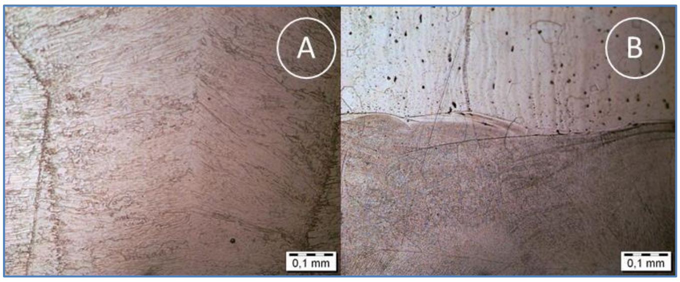

Figure 4. Metallography of austenitic steel 304 (A); Metallography of ferritic steel 441 (B).

The combination of 1% oxalic acid and electrolytic etching promotes a better and more efficient revelation of the microstructure of austenitic steel 304.

LIQUID PENETRANT TEST

Figure 5 demonstrates the application of liquid penetrant on stainless steel plates.

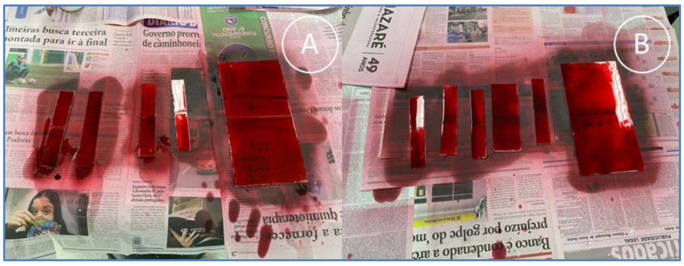

Figure 5. Application of liquid penetrant on stainless steel 304 (A); Application of liquid penetrant on stainless steel 441 (B).

Figure 6 displays the application of the developer after cleaning and removal of excess penetrant on the test specimens to reveal unconformities.

The first stage of the analysis of the welded plates consisted of visual inspection, this stage allows the identification of macroscopic defects such as cracks, cavities, pores and burrs on the edges. Thus, it can be seen that the penetrating liquid was not revealed, there are no surface cracks on any of the plates in the weld region. Therefore, it was possible to analyze and verify that laser welding did not induce any surface imperfections, such as cracks, surface porosities or fractures.

What becomes the distinguishing factor is that due to the high cooling speed, the process becomes susceptible to cracks and fractures in the weld. The part was made without the addition of shielding gas, yet the weld remained intact.

HARDNESS

Figure 7 presents the Vickers hardness results on stainless steel 441. The colors correspond to the averages of the results obtained in the hardness test of the points presented in table 1, where the light green line corresponds to the sequence of point 1 in the table, the pink line corresponds to the sequence of point 2, the red line corresponds to the sequence of point 13, and the dark green line corresponds to the sequence of point 13..

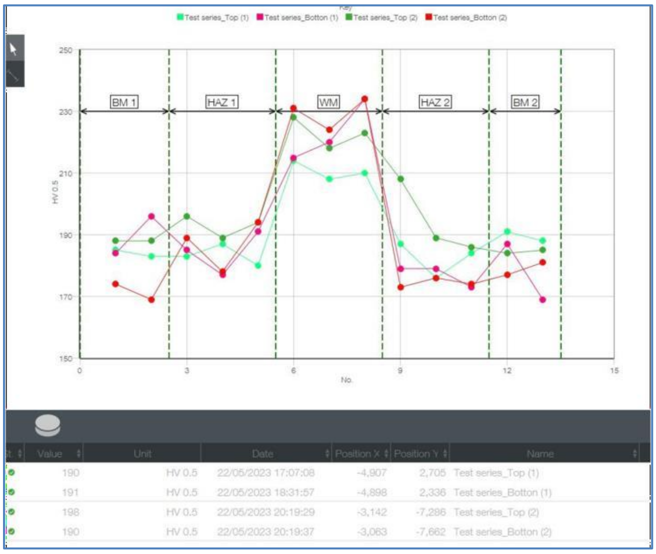

Figure 7. Average Vickers hardness of steel 441.

And figure presents the average Vickers hardness results on stainless steel 304, where the dark green color corresponds to point 1, orange to point 2, dark blue to point 12, and light blue to point 13.

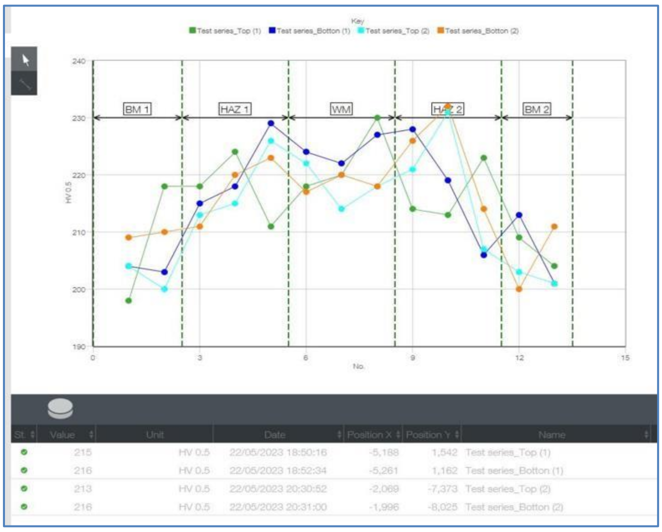

Figure 8. Average Vickers hardness of steel 304.

As an inherent characteristic during welding, grain growth occurs in stainless steel 441, causing a decrease in hardness in the heat-affected zone. Although the micrograph shows slightly larger grains, the obtained results did not significantly affect the hardness when compared to the base material in the heat-affected zone.

441								
BM			HAZ			WM		
Ponto	441-1	441-2	Ponto	441-1	441-2	Ponto	441-1	441-2
1	185	184	3	183	185	6	214	215
2	183	196	4	187	177	7	208	220
12	191	187	5	180	191	8	210	234
13	188	169	9	187	179			
			10	176	179			
			11	184	173			
Média:	185,3		Média:	181,7		Média:	216,8	

Table 1: Hardness of alloy 441.

304								
BM			HAZ			WM		
Ponto	304-1	304-2	Ponto	304-1	304-2	Ponto	304-1	304-2
1	198	204	3	218	215	6	218	224
2	218	203	4	224	218	7	220	222
12	209	213	5	211	229	8	230	227
13	204	201	9	214	228			
			10	213	219			
			11	223	206			
Média:	206,2		Média:	218,1		Média:	223,5	

Table 2: Hardness of alloy 304.

Comparing the hardness of the base material of stainless steel 441 with the hardness found in 304, a variation of 20.9 HV 0.5 was obtained. There was a hardness variation of 36.4 HV 0.5 in the heat-affected zone (HAZ) and a variation of 6 HV 0.5 in the fusion zone.

According to the conducted procedures, an increase in hardness can be identified in the HAZ of stainless steel 304, with a significant increase in the fusion zone. Similarly, in stainless steel with 441 alloy, an increase in hardness can beidentified in the HAZ, with a significant increase in the fusion zone.

When comparing the two, there are no significant variationsin hardness in the fusion zone. In the HAZ, there were also small variations as shows tables 1 and 2.

The laser welding process without gas shielding is effective for joining austenitic 304 alloys and ferritic 441 alloys. It does not show significant variation that could restrict its use.

LEVELING

The figures 8, 9 ,10, 11 and 12 below display the results of the leveling studybetween the base material and the weld, conducted on the304 and 441 steels.

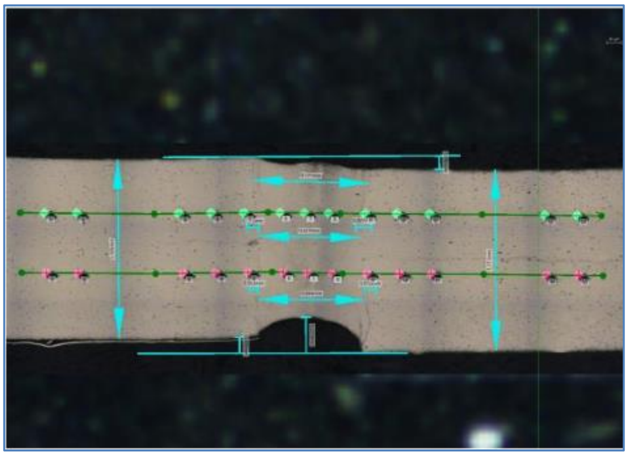

Figure 9. Sample 1 steel 441

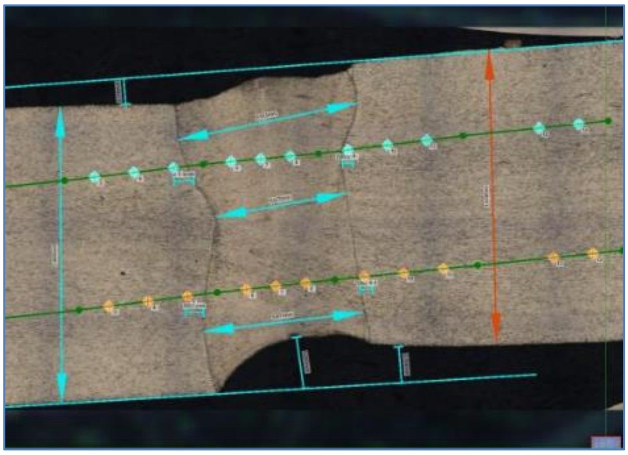

Figure 10. Sample 1 steel 304.

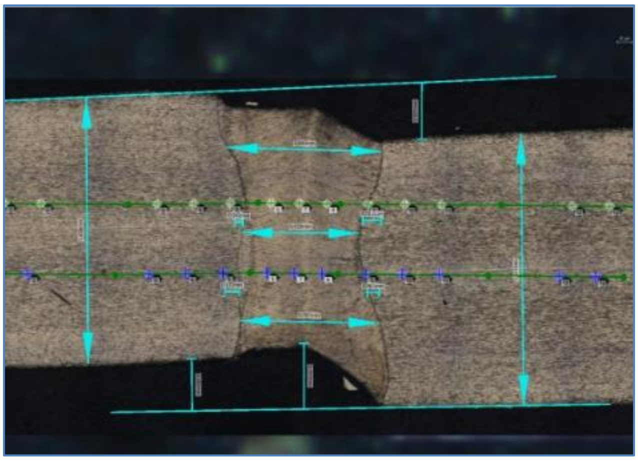

Figure 11. Sample 2 steel 304.

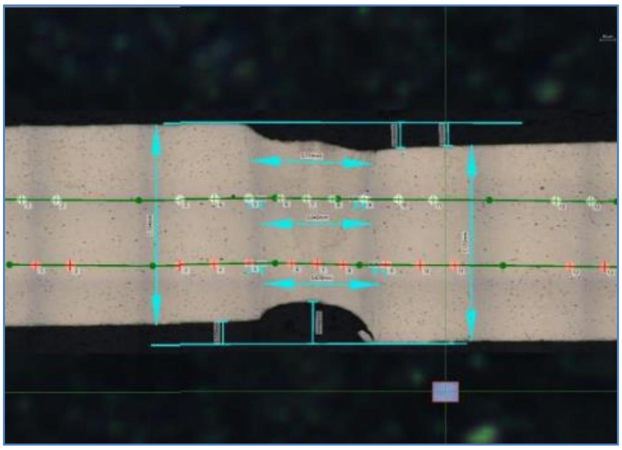

Figure 12. Sample 2 steel 441

Due to the extremely low electrical conductivity of stainless steel, distortion of the sheet occurs, leading to unevenness, and there is a variation in thickness in the heat-affected zone, as observed in images from 9 to 12, highlighted in blue and orange in the measurements.

CONCLUSION

Liquid Penetration test - The samples remained intact and without cracks, as observed in the liquid penetrant testing. Despite the part being welded without mechanical restraint and stainless steel having low thermal conductivity as a characteristic, it did not exhibit any type of crack.

Based on the conducted procedures, it is possible to identify an increase in hardness in the heat-affected zone (HAZ) of stainless steel 304, with a significant increase in the fusion zone. Similarly, in stainless steel with 441 alloy, there is an increase in hardness in the HAZ, with a significant increase in the fusion zone.

When comparing the two steels, it can be observed that the hardness in both fusion zones does not show significant variations. Likewise, in the HAZ, there were no significant variations.

In future works it becomes clear the importance of carrying out the tensile strength test in order to obtain results that provide information on the mechanical strength of the material and the behavior of welded plates, seeking to understand and compare the strength in relation to the different types of steel laser-welded stainless steel.

Comparison of the mechanical properties between these materials is crucial to select the best option for each specific application, taking into account requirements such as resistance, durability and cost.

Finally, it is concluded the laser welding process without gas shielding is effective for joining austenitic 304 alloys and ferritic 441 alloys.

BIBLIOGRAPHIC REFERENCE

AVENTA**, Você já ouviu falar em soldagem a laser?,** 12 de ABR. de 2018, Disponível em:<https://aventa.com.br/novidades/voc%C3%AA-j%C3%A1-ouviu-falar-em-soldagem-laser>. Acesso em: 23 de abr. de 2023.

C2LAB**, Metalografia: entenda o ensaio e seus objetivos**, 28 de mar. 2022, Disponível em:< https://c2lab.com.br/blog-metalografia-entenda-o-ensaio-e-seus-bjetivos/#:~:text=Solicite%20um%20or%C3%A7amento-,Metalografia%3A%20o%20que%20%C3%A9,qu%C3%ADmicas%20e%20mec%C3%A2nicas%20em%20aplica%C3%A7%C3%A3o.>, Acesso em: 20 de Maio 2023.

DEKRA, ON THE SAFE SIDE**, Liquid Penetrant Testing**, 2023, Disponível em: <https://www.dekra.com/en/liquid- penetrant-testing/> Acesso em: 25 de Maio 2023.

INFOSOLDA, **Pequeno Histórico da Soldagem,** 1 de dez. De 2021, Disponível em:< https://infosolda.com.br/pequenohistoricodasoldagem/#:~:text=Os%20Estados%20Unidos%2C%20nos%20anos,soldag em%20cada%20vez%20mais%20automatizados.>. Acesso em: 23 de abr. 2023

INFOSOLDA, **Soldagem a laser – Características do processo,** 22 de fev. De 2013, Disponível em:<https://infosolda.com.br/190-soldagem-a-laser/#:~:text=O%20processo%20de%20soldagem%20a%20laser%20apresenta%20algumas%20limita%C3%A7%C3%B5es%2C%20entre,e%20as%20estreitas%20toler%C3%A2ncias%20de>Acesso em: 01 de Maio. 2023.

KOU, S., Welding Metallurgy. 2nd Edition, Wiley Interscience, New Jersey, v.2, 2003.

MODENESI, Prof. Paulo J., **Soldabilidade de Algumas Ligas Metálicas,** UNIVERSIDADE FEDERAL DE MINAS GERAIS, Departamento de Engenharia Metalúrgica e de Materiais, Minas Gerais, v. 1, n. 27, p. 2, 2011.

PADILHA, Angelo Fernando e GUEDES, L C. **Acos inoxidaveis austeniticos: microestrutura e propriedades.** . São Paulo: Hemus. . Acesso em: 26 maio 2023. , 1994

PINTO, Daniel, **Comportamento em Corrosão Sob Tensão de um Aço Inoxidável Ferrítico** AISI 444 Soldado com Aço Inoxidável Austenítico AISI 316LSi, em Meios Contendo Cloretos, Programa de Pós-Graduação em Engenharia de Materiais da REDEMAT, Ouro Preto, v.1, pag. 1, 2006.

ROHDE, Regis Almir**,** **METALOGRAFIA PREPARAÇÃO DE AMOSTRAS**, LEMM Laboratório de Ensaios Mecânicos e Materiais, Santo Angelo, v.3, 2010.

STRUERS ENSURING CERTAINTY, **Hardness Testing,** 2023,Disponível em:https://www.struers.com/en/Knowledge/Hardness-testing#.> Acesso em: 22 de Maio 2023.

MINAS GERAIS, Departamento de Engenharia Metalúrgicae de Materiais, Minas Gerais, v. 1, n. 27, p. 2, 2011.

PADILHA, Angelo Fernando e GUEDES, L C. **Acos inoxidaveis austeniticos: microestrutura e propriedades**. . São Paulo: Hemus. . Acesso em: 26 maio 2023. , 1994

PINTO, Daniel, **Comportamento em Corrosão Sob Tensão de um Aço Inoxidável Ferrítico AISI 444 Soldadocom Aço Inoxidável Austenítico AISI 316LSi, em Meios Contendo Cloretos**, Programa de Pós-Graduação em Engenharia de Materiais da REDEMAT, Ouro Preto, v.1, pag. 1, 2006.

ROHDE, Regis Almir, **METALOGRAFIA PREPARAÇÃO DE AMOSTRAS,** LEMM Laboratório de Ensaios Mecânicos e Materiais, Santo Angelo, v.3, 2010.

STRUERS ENSURING CERTAINTY, **Hardness Testing**, 2023, Disponível em:https://www.struers.com/en/Knowledge/Hardness-testing#.> Acesso em: 22 de Maio 2023.

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