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EFFECTS OF THE WELDING PROCESS ON THE STRUCTURE AND MECHANICAL PROPERTIES OF STEEL 4130

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Abstract. *Welding of low alloy and high strength steels represents a constant challenge to the metallurgical industry due to the great industrial need to associate rigorous requirements of high mechanical strength and toughness simultaneously with a material. In this context, the present work aimed to conduct a comparative study on the weldability of SAE 4130 steel, commonly used in the aeronautics and automotive industry. The first analyzes aimed to characterize the steel in its state of supply with mechanical tensile and hardness tests in addition to a metallographic analysis. Later, conventional welding techniques such as Tungsten Inert Gas and Coated Electrode were applied. Shielded Metal Arc Welding - SMAW), being manufactured test specimens following the AWS - American Welding Society standards. After welding, a detailed metallographic analysis was carried out with the purpose of obtaining and comparing information related to the changes caused to both welding processes. A microstructural characterization of the Fusion Zone (ZF) and Thermal Affected Zone (ZTA) was performed.*

Keywords: *SAE 4130 Steel, Weldability, GTAW Welding, Welding with Coated Electrode..*

1. INTRODUCTION

The process of fabrication of metallic materials has an unparalleled importance in the economic sector of the society, so there is a great need for evolution only increased, being implemented techniques for better performance of these materials, using secondary processes such as welding and treatments which in turn mold all the material to the required new properties.

Welding as a secondary process in metallurgy has become very necessary, due to the transformation that the material undergoes, from its properties, that influences all the performance of the material, until the lifetime of the same, classically defined as a "method of union between two metal parts, using a heat source, with or without application of pressure "(BRANDI, 1991).

Thus, one of the main characteristics for the commercialization of the metallic materials is the weldability, which required a technological development in this area, in order to make its use feasible.

1.1. Steels

As the most versatile metal alloy materials, steels are produced in large varieties of types and shapes, to effectively meet one or more applications. This variety stems from the need for uninterrupted product adaptations, to the demands of the market that demands specific applications, be they in the changes of the mechanical properties, the chemical composition, or even in the final form of the material. (Brazilian Center for Steel Construction, 2014)

The material studied in the present work belongs to the 41XX family of steels, which includes low alloy and high strength steels as specified by the American Iron and Steel Institute (AISI). The 4130 series steel, also known as chromium-molybdenum steel, is classified as medium carbon steel.

The advantages of using an alloy steel, that is, an alloy-added steel, compared to carbon steel, according to SOUSA, 1989:

1 - Greater temperability;
2 - Minor distortion and cracks after tempering heat treatment;
3 - High stress relief to achieve a certain hardness of the material;
4 - Higher elasticity;
5 - Higher ductility with more mechanical resistance.

AISI 4130 steel assumes carbon contents between 0.2% and 0.3% in its structure, reaching temperatures up to 480 ° C, but values above that reduce the resistance of the material rapidly (Rocha, 2004).

Its properties of high mechanical strength and high temperatures enable its application in racing car structures, bicycle and motorcycle frames, piping structures, petrochemical industry and aircraft (Oberg et al., 2004).

The highest requirements for this type of steel are the requirements of mechanical strength, adequate ductility, impact strength and toughness, fatigue strength and good weldability (Pickering, 1978).

2. **WELDING PROCESSES**

The welding process is used to attach materials, similar or otherwise, permanently, from a heat source, and may or may not use pressure. Its application varies according to the various existing methods and joints characteristics, such as thickness, part geometry, type of material used and type of performance expected.

Welding seeks to provide strong mechanical adhesion of the materials being a process involving many metallurgical procedures such as melting and solidification. This is one of the greatest difficulties encountered in working with welding, because metals react very quickly to the atmosphere when they receive heat.

The aspects related to the heat flow and the temperature distribution existing in the welding process have a significant influence on the microstructure and the mechanical properties of a welded joint. In single-stranded or multipass welding, the ZAC (Heat Affected Zone) may exhibit a large incidence of microstructurally heterogeneous zones, and highly fragile constituents, which can greatly reduce the strength of a welded joint (Silva, 2009).

In the current work, two welding processes were used in order to see the weldability of the 4130 steel, the process with Coated Electrode (SMAW) and Tungsten Inert Gas (TIG).

2.1. **Welding with Coated Electrode - SMAW**

Shielded Metal Arc Welding (SMAW) is a process that produces coalescence between metals by heating them with an electric arc established between a coated metal electrode and the part being welded (Bracarense, 2000). The process is outlined in figure 01.

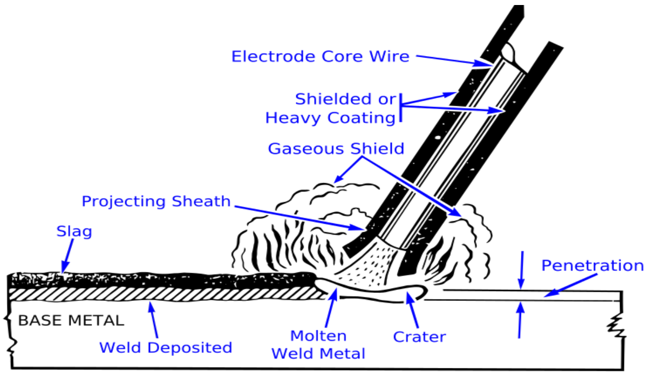

Figure 1. Welding Process with Coated Electrode.
Available from: https://archive.org/details/TM9-237

The process coated electrode consists of a metal rod, called "core", drawn or cast, which conducts the electric current and provides addition metal for filling the joint. The core is covered by a mixture of different materials in a layer that forms the "coating" of the electrode. Welding is performed with the heat of an electric arc maintained between the end of a coated metal electrode and the workpiece. The heat produced by the arc fuses the base metal, the electrode core and the coating.

When the molten metal droplets are transferred through the arc into the melt pool, they are protected from the atmosphere by the gases produced during the decomposition of the coating. The liquid slag floats toward the surface of the melt pool, where it protects the weld metal from the atmosphere during solidification.

The welding with coated electrode is used in the manufacture and assembly of different equipment and structures, both in workshops and in the field, being particularly interesting in the latter case. It can be used in a large number of materials, such as low carbon, low alloys, medium alloys and high alloys, stainless steel, cast iron, aluminum, copper, nickel and alloys.

2.2. **Welding Tungsten Inert Gas (TIG)**

The Tungsten Inert Gas or Gas Tungsten Arc Welding (GTAW) welding process, as is technically known, is an electric arc welding process that uses a non-consumable tungsten electrode to form the electric arc and thus the fusion (Bracarense, 2000).

The melt puddle, tungsten electrode and part of the cord are protected by the shielding gas flowing through the torch nozzle. In the GTAW process, the shielding gases are directed by the torch to the arc and the melt pool, to protect the electrode and the molten metallic material from atmospheric contamination, as shown in figure 02.

The most common types of gases used in the process are argon, helium, and mixtures thereof, as well as mixtures with hydrogen and nitrogen.

The argon that is normally used has a purity of 99.95% and is acceptable for most metals. However, in special applications where high quality welded metal is required, ultrahure 5.0 argon is used, which has a purity of 99,999 % (Louriel, 2009).

In the process, addition or non-addition metal (autogenous welding) may be used. It has great application in the welding of materials of difficult weldability, such as alloys of aluminum, magnesium, titanium, carbon steels.

In addition to places where welding is required without inclusions such as applications of root pass in pressure vessels, boilers and applications directly linked to the aviation industry such as special alloy welding.

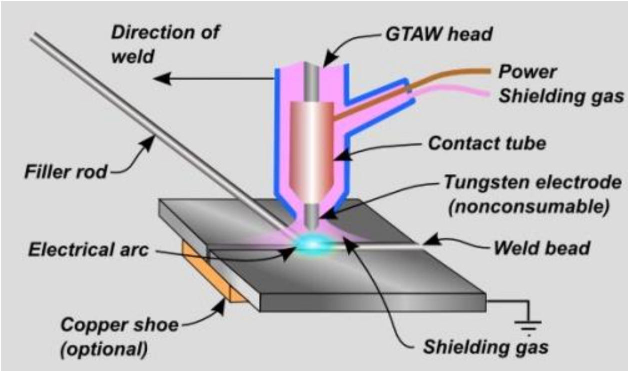

Figure 2. Welding Process Tungsten Inert Gas.
Available from: https://www.weldingis.com

The basic equipment used in this process consists of a power source (DC and / or AC), torch with tungsten electrode, source of protection gas and an igniter system for opening the arc. The ignitor ionizes the gaseous medium, eliminating the need for contact between the electrode and the arc opening piece, which can cause mutual contamination of the electrode and metal.

2.3. **Influences of Welding Process on Metal Base**

The aspects related to the heat flux and the welding temperature distribution have a significant influence on the microstructure and the mechanical properties of a welded joint. In single-stranded or multipass welding, the ZAC (Heat Affected Zone) may exhibit a large incidence of microstructurally heterogeneous zones, and highly fragile constituents, which can greatly reduce the strength of a welded joint (Silva, 2009).

Due to the heating generated in the welding process, new microconstituents can be formed in the steel structure, which may end up modifying the mechanical properties of the welded metal. Below is a list of the microconstituents that can be formed after the application of the AISI 4130 steel welding process (Voot, 2011 and Nascimento, 2004).

• Primary Ferrite: It can occur in grain boundary ferrite or intragranular polygonal ferrite.

• Acicular Ferrite: It consists of small grains of non-aligned ferrite inside the primary austenite grain. The length / width ratio should be less than 4: 1 for two adjacent or non-aligned slats.

• Ferrite with Second Phase: Ferrite with second phase aligned, where two or more adjacent slats occur and the length / width ratio is greater than 4: 1 and ferrite with second non-aligned phase, which surrounds regions of acicular ferrite.

• Ferrite / carbide aggregate: Structure of fine ferrite and carbides, which may be an interface precipitation, such as perlite.

• Martensite: This microconstituent can be presented in two forms: sliced martensite or maclate martensite.

The ZTA (Thermally Affected Zone) comprises regions of the base material whose structure or properties have been altered by variations in temperature during welding. Due to the peculiarities of these variations and to the development of a complex state of tensions and deformations, the changes that occur in the ATZ can lead to undesirable results. Thus, grain growth will be greater the higher the peak temperature and the residence time at that temperature (Modenesi et al., 2004).

The characteristics of the ZTA essentially depend on the type of base metal as well as the process and welding process, ie, the thermal cycle and the thermal distribution.

The development of residual stresses in welded parts and structures can generate a number of problems, such as cracking, increased brittleness or fracturing, and loss of dimensional stability (Marques, 2005).

Residual stresses arise due to the faster cooling of the surface, as the heating and cooling process is not homogeneous, not reaching equilibrium along the thickness.

3. OBJECTIVES

3.1. General objectives

• To evaluate the mechanical properties of tensile and hardness of the welded joint of a structural steel AISI 4130, welded by the TIG and Coated Electrode processes, besides the analysis of the joint after the welding process.

3.2. General objectives

• Present the main characteristics of welding;
• Discuss the welding processes and the different welding parameters;
• Perform the welding qualification performed with the described parameters and by means of mechanical tests of tensile strength and hardness.
• Characterize the microstructures of the Thermally Affected Zone (ZTA) by microscopy;

4. METHODOLOGICAL PROCEDURE

4.1. Flowchart of activities developed

Figure 3 with the flowchart represents the steps of the project carried out

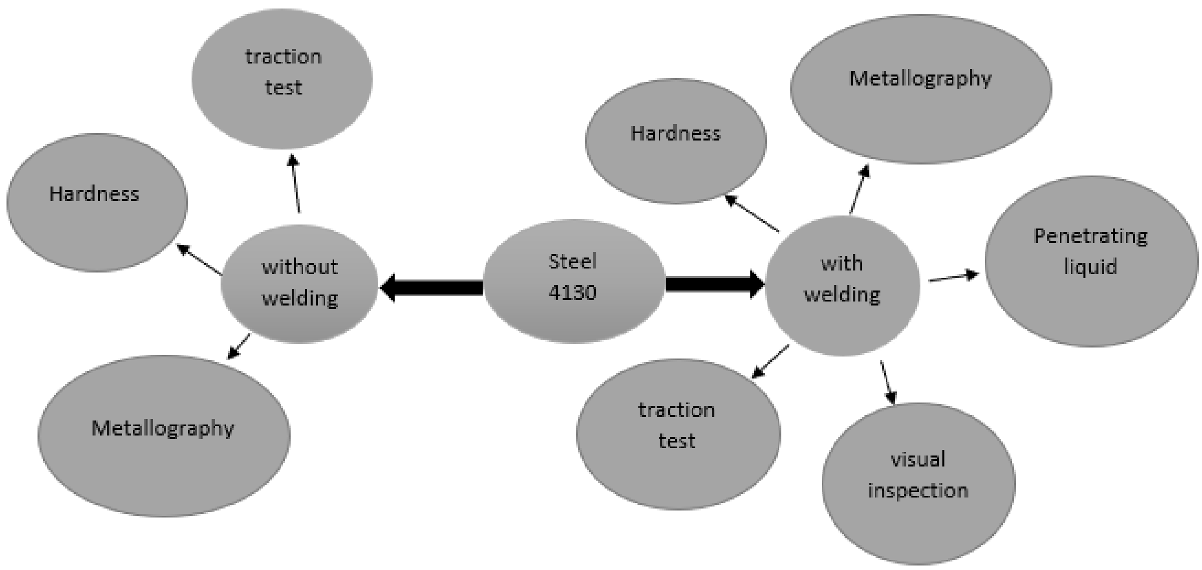

Figure 3. methodology adopted in the project
Available from: author, 2019

The material used for the study is the steel AISI 4130, in sheet form represented in figure 4, firstly a detailed study was carried out on the use and an analysis of the material in a state of supply, later the welding parameters were defined.

Figure 4. material used in the project
Available from: author, 2019

At the outset a metallography, hardness and tensile test was performed on the material supplied to compare the results obtained after the welding processes.

A tensile test was performed in the material as supplied to observe the elongation properties, yield strength, tensile strength, and area reduction. figure 05 below shows the specimen used in the tensile test.

Figure 05. weldless test body
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In view of all the study done on the material as supplied, the plate with the dimensions 200 mm x 45 mm x 6.35 mm was cut to carry out the welding processes using the parameters selected by the American Society Welding (AWS) standards. Figure 06 below shows the cut samples

Figure 06. made cuts
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At the end of the cuts, the TIG and SMAW type welds were made, for the preparation of tensile specimens and mechanical tests, in order to characterize the effects that each welding process exerts on the metal. The welding parameters were selected aiming at a good quality welded joint, without a high penetration due to the reduced thickness of the sheet, in order to obtain a good welded joint.

The first process was with a coated electrode, the coated electrode E7018 with a diameter of 3.2 mm was used, with current of 100 A. For the realization of the TIG welding process was used argon gas, addition rod 80b2 with diameter of 3.2 mm, tungsten electrode and current of 90A.

All the specimens underwent a visual inspection, which aimed to rule out possible failures in the welding process, lack of penetration or porosity. The bodies approved were immediately for the test with the penetrating liquid. The test with penetrating liquid was aimed at detecting open discontinuities on the surface of the pieces.

After all the analysis and result with the penetrating liquid, the tensile test specimens were made for both welding processes. Figure 07 shows the preparation of the specimens.

Figure 8. test specimens for tensile testing
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Test specimens were fabricated for each analyzed condition. After the tensile test, the preparation for a metallographic analysis was performed to verify all possible microstructural changes that may have occurred in the material due to all the welding processes, making a cut-off, considering the regions for analysis from the thermally affected zone (ZTA) to the molten zone (ZF).

After the cuts were inlayed to facilitate the handling of the part during sanding and polishing. Figure 08, below, shows the inlay on the cut samples

Figure 08. sample inlay
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After the inlay, water sanding was used to obtain a flat, non-deformed surface, which will serve as the basis for subsequent polishing. It is one of the most important steps because it can change the original microstructure without the operator noticing its influence. The most common abrasive used is the silicon carbide in the form of sandpaper (METALAB, 19---). Polishing was carried out after sanding, which consists in the elaboration of a scratch-free surface, in order to obtain a clear and perfect image under the microscope, allowing to reveal the real microstructure of the material. Usually the alumina and diamond paste are used as the abrasive.

For the polishing of the specimens he used diamond paste next to a thick velvet fabric. Consequently, superficial attacks of the polished samples were carried out to reveal the microstructure of the material, giving precise information about the existing phases. For each material we have a specific type of reagent, there are also several forms of attack such as dripping, immersion and cyclic (MALISKA, 2001).

For the chemical attack, picral was commonly used for steels. Finally the hardness test was carried out. It consists of the application of a penetrator under controlled load conditions and application rate. The resulting print depth or size is measured, which is related to an index number of hardness (SOUZA, 2000).

5. RESULTS AND DISCUSSION

5.1. Metallographic analysis

In view of the whole scenario, the use of welding presents great advantages for the metallurgy sector in the aeronautical area, innovations are constantly sought, in the processes of union by welding in place of the rivets, which could significantly reduce the weight of aircraft beyond to reduce rework (Cardoso et al, 2014; Nascimento, 2004).

Considering the test with penetrating liquid carried out on the welding bodies, no revelation was found, thus considering a well done welding process.

The TIG welding process is characterized by having a high quality weld bead with few inclusions.

A microstructural analysis was carried out on 15 samples welded by the TIG process and another 15 by the SMAW process, in order to characterize the influence of the heat generated in each of the welding processes, and respectively the characteristics of the ZTA.

In the samples of the TIG weld, the presence of fine martensite grains with many fine ferrite grains could be observed in the microstructure. As it moves toward the melting region these ferrite grains disappear and the microstructure is composed only of fine martensite grains. As it approaches the region of higher heating it is possible to perceive a microstructure formed by coarse grains of martensite due to the thermal input, the transition region of the ZTA to the base metal is clear, and the high level of inclusions in this region of the weld. In the analysis made in the SMAW weld samples, due to the higher thermal input, it was possible to observe an all-round structure in the ZTA and ZF region, being directly related to the diffusion of the carbon in the ferrite, and that it decreases with the growth of the average size of the particle, which explains the low hardness found. The structure is spherical due to the high heating in the base metal at the time of making the weld bead.

5.2. Hardness Analysis Obtained by the two processes

The microhardness analysis was carried out before and after the welding processes, in order to analyze the material in a state of supply and to serve as a comparison after the welding processes carried out, thus characterizing how the hardness of the material was influenced by the processes described previously.

The result of the hardness test of the material in the provided state was 30 HRC, not according to the literature, and a tempering of the sample was performed in order to correct the excessive hardness of the material after the treatment an average hardness of 14 HRC was found, it being evident that the material as supplied had its structure altered by virtue of some manufacturing process. The structure revealed with the metallography is in figure 09, which shows the contours of the exposed grains. The steel 4130 as received shows two types of microstructures: Perlite and ferrite, with a percentage of 48.65% and 51.35%, respectively, analyzed through ImageJ.

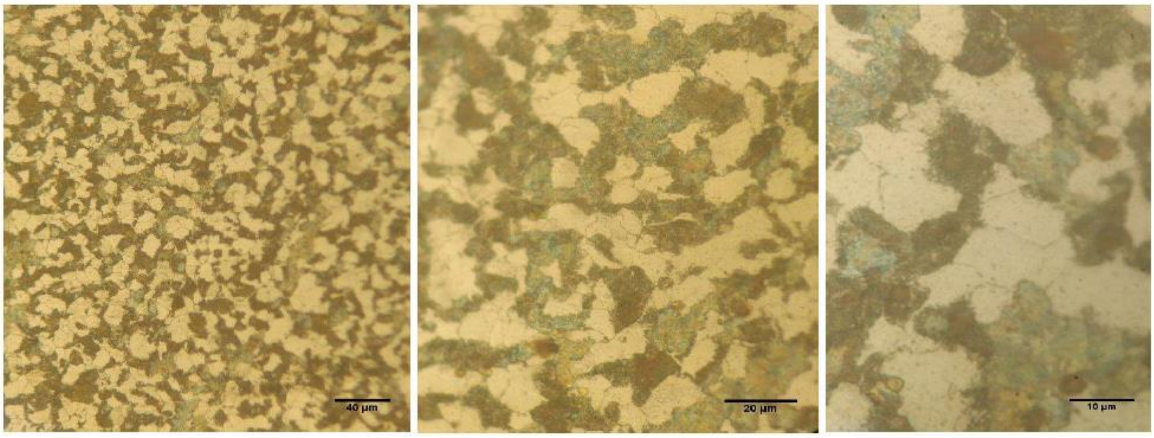

Figure 09. Microstructure of steel 4130, with magnification of 350x, 750x and 1500x respectively.
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Before the result after the completion of the welding processes, the sample that presented the highest hard point was obtained by the TIG process. In a transition region between the addition metal and ZTA, the average hardness reached 28 HRC, while at this point the sample welded by the SMAW process obtained a maximum average hardness of 22.5 HRC. Table 01 below shows the hardnesses obtained.

Table 01 - Hardness test results

Hardness HRC								
Welding process		Hardness Measurements						
SMAW		4 Left	3 Left	2 Left	middle	2 Right	3 Right	4 Right
	1	24	18	19	19	23	25	27
	2	26	22	27	23	24	28	21
	average	25	20	23	21	23.5	26.5	19
TIG	1	4 Left	3 Left	2 Left	middle	2 Right	3 Right	4 Right
		27	35	28	27	24	29	23
	2	30	32	24	25	27	31	26
	average	28.5	33.5	26	26	25.5	30	24.5

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The higher values of hardness presented by the sample welded by the TIG process are due to the higher welding energy used in this process, thus generating a higher thermal input, which resulted in a structure with martensite grains. While the lowest hardnesses observed in the SMAW weld were generated by the stiffening that occurred in the base metal, which eventually left the weld region more vulnerable to a fragile fracture, a fact that is undesirable for the project.

5.3. **Tensile Testing**

The determination of the hardness result before welding in the material is shown in Table 02 below.

Table 02 – Result of the tensile test before the welding process

Flow	429 Mpa
Tensile Strength	620,30 Mpa
Modulus of elasticity	190 – 210 Gpa
Stretching	12,5%
Area Reduction	28%

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According to the results collected through the tensile tests, after the welding process, Tables 03 and the graphs presented below were assembled.

The samples presented similar behavior in their analysis groups. The lower results presented in the SMAW weld samples are due to the stress that occurred in the structure.

Table 03. Traction Test Data after welding

Welding Processes	SMAW		TIG	
	CP1	CP2	CP1	CP2
Flow	360 Mpa	400 Mpa	360 Mpa	390 Mpa
Tensile Strength	478.13 Mpa	529.31 Mpa	494.95 Mpa	514.08 Mpa
Modulus of elasticity	20%	10%	10%	2.5%
Stretching	22%	18%	21%	9%

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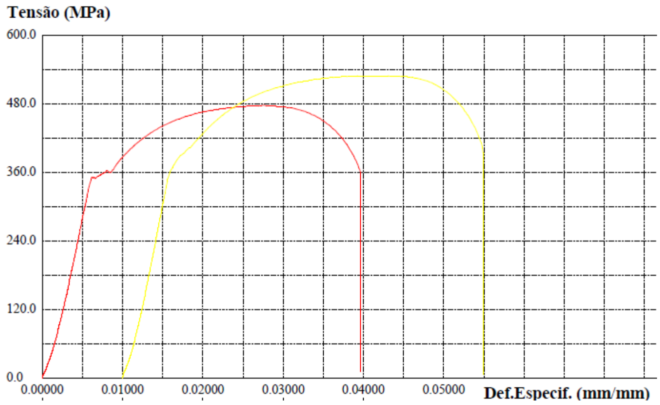

Graph 1: Traction Test on Coated Electrode
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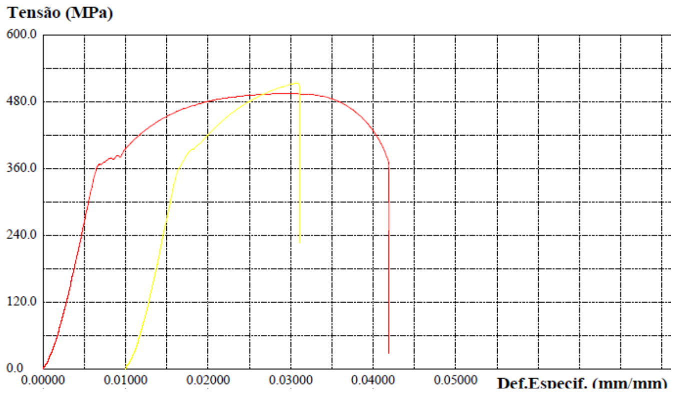

Graph 2: TIG Traction Test
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With the data obtained in the table and the graphs presented above, it can be seen that only one TIG test specimen fractured in the weld region, due to the fact that there was not a good penetration as occurred in the others, it could be due to the bevel used in the processes, being it straight 90º.

6. CONCLUSION

In this work it was evident that both the SMAW and TIG welding processes presented favorable and unfavorable points in the AISI 4130 steel welding. The study made it evident that:

• Both the weld region and the ZTA showed a lower hardness in the samples welded by the SMAW process, providing a better safety for the propagation of cracks and fatigue failures.

• The elongation measured in the specimens welded by the TIG process was smaller than that of the specimens welded by the SMAW process. The elongation is directly related to the toughness and ductility of the material, due to the greater general heating in the TIG welding process, a greater hardening of the ZAC region occurred, and this can generate the brittle fracture of the material.

• The SMAW process presents a lower cost, since to obtain AISI 4130 steel with better quality in the TIG process, it was necessary to purchase argon, costing 6 times more than the gas used to weld the samples by the SMAW process.

REFERENCES

Wainer E.; Brandi S.D; Melo V.O - **Soldagem Processos de Metalurgia**; 4ª edição., São Paulo, Edgard Blucher, 2004.

SOUZA, G. A., **Caracterização Microestrutural De Um Aço Médio Carbono E Baixa Liga** (com estrutura Bainítica / Martensítica) Via Microscopia Óptica**.** São Paulo, Faculdade de engenharia de Guaratinguetá, 2008;

Pickering, F. B. **Physical Metallurgy and the Design of Steels**. 1st ed., Applied Science Publisher, 1978.

Oberg, E. et al. *Machinery's handbook*. 27th ed., Industrial press Inc, 2004.

Louriel, V. O. **O Arco TIG a 100 A e Argônio Puro É um Arco Especial?.** Universidade Federal de Uberlândia, Laprosolda – Centro para Pesquisa e Desenvolvimento de Processos de Soldagem, Uberlândia, 2009.

BRACARENSE, A. Q., **Processo de soldagem TIG-GTAW**. Universidade Federal de Minas Gerais, Belo Horizonte, 2000;

Silva, M. C. **Determinação experimental da tenacidade à fratura da zona afetada pelo calor de junta soldada de aço** *API 5LX80*. 2009, 134f. Tese de Doutorado em Engenharia Naval e Oceânica. Escola Politécnica da Universidade de São Paulo. São Paulo, 2009.

Modenesi, P. J.; Marques, P. V.; Santos, D. B. **Introdução à metalurgia da soldagem**. Universidade Federal de Minas Gerais – Departamento de Engenharia Metalúrgica e de Materiais, Belo Horizonte, 2004.

Norma ASTM – A 370 – 03a Standard Test Methods and Definitions for Mechanical Testing of Steel Products.

Norma ASTM – E 8M - 04. Standard Test Methods for Tension Testing of Metallic Materials.

Norma Brasileira NBR ISO 6892 – Materiais metálicos – Ensaio de Tração à temperatura ambiente.Rio de Janeiro, 2002.

Bhadeshia, H.K.D.H. and Honeycombe, R.W.K., **Steels - Microstructure and Properties**, 2ª ed., Butteworth Heinemann, 1995, 324 p.

Marques, P.V. **Soldagem – Fundamentos e Tecnologia**. Universidade Federal de Minas Gerais, Belo Horizontal, 2005.