ISSN 2176-5480

STUDY OF THE THERMODYNAMIC CONDITIONS OF SUB-REGIONS OF ZTA, IN STANDARDIZED SPECIMEN FOR THE TESTING OF THE STRENGTH

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Abstract. *The reproduction of the thermodynamic conditions of the sub-regions of the HAZ, in specimens of large size, is important for the study of the fabrication process by welding, facilitating microstructural analyzes which can be associated with mechanical properties of metals. Based on grain size analysis and a microstructure/mechanical properties relationship a theoretical and experimental methodology was developed in a thermomechanical simulator in which can be possible the reproduction of thermal conditions of the HAZ. The multiplicity of phenomena involved in a welding process and microstructural heterogeneity resulting from temperature gradient, hamper enormously the theoretical analysis and forecasts of physical and mechanical properties of welded joints. The reproduction of the thermodynamic conditions of HAZ points, with cooling* $t(s) = \Delta\theta_{800\text{-}500}$ *comparable to a real thermal cycle, ensured the homogeneity microstructural in a specimen with standard dimensions, allowing the determination of the discretized mechanical properties at different points in the HAZ.*

Keywords: *API X80 microalloyed steels; HAZ; Mechanical properties; welded joint.*

1. INTRODUCTION

Structural changes in the heat affected zone (HAZ) have been considered in the design of steel welding, because there is an intrinsic relation to the mechanical properties of the material, where new projects and fields of application require challenging properties in this manufacturing process (Koçak, 2010). The large number of articles has been found in the international literature, (ZOU et al, 1990; WOOD, 1994; BARABASH et al, 2004; KHLUSOVA and ORLOV 2012) relating to a persistent research on this topic in order to specify the best production techniques and testing of welded joints, ensuring a similar microstructure of this region with the base metal (BM). The metallurgical heterogeneity both in BM as well as in the fusion zone (FZ) is a consequence of the cooling rate and the associated phase transformations, affecting the mechanical properties of the welded joint, with the possibility of causing weakness in certain regions.

Analysis of the microstructural effects on mechanical properties made by experimental tests and mathematical models is important to ensure the quality of any manufacturing process, including the process of welding with filler metal. The versatility of this fabrication process and its importance to the industrial production gave rise to large number of research papers that validate models of new techniques which aims to ensure the structural integrity of the weld (COFIÑO, 2010).

This study was conducted in 3 parts, as described below: firstly, specimens produced in thermomechanical simulator were studied; the second specimens made from a welded joint were studied and thirdly a mathematical model connecting the first and the second parts of the study allowing the final analysis of the mechanical properties in the HAZ of the welded joint, considering the size of grains (GS) as the following items:

i. Specimen produced in thermomechanical simulator.

i.1. Production of test samples in a termomechanical simulator, reproducing thermodynamic conditions compatible with the regions of the HAZ of a welded joint.
i.2. Conducting tensile tests to obtain resistance values.
i.3. Conducting micrographs to quantify grain size in each specimem.

ii. Specimem revomed from the welded plate:

ii.1. Preparation of a plate tests (two-part) for welding process by MAG,
ii.2. Welding the plates by MAG process overseeing the thermal cycles.
ii.3. Extraction of a specimen of welded plate in the transverse direction of the weld.
ii.4. Perform micrograph to determine the HAZ size, dividing it into five regions to quantify the average grain size in each of these regions.
ii.5. Analysis of values of average grain size of each regions.

iii. Numerical model:

iii.1. Use of data of the specimen produced in the thermomechanical simulator and, based on the Hall-Petch equation, find a constitutive equation to determine the mechanical strength comparing them with to the values obtained experimentally by uniaxial tensile.
iii.2. Based on the stress versus grain size, establish the values of yield stress (s_0) and the material characteristic constant (k_d) of the Hall-Petch equation.
iii.3. Find stress values of the points of the regions in the HAZ analyzed through a numerical model using software.
iii.4. Establish relationships between the values of the stresses found by modeling with the stresses experimentally obtained, validating this experimental methodology to determining the mechanical properties of the welded joint.

2. MATERIALS AND METHODS

2.1 The Steel API 5L X80

The material used for this study was high strength low alloy (HSLA) steel, referring to API 5L grade X8, extracted from the pipe line, with a diameter of 864,0 mm and thickness of 19,0 mm for using in oil and gas. The chemical composition of this HSLA steel in weight (%) was obtained optical emission spectrometry (tab. 1).

Table 1 - Chemical composition (mass %) analyzed by optical emission spectrometry (SIMISA-PE)

C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Nb	Ti	V
0,08	0,28	1,80	0,021	0,003	0,15	0,20	0,02	0,01	0,062	0,016	0,021

2.2 Sample produced in thermomechanical simulator

For testing in the thermomechanical simulator, samples were extracted from the steel tube and prepared in a machining center, according to NBR 6152 of metallic materials - Tensile test at room temperature. Three specimens (one for each temperature) were treated in thermomechanical simulator at temperatures of 1100, 1000 and 900°C, as well as three others produced without treatment, representing the base metal.

The specimens where heat-treated in a muffle furnace up to the treatment temperature for a time of 10 min followed by cooling in the thermomechanical simulator (fig. 1), reproducing the thermodynamic conditions of distinct points of HAZ. The thermomechanical simulator comprises two steel blocks acting as substrate of infinite mass, allowing the removal of heat from the specimens and dissipating the heat as in the welded joint (SILVA JR. et al, 2010).

Figure 1 - thermomechanical simulator (Lab. Mechanical - UFPE)

The thermodynamic conditions of sub-regions of HAZ were produced in order to obtain samples of large size (normalized to tensile test), which can be tested by generating true values of mechanical properties which, together with the others microstructure analysis could validate this theoretical-experimental methodology.

2.3 Specimen of the weld

For welded joints, two plates measuring 200 x 80 x 7.5 mm were produced. Each plate was prepared with Basel angle of 50º (25° in each plate) and welded by Metal Active Gas (MAG) process. The CO_2 was used as protection gas and filler metal was the wire AWS- ER70S-6 5.18 with 1.20 mm diameter. The welding parameters are shown in Table 2.

Table 2. Welding parameters used in the welded joints

Current intensity	Voltage	Efficiency	Speed welding
127 A	18,3 V	80 %	0,1 cm/s

Based on the parameters shown in Table 4, the welding energy was calculated by equation 1. The calculated value of the energy will allow making an analysis on the effects of energy on the microstructure and properties, in subsequent studies.

$$E = \eta \frac{U.I}{v} \tag{1}$$

Where: ***E***, is the energy absorbed in J/mm; $\boldsymbol{\eta}$, the thermal efficiency of the process; ***U***, the arc voltage in volts; ***I***, the welding current in A and ***v***, the welding speed in mm/s.

After welding, the sample was removed from the plate to microscopic analysis, quantifying the average grain size. These samples were prepared by conventional metallography with a chilled cutting, sanding and the polishing. Sandpaper of 280, 400, 600 and 1000 mesh were used and polishing in the carpet with diamond paste of 1µm, according to NBR 13284. (ABNT NBR 13284). After polished, the samples were etched with Nital 5% for 10 seconds, revealing the microstructure according to NBR 8108. (ABNT NBR 8108). The samples were characterized by optical microscopy (OM) Olympus Model BX 51M, and the quantification of the microstructure were made by using of a commercial software.

2.4 Mathematical modeling

Based on the Hall-Petch equation and data from the bodies of evidence produced in the thermomechanical simulator (properties and the average grain size) were applied in numerical software and calculated voltage values for each of the five specified regions of the specimen of welded joint using commercial software.

3. RESULTS AND DISCUSSION

The individualized results obtained in the first two phases of this study were initially treated, considering the samples produced in the thermomechanical simulator and samples removed from the welded joint. At the end of this study all previous results, together with the data obtained by simulation with numerical model were analysed.

3.1 Sample produced in thermomechanical simulator

Specimens produced in thermomechanical simulator were prepared for microscopic characterizations in optical microscopy to obtain the grain size. Following microstructural characterization, these specimens were machined (fig. 2) and subjected to tensile test. Based on stress vs strain curve the mechanical properties were determined in the twelve test samples, three from each treatment temperature, 1100, 1000, 900°C and also three as received material (RM).

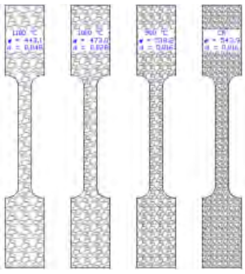


Figure 2 - Schematic drawing of the specimens of tensile test

Analyses with these specimens were carried out either to determine the values of mechanical properties or quantification of grain sizes of each of them. The thermodynamic conditions of some points of heat affected zones were simulated to reproduce the real conditions of the MAG welding processes. Both microstructures and mechanical properties of these discrete points in ZTAs were reproduced in specimens of largest extent.

3.1.1 Tensile Test

Results of tensile tests are shown in table 3. For each temperature, three samples were assayed, allowing to highlight the mechanical behavior of these points of HAZ with its error estimate.

Table 3 - Results of the tensile test of samples produced in the thermomechanical simulator. (* as received material)

Sample	Temp. (°C)	Yeld Stress (MPa)
1	1100	443,1 (±11,73)
2	1000	473,0 (± 5,52)
3	900	518,2 (±10,16)
4	RM*	543,9 (±19,72)

These results show that the higher the temperature the lower the resistance value and are all related to grain size, as will be discussed below. For temperature of 1100°C, the lowest value of mechanical property (443.1MPa ±11,73) was found that is justified by simulating points closer to the fusion zone (FZ). On the other hand, the material processed at 900°C shows the highest value of mechanical property (518,2 MPa ±10,16), simulating the HAZ points farther away from the fusion zone (FZ).

3.1.2 Metallographic analysis

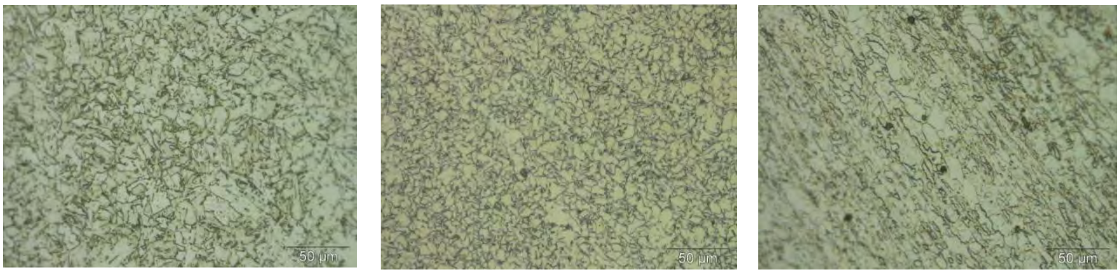
The measurements of grain size were performed by the intercept method according to ASTM E-1122 (1989). The microstructures observed in the samples produced in thermomechanical simulator at different heating temperatures are shown in fig. 3. For each temperature, three test samples produced in thermomechanical simulator were inspected and the results of average grain sizes are shown in tab. 4.

Table 4 - Results of grain sizes of samples produced in the thermomechanical simulator.

Sample	Temp. (°C)	Grain Size (mm)
1	1100	0,048 (±0,0015)
2	1000	0,028 (±0,0010)
3	900	0,024 (±0,0010)
4	CR	0,016 (±0,0015)

For temperature of 1100°C, simulating a region of HAZ, the average grain size is 0.048 mm ± 0,0015. This largest average is justified by the greater proximity with the fusion zone (FZ). Temperatures of 1000 and 900 ° C, simulating the most remote regions of the weld zone showed values of average size 0,028 mm and 0,024 mm, respectively.

During welding process, different regions of the HAZ subjected to different heating and cooling have quite different microstructures producing different metallurgical characteristics and mechanical properties (LANCASTER, 1999). Following DA COSTA (apud Pinto, 2006), the region of the coarse grain in pipe line steel Fig. 3 is one that has always the greatest weakness among the other regions of the HAZ.



(a) (b) (c)

Figure 3 - Microstructures of the specimens simulated: (a) Heated at 1100°C; (b) Heated at 1000°C and (c) Heated to 900°C.

These results obtained with the thermomechanical simulator showed a good relationship between the microstructure and mechanical properties.

3.2 Sample of the welded plate

In order to compare the results produced by the thermomechanical simulator, a real welded joint was produced by MAG process in plates of the API 5L X80 steel. During welding, a globular transfer mode was observed. This filler metal transfer condition was mainly influenced by the current intensity (SEABRA, 1990). Specimens taken from welded plate were microstructurally analyzed. A metallographic analysis was performed to determine the grain size of the five sub-regions of the HAZ. Finally, the microstructures of the HAZ of the welded joint were compared with the microstructures produced by simulations..

3.2.1 Metallographic analysis

The heat affected zone of the welded joint was characterized by optical microscopy. The extent of the HAZ with 4.6 mm was divided into five regions, as shown in Figure 4.

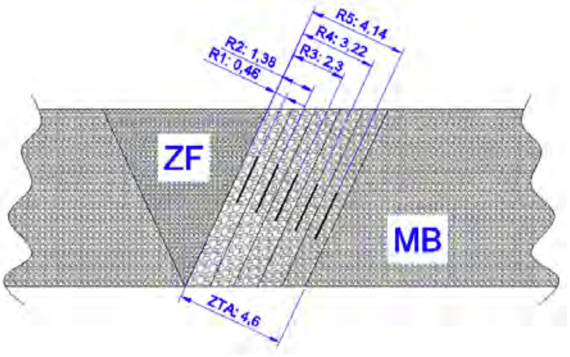


Figure 4 - Schematic drawing of the welded joint with five regions of the HAZ

All five regions of the HAZ had their grains measured. The values of the average grain size in each of these regions of the HAZ are shown in tab. 5.

Table 5 - Results of grain size in samples produced in welded joint.

Specimem	Region	Grain Size (mm)
welded joint	R1	0,120
	R2	0,092
	R3	0,088
	R4	0,064
	R5	0,020
	CR	0,016

The region R1, closest to the fusion zone has the largest grain size (0:12 mm). On the other hand, the R5 region bordering the base metal has a smaller grain size (0.020 mm). All these values (tab. 5) were compared with values obtained from test samples produced in thermomechanical simulator, as previously described.

As might be expected, the grain size of these different regions is directly related to the exposure that each point was subjected to a certain time and temperature during welding. This time is related to the welding speed, which is a controlled welding parameter (LOPES, 2005).

3.3 Numerical model

The resistance to deformation of a polycrystalline material may be related to its grain size (FONSECA, 2011). Based on the Hall-Petch equation, the mechanical properties of the five regions of the heat affected zone were determined. For comparison, the values of the mechanical properties of the specimens were produced in silmulador were determined by Hall-Petch relationship (Eq. 2) and experimentally by uniaxial tensile test.

$$\sigma_d = \sigma_0 + k * d^{-1/2} \tag{2}$$

where $\boldsymbol{\sigma_d}$ and $\boldsymbol{\sigma_0}$ represent the limit resistance and the stress theoretical (friction) respectively, $\boldsymbol{k_d}$ is a constant related to the extent of stacking disagreement of the grain boundary and $\boldsymbol{d}$ refers to grain size.

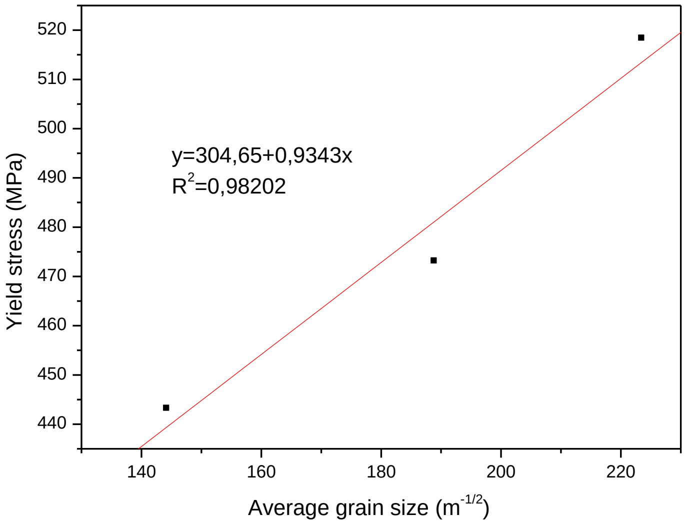


Figure 5 - Yield stress vs. average grain size

After linearization of the equation 2, the values of the properties could be calculated. Using a linear regression the equation 3 was obtained with a good correlation factor. R=0,98 (fig. 5).

$$\sigma_d = 304{,}65 + 0{,}9343 * d \tag{3}$$

The values obtained by equation for friction stress was σ_0 = 304.66 MPa (± 33.85) and calculated for the constant of the material is k_d = 0.9343(± 0.18). All results analytical (simulated) and experimental are shown in Table 6. Specimens obtained from welded joint and from thermomechanical simulator could be compared.

Table 6 - Values of stress calculated in the five regions of the weld compared to the experimental values obtained from tests of specimens produced in thermomechanical simulator

Specimem	Region	Grain size (mm)	Yeld stress (MPa)	
			Calculation Function Curve	Calculation Equation Hall-Petch
wj	R1	0,120	389,94	385,97
wj	R2	0,092	402,06	397,53
wj	R3	0,088	404,25	399,61
wj	R4	0,064	421,44	416,00
ts	1100	0,048	443,10	443,10
ts	1000	0,028	473,00	473,00
ts	900	0,020	518,20	518,20
wj	R5	0,024	513,57	503,84
bm	MR	0,016	543,90	543,90

wj - removed from the weld joint
ts - produced in thermomechanical simulator
bm - Base metal

The stresses calculated with the mathematical model, obtained by linear regression of the Hall-Petch equation, have values very close to the values obtained experimentally with the samples produced in the thermomechanical simulator. Although the values obtained by the Hall-Petch equation present values of stress slightly below the values calculated by the model, one can validate the theoretical and experimental methodology, taking into account the estimated error.

4. CONCLUSÕES

Both the true (tensile test) and simulated stresses (Hall-Petch) obtained from the samples produced in the thermomechanical simulator were compared to stresses of five points of the HAZ of the welded joint. Based on the microstructural characterization were identified points of the HAZ microstructural equivalent to specimens produced in the thermomechanical simulator.

The results observed for the material under study, based on the quantification of the grain size of the HAZ and the material produced in the thermomechanical simulator, demonstrate the feasibility of using the simulator for the discretization of HAZ points of a welded joint, allowing mechanical properties could be determined.

5. ACKNOWLEDGEMENT

The Training of Human Resources in Technology Equipment for actuation in the oil, gas and biofuels PETROBRAS for the scholarship that enabled the development of this work and SIMISA by tests.

6. REFERENCES

Barabash, O. M. at all, 2004. Evolution of dislocation structure in the heat affected zone of a nickel-based single crystal, Metals & Ceramics Division, Oak Ridge National Laboratory, Oak Ridge.

Cofiño, R. C., 2010. Análise das tensões residuais em uma junta soldada em condição overmatch, Centro Universitário da FEI, São Bernardo do Campo, São Paulo.

Fonseca, P. M. F., 2011, Filmes finos para sensores de pressão em próteses de membros inferiores Dióxido de titânio dopado com prata, Universidade de Coimbra.

Hall E. O., 1951. Proceedings of the Physical Society of London, 643, 747.

Hippert Jr. E., 2004. Investigação experimental do comportamento dúctil de açosAPI X70 e aplicação de curvas de resistência J- a para previsão de colapso em dutos. Tese Doutorado. Escola Politécnica da Universidade de São Paulo, São Paulo.

Khlusova E. I. and Orlov, V. V., 2012. Change in the structure and properties in the heat affected zone of welded joints made from low-carbon ship-building and pipe steels, Metallurgist, Vol, 56, Russian

Koçak, M., 2010. Structural Integrity of Welded Structures, Gedik Holding, Ankara Cad. No. 306 Seyhli - 34913 Pendik, Istanbul, Turkey

Lancaster, J.F., 1999. Metallurgy of Welding , 6 Ed., Woodhead Publishing Limited, Cambridge, England.

Lopes, A. C., 2005. Avaliação da soldabilidade dos aços inoxidáveis ferriticos extra baixo intersticiais EBI/P444. Dissertação de Mestrado em Engenharia Mecânica da Universidade Federal do Paraná, Paraná.

NBR 13284, 1995 . Preparação de corpos-de-prova para análise metalográfica – Procedimento. Associação Brasileira de Normas Técnicas.

NBR 6152, 2002. Materiais metálicos – Ensaio de tração à temperatura ambiente. Associação Brasileira de Normas Técnicas.

NBR 8108, 1983. Ataque com reativos metalográficos em ligas ferrosas – Procedimento. Associação Brasileira de Normas Técnicas.

Petch N. J., 1953. Journal of Iron and Steel Institute, 174, pp. 25.

Pinto, P. M. A. S., 2006. Soldagem Circunferencial de Tubo API 5L X80 Empregando Processos Manual/Semi-automático, Tese, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro.

Seabra A. L., 1990. Estudo Microestrutural da Zona Afetada Pelo Calor (ZAC) de um Aço ARBL Temperado e Revenido. Dissertação (Mestrado em Ciencias dos Materiais – Materiais) - PUC-RJ, Rio de Janeiro, Brasil.

Silva Jr, L. A.; Yadava, Y. P.; Ferreira, R. A. S., 2010. Simulação das transformações de fase em pontos da ZTA de juntas soldadas do aço API 5L X70. In: VI CONGRESSO NACIONAL DE ENGENHARIA MECÂNICA, Campina Grande, Paraiba, Brasil.

Wood W. E., 1994. Heat-Affected Zone Studies of Thermally Cut Structural Steels. Publication No. FHWA-RD-93-015

Zou Z., Wang Y., Ren D., 1990. Structural change in heat affected zone and its influence on properties of welded white cast iron, Shandong Polytechnic University, Jinan.