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COMPARATIVE STUDY OF PHYSICAL AND SIMULATED TENSILE TESTS OF STEELS SA-516 GR.70, SA-240 TP.316L AND SA-516 GR.70 + SA-240 TP.316L CLADDED BY ROLLING PROCESS

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Abstract. *The cladding process involves depositing a dissimilar material, called coating, on the surface of a base material, called substrate, resulting in a strong metallurgical bond at the bimetallic interface, so that the sheets are integrally adhered. This arrangement has been widely used in equipment constructions that requires different properties, which would not be possible using only one material. This paper presents a comparative study of the combination of two materials' properties, mechanically joined by hot rolling and the same materials in the isolated condition. It was evaluated the mechanical properties obtained from tensile test and compared with the structural simulation of samples by the finite element method (FEM), also analyzed the morphology of the fracture of the test samples that were used stainless steel SA-240 TP.16L as coating and steel SA-516 Gr.70 as a base metal. It was observed that both materials were work-hardening during the rolling process and, consequently, there were changes in the mechanical properties. It was observed that the material that had the greatest structural influence on the composite was the stainless steel, so the bimetallic plate had the yield and rupture limits close to the stainless steel, despite the lower thickness. The fracture analyses shows an adherent interface and a fragile behavior of the stainless steel. The methodology used for modeling and simulation was highly efficient presenting small errors in relation to the physical tests.*

Keywords: *Clad, tensile test, Finit elements method, stainless steel, carbon*

1. INTRODUCTION

The suitable manufacturing design is one that ensure a safe operation by the equipment, without significant risk, subjected to expected loads, temperatures and pressures. To attend the increasing severity of the operating conditions, sometimes it's necessary to combine two or more materials with different properties leading to the development of composite materials, especially as regards the need to combine properties incompatible with each other, eg. mechanical strength and toughness.

The importance of ensuring these combinations is to prevent the equipment from failing in service. Therefore, it is necessary to ensure the structural and material characteristics in such a way that any deformation is not excessive and does not lead to any fracture.

Composite materials are results of combining two or more materials to form a useful engineering material, conferring new properties that would not be found in separately materials. A widely used composite material class it's the bimetallic composites, which are mostly made of carbon steel or low alloy steels, also called base metal, and clad material in one or both sides of this base metal, resulting in a high quality coating that provides mechanical strength required for structural material and corrosion resistance of the protective material. Among the most common applications of cladding at industry there's the one to increase the corrosion resistance of components. (Pereira, 2005)

The SA-240 TP.316L is an austenitic stainless steel widely used by engineering due to its excellent corrosion resistance and high conforming capacity. However, an application of such material is difficulted for its low mechanical strength and the high cost. Therefore, the association with the carbon steel SA-516 Gr.70 gives this one the mechanical resistance for applications in industrial equipment, because the resistance of the carbon steel is greater than a stainless steel, but does not present corrosion resistance properties. This blend of materials is characterized by a combination of mechanical properties and corrosion resistance, so it is quite versatile.

To ensure the performance of this composite, it's necessary the correct design and structural project. For this, the analysis of stresses by the finite element method is a high technology methodology that assists in the proper dimensioning of an equipment, evaluating the stress points, making the designer able to change the design in order to meet the minimum requirements specified by the standard.

1.1 Cladding

The combination of two or more materials that differ in chemical composition and shape and are insoluble form the composite material (Smith, 1998). The composite materials have their mechanical properties projected in order to optimize certain applications, different from those of each constituent material, or phase, separately (Beim, 2008).

In the case of composite materials, the clad plates stand out. Cladding is a process of depositing a dissimilar material on the surface of a base material, called a substrate, obtaining a strong metallurgical bond at the interface between them. The two bonded materials come to have different mechanical properties, such as modulus of elasticity, ductility, toughness, among others, when they were separated. The material deposited on the substrate performs the function of a coating, which confers some characteristics to the clad material that would not be possible using only the base material.

Among the most common applications of cladding in the industry are those that increase the corrosion resistance of the components and the improvement in the surface hardness of the components (ASM - American Society For Metals, 1983).

2. EXPERIMENTAL PROCEDURE

The clad steel plate for test samples, 16x750x1000 mm in size, was received from the supplier in the hot rolled condition. This plates was cut in the direction of lamination through a bandsaw, brand Franho.

These were milled to the dimensions of the specimens according to ASTM E8/E8M - Standard Test Methods for Tension Testing of Metallic Materials, 1995. Three specimens were removed for each thickness variation configuration, according to listed in Table 1. The samples were deformed until fracture, with tensile load uniaxially applied according to standard.

Table 1. Schematic of samples division

Samples nº	Thickness (mm) SA-516 Gr.70	Thickness (mm) SA-240 TP.316L
3	100%	***
3	***	100%
3	12	3
3	9	3
3	6	3

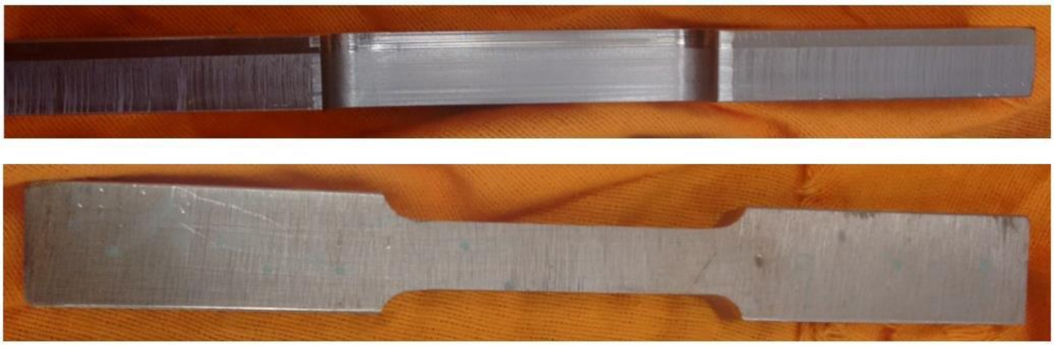


Figure 1. Tensile test samples according to standard

The equipment used to perform the tensile test was an Instron universal testing machine with hydraulic system and 300kN load cells. For strain measurement, two strain gages were installed along the width and thickness of the plate. Signs of force in the direction of the length of the specimen and displacement in the directions of width and thickness were respectively sent to the computer and subsequently made available through a text file.

In the test procedure, the initial length of the test specimens (measuring base) and width were measured using a caliper, with a sensitivity of 0.1 mm. The measurement base was used to calculate the conventional deformation through equation 1:

$$\varepsilon = \frac{\Delta l}{l_0} \tag{1}$$

Where Δl is the variation of base measurement and l_0 is the base measurement. The conventional stress, σ_c, was calculate by the equation 2:

$$\sigma_c = \frac{F}{S_0} \tag{2}$$

Where F is the axial force and S_0 is the sample area. The yield limit value, σ_{esc}, was obtained from the conventional stress - strain plot, for the 0.2% strain. The yield stress was obtained by the equation 3:

$$\sigma_{esc} = \frac{F_{esc}}{S_0} \tag{3}$$

Where F_{esc} is the yield force and S_0 is the initial sample area.

The value of the resistance limit σ_r was obtained from the conventional stress - strain plot for the deformation corresponding to the maximum load. The tensile strength was obtained by equation 4.

$$\sigma_r = \frac{F_{max}}{S_0} \tag{4}$$

Where F_{max} is the maximum force.

From the conventional stress (σ_C) by strain (ε_C) curve, which are the data taken directly from the tensile test, the true stress (σ_V) by strain (ε_V) curve was calculated through equations 5 and 6.

$$\sigma_V = \sigma_C(1+\varepsilon_C) \tag{5}$$

$$\varepsilon_V = \ln(1+\varepsilon_C) \tag{6}$$

After the tensile test, the fracture region of the test specimens was analyzed by scanning electron microscopy (SEM) in order to qualitatively characterize the fracture.

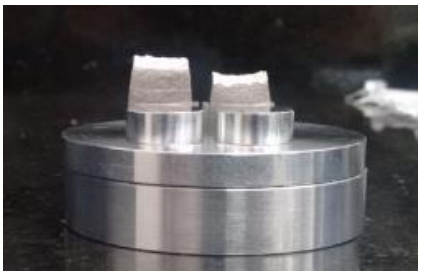


Figure 2. Fracture regions tensile test samples, sectioned at the sample port for analysis in the SEM

In addition, the curve obtained experimentally for carbon and stainless steels were used to feed the ABAQUS® finite element software, in which tensile test simulations were performed for clad plate in order to compare the results obtained by numerical simulation with the experimental data. The element finit model of the tensile test sample was constituted of linear quadratic axisymmetric elements S4R (4 nodes, 66 degrees of freedom for each node).

Figure 3 shows the mesh used composed of 694 elements. A complete nonlinear analysis was performed considering the material and geometric nonlinearity. This kind of analysis enables obtain a global response of the material after the yield strength until rupture.

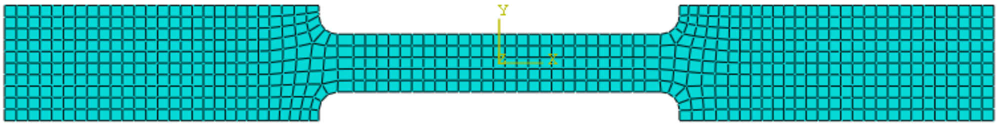
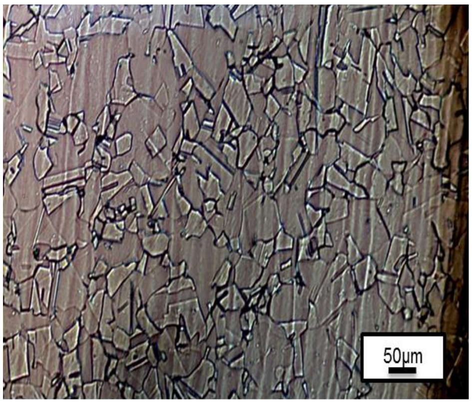


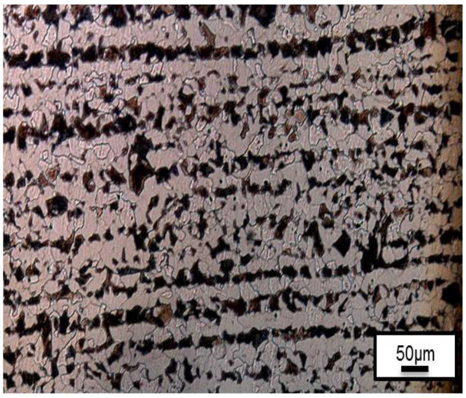
Figure 3. Tensile test specimen mesh

3. RESULTS AND DISCUSSION

The base material, carbon steel SA-516 Gr. 70, presented on the structure ferrite and perlite in a banded form. The clad material, stainless steel SA-240 TP.316L presented microstructure with austenitic equiaxes grains with the presence of annealing masts, according Figure 4:



(a)



(b)

Figure 4. Micrograph of samples (a) stainless steel and (b) carbon steel

Figure 5 shows the micrograph of the bimetallic interface of the cladding material. It is possible to observe the adhesion of the material without gaps, characterizing the strong metallurgical bond of the cladded steels by colamination.

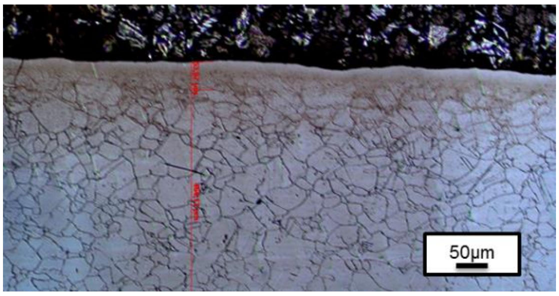


Figure 5. Bimetallic interface micrograph

The Table 2 resume the physical tensile tests results of steels in the configurations presented in Table 1.

Table 2. Physical tensile test results

	ASTM-516	TP.316L	6 vs 3	9 vs 3	12 vs 3
Yeld Strength $\sigma_{0,2}$ (MPa)	328.26 ± 6.47	377.05 ± 7.84	342.62 ± 1.51	329.07 ± 3.55	335.55 ± 2.06
Tensile Strength σ_u (MPa)	516.19 ± 2.38	588.45 ± 1.97	536.82 ± 2.69	531.39 ± 4.13	526.17 ± 1.21
Elongation (%)	29.33 ± 0.19	38.20 ± 2.14	33.93 ± 0.09	35.13 ± 0.25	35.47 ± 0.19

As can be observed, the values found for the resistence and yield limits of isolated materials were higher than the reference values (extracted from ASME standart, section II, part D), with the greatest difference in stainless steel.

The hypothesis is that the materials have been hardened during the rolling process. It is observed that stainless steel was the material that had the greatest increase in the yield limit, compared to the standard (122.06 %) and presented greater percentage elongation, showing that it has a higher hardening rate than carbon steel.

It is also observed that the clad that presented higher values of tensile and yield limits was the clade with lower carbon thickness (6 vs 3 mm). This result indicates that stainless steel exerted greater influence on the mechanical properties of the clad plate.

Table 3. Reference values

	ASTM-516	TP-316L
Yeld Strength $\sigma_{0,2}$ (MPa)	260	170
Tensile Strength σ_u (MPa)	485	480

In the fracture analysis of the materials was observed a predominantly brittle behavior of the stainless steel, which reinforces the hypothesis of material hardening during lamination. Figure 6 shows the insulated steels fractures, where the stainless steel presenting dimples only in a small central region of the sample and the carbon steel presented ductile fracture morphology, that is dimples.

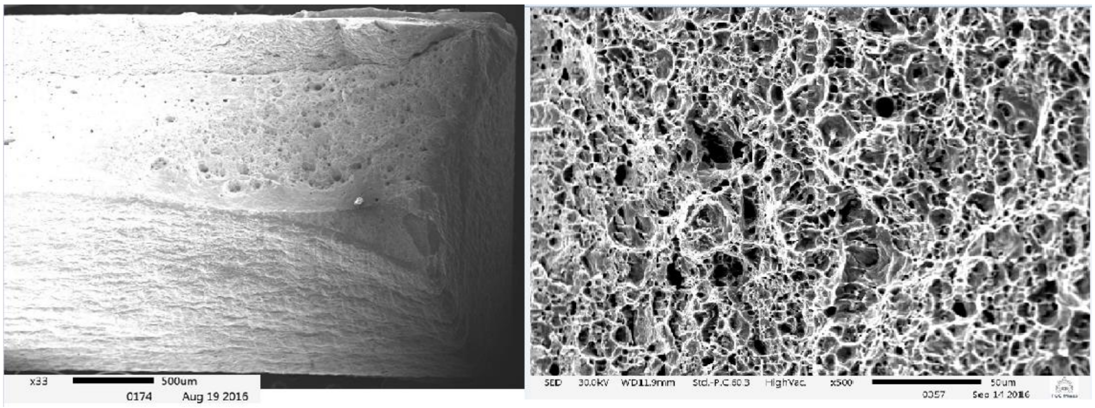


Figure 6. Fractography of steels a) SA-240 TP.316L; b) SA-516 Gr.70

In the analysis of the cladded samples, it was observed that the interface remained well adhered. The carbon steel as well as the insulated condition presents dimples. The stainless steel, in clad condition, presented three differents regions: the first, from de surface, with cleavage plains tipics of fragile fracture; the second as being a transition region and the third, near the edge of the sample, presented dimples, typical of ductile materials, according Figure 7.

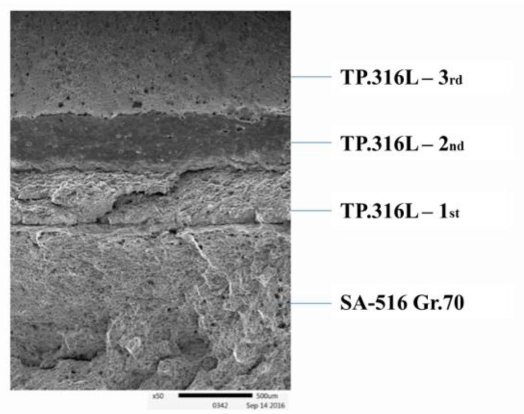


Figure 7. Clad fracture

This phases' separation shows that, considering the hardening of the material during the rolling, there was an increase of the hardening through the thickness of the stainless steel, the interface being the region most affected. This is consistent with the process, since the cladding occurs by localized deformation of the surfaces in contact through the pressure of the rolling rollers.

The simulation of tensile test was performed as the physical tests. The linearization of the values obtained during the physical test and the simulation are presented in the figures below with the values included between the yield strength and the tensile strength, in other words, the plastic region, for the comparison between the results obtained by FEM and results obtained from the tests.

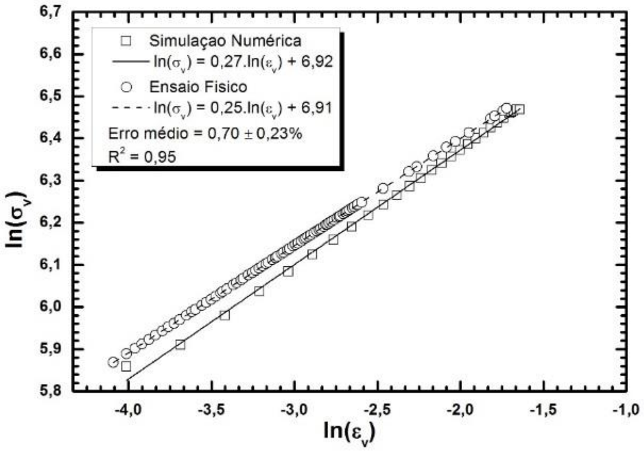


Figure 8. Tensile test results of SA-516 Gr.70

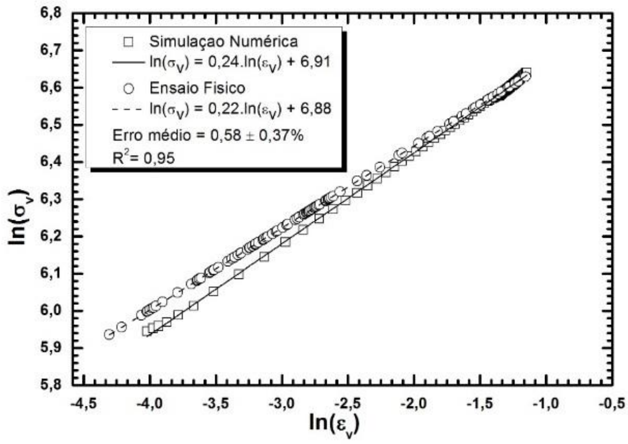


Figure 9. Tensile test results of SA-240 TP.316L

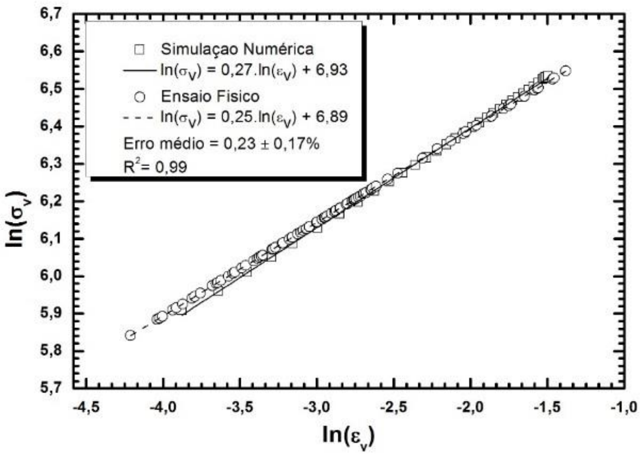


Figure 10. Tensile Test results of 6 vs 3 mm thickness

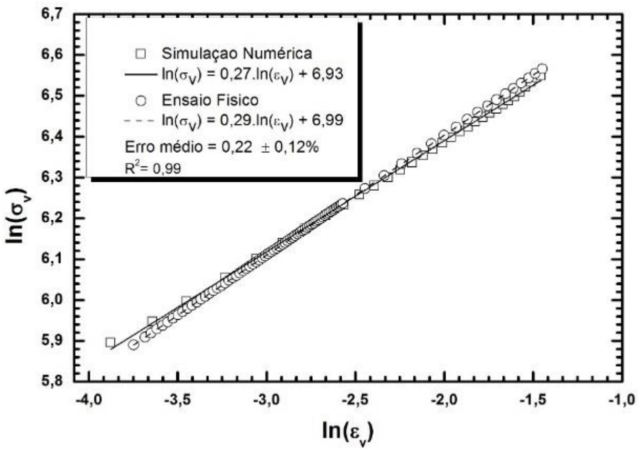


Figure 11. Tensile Test results of 9 vs 3 mm thickness

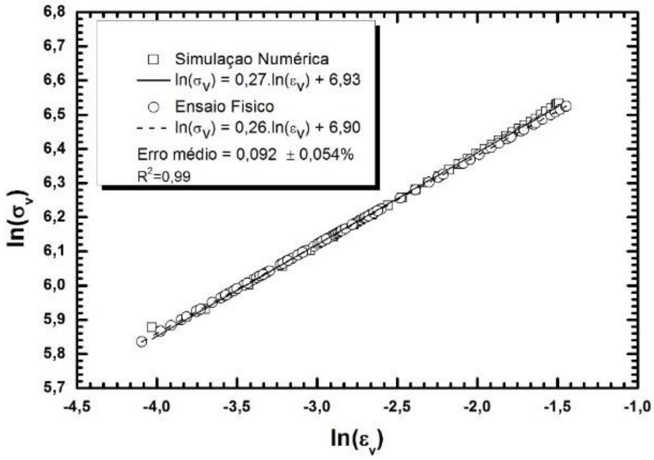


Figure 12. Tensile Test results of 12 vs 3 mm thickness

As indicated in the figures, the mean errors between the curves were low, with the largest error being 0.70 ± 0.23 % for carbon steel in the isolated condition and the lowest error equal to 0.092 ± 0.0054% for the cladding with 12 vs 3 mm, which validates the methodology used for analysis.

It was also calculated the coefficient of determination (R^2) between the lines of the physical and simulated tests, where the physical values were considered the actual observed values and the values of the simulation, the statistical model that seeks the adjustment. The R^2 values of the cloned materials were 0.99.

This result is importante because, as previously described, the materials, although they are hot processed, have different properties and mechanical behavior in the annealed condition, probably due to a hardening of the lamination process, so a reliable numerical simulation of the equipment is of extreme importance that is made using the appropriate material, With the same properties and responses of the actual material, minimizing errors.

4. CONCLUSIONS

- Materials after cladding report higher yeld and tensile strength than annealed conditions, indicating possible bake-hardening during the cladding process.
- The stainless steel bake-hardening rate was greater than the carbon steel, verified by the higher elongation and higher increase in the tensile strength in relation to the norm values.
- SA-240 TP. 316L stainless steel shows higher yeld and tensile limits than SA-516 Gr.70 carbon steel and exerted greater influence on the cladded plates mechanical properties.
- The fractography confirms the stainless steel greater bake-hardening, which in both the isolated and the composite condition presented predominantly fragile morphology.
- The tensile test simulation by finit element methods of the insulated and cladded materials presented satisfactory and reliable results with very small errors

5. ACKNOWLEDGEMENTS

To the Pontical Catholic University, to the FAPEMIG and CAPES.

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