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ASSESSMENT OF MECHANICAL PROPERTIES FOR STAINLESS STEEL AISI 304, AND ITS DEFORMATIONS RESULTING FROM TENSION TESTS AT DIFFERENT TEMPERATURES, SPEEDS AND LAMINATION DIRECTIONS

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Abstract. *Class AISI 304 austenitic stainless steels, in addition to their main characteristic (corrosion resistance), has a good limit of tensile strength, ductility and good deformation. Through a literature review about stainless steel AISI 304, this paper aims to observe and quantify its mechanical properties when exposed to a tensile test, considering the effects of temperature, speed and hardening levels that the material has when tested. It was used the engineering stress-strain diagram and the true diagram with plastic deformation velocities between 2 to 30 mm/min. and 5 to 500 mm/min. With temperatures between -253° and 27 °C, with tests done in the 20°, -10°, -30°, -50°, -166°, -80°, 0° and 27 °C. The rolling directions were between 0°, 45°, and 90° degrees. Results presented that the material was directly affected as to the variables used, but with good UTS and mechanical properties, showing tenacious, ductile, and anisotropic, with low resilience and with uncontrolled and unstable deformation when imposed at critical speeds. Having three levels of speed increment dependent on the imposed temperature and velocity, one observes as well as an apparition of martensitic farms when deformed that affected its own hardness, deformation and resistance*

Keywords: *Austenitic stainless steel 304, mechanical properties, tensile test.*

1. INTRODUCTION

The study of the behavior and mechanical properties of austenitic stainless steel is of great importance for the science and engineering of materials, due to its ability to resist different types of loads and due to its variation of deformation in relation to high and low temperatures.

There are different types of stainless steels such as ferritic, austenitic, martensitic, and precipitation curable, which are based on the chemical structure of the material, giving to them, mechanical characteristics and resistance to corrosion. Austenitic stainless steels are mainly used in engineering applications because of their excellent properties of resistance, corrosion, solubility and mechanical properties. (Santos and Andrade, 2008).

For any engineering project, it is required that one has a thorough knowledge of the material that will be used. With this, the selection and specification criteria led to the performance of standardized mechanical tests in order to know its mechanical properties and behavior when imposed to some effort or temperature in conjunction with it. This standardization is necessary to create a more reliable environment of information obtained, standardization and help in communication between buyer and manufacturer, since the tests are used in the manufacturing process (Garcia et al., 2000a).

The standards applied for the standardization in tests can be national and international, being that the test temperature, test specimen shape and dimensions are determining factors for the choice of standard. The most commonly used standards in Brazil are: ASTM (*American Society for Testing and Materials*), ISO (*International Organization for Standardization*) and ABNT (*Brazilian Association of Technical Standards*). Specifically regulators do not have standards only for the performance of the test but there are standards that specify how much the evaluation of the properties obtained in the test as well as the preparation for the same, fixation of the body of evidence in the machine, and taken into account until its shape prismatic, in metal or in tubes.

Mechanical tensile testing is considered the simplest way to obtain those mechanical properties of a material. Through this test, the tensile strength limit (UTS), resistance coefficient, yield limit (YL), toughness modulus, ductility, resilience modulus, modulus of elasticity and material hardness coefficient can be obtained. (Garcia et al, 2000b).

AISI 304 austenitic stainless steel when deformed at different temperatures may undergo some changes in its crystalline structure and grain structure, being of great importance the study of these modifications due to the fact that these changes would completely alter their mechanical properties and their applications.

The stainless steel differs from carbon steel because when exposed to tensile tests, there are four non-linear stress-strain curves, with no degree of flow and with a well-defined hardening region, altering their absolute behavior when compared to carbon steel (Santos, 2015).

In this perspective, the present work aims, through a literature review, to incorporate researches related to AISI 304 austenitic stainless steel, in order to demonstrate its mechanical properties, deformation at different temperatures, besides analyzing and interpreting the obtained data, as well as their properties, when imposed on an axial load of traction, thus being able to demonstrate its potential.

2. MATERIALS AND METHODS

The present article follows the principle of bibliographical review that according to Tomasi and Medeiros (2008) assists even in the objectives of scientific research, contributing in the theoretical constructions, and in the comparison, obtaining and validation of the results of the works of courses' conclusion and scientific articles.

This research began in the year of 2019, first with the study and knowledge about mechanical testing, properties and regulatory standards. This paper has a qualitative character referring to the properties of the material and its reactive potential to some variables. In addition, being this research of the explanatory type aiming to record data, analyze, interpret and identify its causes (Marconi and Lakatos, 2011).

The main sources of research were from the journal's portal of CAPES (*Coordination of Higher Education Personnel*), through the search for knowledge area: engineering, and as subarea: mechanical engineering, materials engineering and metallurgy.

It was obtained access to the main digital collections such as Univates, Metallum, Lume digital repository, Magazine Matéria, Magazine School Minas: Physical Metallurgy, University of Aveiro. On the other hand, google academic and scielo served as intermediaries for consulting theses, monographs and dissertations.

Ten materials were selected: one monograph, four papers and one dissertation, totaling six papers that were approved for the review of their information, with the following topics: stainless steel AISI 304. Table 1 indicates the chemical composition for AISI 304 stainless steel.

Table 1. Chemical composition for AISI 304 stainless steel (% wt.). (FAVORIT, 2019).

AISI	**$C_{máx.}$**	**$Mn_{máx.}$**	**$P_{máx.}$**	**$S_{máx.}$**	**$Si_{máx.}$**	**Ni**	**Cr**	**$N_{máx.}$**
304	0.08	2.00	0.045	0.030	0.75	8.00 -10.50	18.00 -20.00	0.10

The inclusion criteria were articles published in the period from 2005 to 2019 and that reported on the mechanical properties of AISI 304 and its deformations when imposed on the tensile test, and included articles that material of AISI 304 corresponded to the ABNT table of chemical composition by weight measured as a percentage.

The exclusion criteria were materials that did not fall into the class of AISI 304 stainless steels, articles that exceeded the exploratory period, and also excluded research, in which the mechanical properties of the material were obtained by means of any other test. Those other tests were that ones, which was not of and did not contain any of the key words, even the material being equivalent.

The present bibliographic review has a qualitative character referring to the properties of the material and its reactive potential to some variables. Moreover, its research is of the explanatory type in order to record data, analyze it, interpret and identify its causes.

3. RESULTS AND DISCUSSIONS

The results obtained will be related to the analysis and interpretation of the values and qualifications, which has the studied material and its graphs, tables and figures present in these articles referring to the values and observations found in diagrams σ-ε or true (tension and elongation), and diagram σ-ε with the different angulation directions for lamination and micrographs. It is also important to analyze the values of the tensile tests of the respective samples because through this information we can arrive at a result and discussion related to the objective of this article. Table 2 presents the synthesis of the analyzed works, showing their objectives, results and conclusions.

Table 2. Authors and their methodology, objectives, results and conclusions.

AUTHOR	YEAR	METHOD	OBJECTIVES	RESULTS	CONCLUSION
Anderson et al	2016	Field research	To evaluate the microstructure of the SAE 304 steel (micrographs).	The traction proposed by the mechanical flexural test had a greater capacity for deformation of the grains than the tensile test itself.	For the flexural test in the traction area, it was observed the growth of this grain, already for the compressed area, its decrease.
Antunes and Antunes	2007	Field research	To relate the plastic deformations of the austenitic stainless steel with different temperatures with detected hatch levels.	The temperature directly affects the UTS, YL, magnetic force, deformation and the hardening regions of austenitic steel.	Depending on the test temperature, it can present up to three levels of hardening, when temperatures are low, there is the appearance of martensitic phases, resulting in less deformation.
Purper	2016	Field research	To analyze and verify the influence of the anisotropy on the flow limit, tensile strength and magnetism of AISI 304 stainless steel.	The values obtained in the mechanical tensile tests, in different directions of lamination, showed changes in YL, UTS and elongation.	In all tests, the material was shown to be anisotropic, but the test specimens with a 45° rolling direction proved to be isotropic.
Rocha	2005	Field research	It is evidenced if the deformation speed changes the properties of AISI 304 stainless steel.	Tension-strain diagram in three directions of lamination, in three different speeds $1,1x10^{-3}$ s^{-1}, $1,1x10^{-3}$ s^{-2}, and $1,1x10^{-3}$ s^{-3}, with the increase of speed happened the increase of the internal temperature.	Strong anisotropy; high velocity values caused plastic instability; martensitic phases in the deformation were evidenced and the increase in velocity caused a decrease in deformation.
Santos and Andrade	2008	Field research	To obtain and dilatometrically evaluate different quantities of martensites as the deformation occurs in ABNT 304 austenitic steel.	It was observed that when exposed to low temperatures there is an increase in its ability to resist stress due to the ease of appearance of martensitic phases.	The martensites reversal was from 50 to 200 °C and 500 to 800 °C; the appearance of martensites α’ is larger at low deformation temperatures and at the same temperature it increases with deformation.
Zheng and Yu	2018	Field research	To determine the influence of low and high temperatures in the mechanical properties of AISI 304 stainless steel, real yield strength, and true uniform tension.	Conventional and true σ-ε graphs at different temperatures, with predefined stages levels as a function of the rate of hardening and deformation at different temperatures.	With the decrease in temperature from 20 to 77 Kelvin, the tensile strength and tensile strength increased, while the resistance decreased rapidly, for the temperature range of 77 to 298 K. It was also observed three hardening stages between the temperatures of 20-298K.

Purper (2016) carried out the tensile test on 15 specimens with different directions of lamination 0°, 45° and 90°, using five test pieces for each angle, where it is possible to obtain the flow limit (YL), limit of tensile strength (UTS) and elongation (in %). In this work, it was observed that the values varied in a controlled way and with a small difference of integers and decimals; however, the graph of stress and deformation of these tested samples will have almost the same characteristic. It can also be noticed that the YL in the three angles was at least 300 MPa, UTS 600 MPa, and elongation around 60%.

Table 3. YL values, UTS and elongation of test specimens (Purper, 2016).

Direction of lamination	YL (MPa)	UTS (MPa)	Elongation (%)
0°	331.70 - 335.63	630.61 - 638.63	63.52 - 70.12
45°	332.10 - 340.15	603.15 - 624.43	65.65 - 73.53
90°	325.83 - 328.60	629.73 - 643.06	71.37 - 73.53

Similarly, Rocha (2005) proposed in his study that the mechanical tests should be done at different angles relative to their rolling and exposed the results in the form of the real stress graph (σ-ε), as shown in Fig.1. One can see here a small elastic zone, but with a great area of tenacity and a good ductility, reaching over 50% when its rolling direction is 90°, and with a plastic deformation speed of 1.1×10^{-3} s^{-1}. Rocha analyzed at different speeds in order to determine whether the time variation of the test had influence on the plastic deformation and hardening of the steel. Figure 2 demonstrates the curves in different test speeds.

Figure 1. Stress-strain curve of the AISI 304 austenitic steel, in different directions of rolling (0°, 45°, 90°), with deformation and true tension (Rocha, 2005).

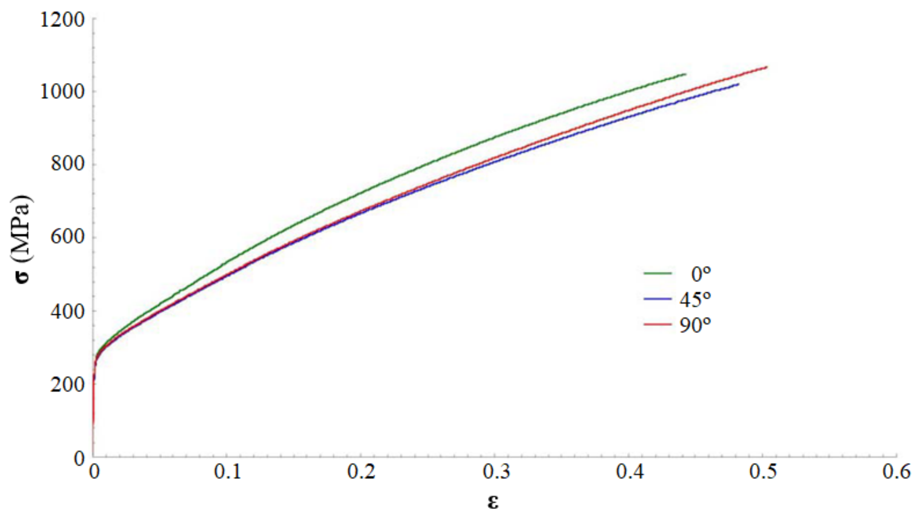
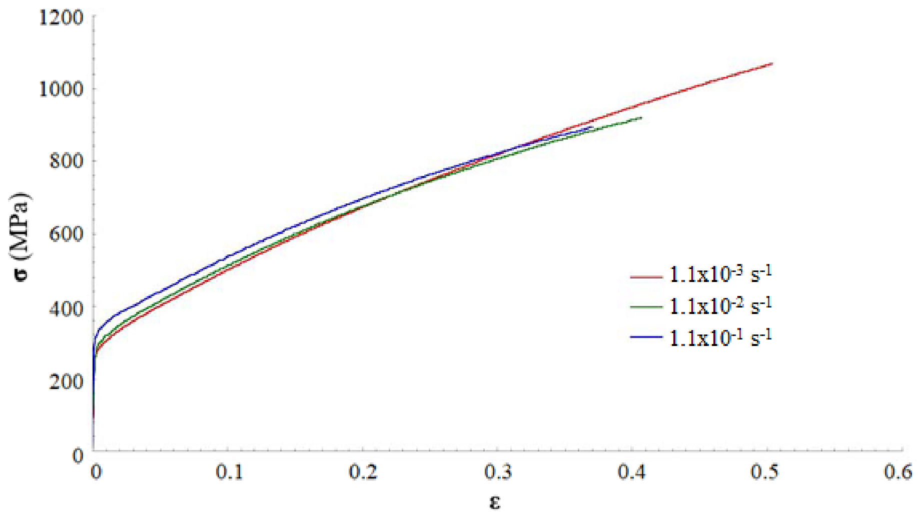


Figure 2. True σ-ε curves of AISI 304 steel at different test speeds: 1.1×10^{-3} s^{-1}, 1.1×10^{-2} s^{-1}, 1.1×10^{-1} s^{-1} from 5 to 500 mm/min. (Rocha, 2005).



Crushing of the grains was demonstrated through a transverse micrograph of the specimen from the lamination process made by Rocha (2005), comparing work with that of Anderson et al. (2016), this demonstrated via micrograph that before the test, the grains had a dimension of 9.36µm and after 13.25µm, a small difference when expressed in the order of percentage, which was around 3.89%. In addition, it has a small elongation, but taking into account the process of mechanical conformation that already places this grain in deformation. When compared to the Purper (2016) assays, its UTS was considerably reasonable but significant, being of approximately 513 MPa at different rotations in speed/min.

Rocha (2005) has shown that the higher the deformation velocity, the less the elongation of the useful part of the specimen. Consequently, its supported stress also changes due to the fact that the material loses its ductility due to the increase in velocity, and its tenacity changes because the UTS decreases and the area below the graph. Then, an increase in hardness as a function of the deformation is observed since with the increase of velocity the deformation occurs with a shorter time interval, causing martensitic work in the austenitic steel.

According to Santos and Andrade, (2008) the performance of the mechanical tests in different temperatures could cause modifications in its mechanical behavior of deformation and alteration in its graph. It is also perceived that the studied works have different speeds and temperatures even in the form of obtaining the results by the use of more technological or conventional means. In contrast, the graphical results with authors who proposed their tests under the same conditions, that is, by mentioning the true analysis forms, which are more similar to what happens instantaneously with the object to be studied.

In comparison, Antunes and Antunes (2007) performed the same analysis at temperatures of -196°C, -80°C, 0°C and 27°C, whereas in the Santos and Andrade tests (2008), it varied only from -50°C and 20°C. The behavior of the three visible phases of hardening occurs at a lower temperature because, according to Antunes and Antunes (2007), when the austenitic stainless steel is cold deformed, it creates martensitic phases, thus allowing an increase of the UTS, and a decrease of the elongation due to the properties of the new phase. Its amount is directly related to the stability of the austenite, but this only happens until a temperature limit after this limit will no longer create martensitic phases.

Zheng (2018) proposed the same form of analysis at various temperatures, -253.25°C to 24.85°C, seeking to evidence the influence of temperature on the mechanical properties of steel. Then, it was noted that the lower the temperature, the greater its tensile strength and the less elongation, and the higher its temperature, the lower the supported tension, but with a greater elongation as shown in Figs. 3 and Fig. 4 in Santos and Andrade (2008).

Figure 3. Engineering stress-strain curves (a) and true stress-strain curves (b) of the AISI 304 at various temperatures ranging from 20 K to 298 K (Zheng and Yu, 2018).

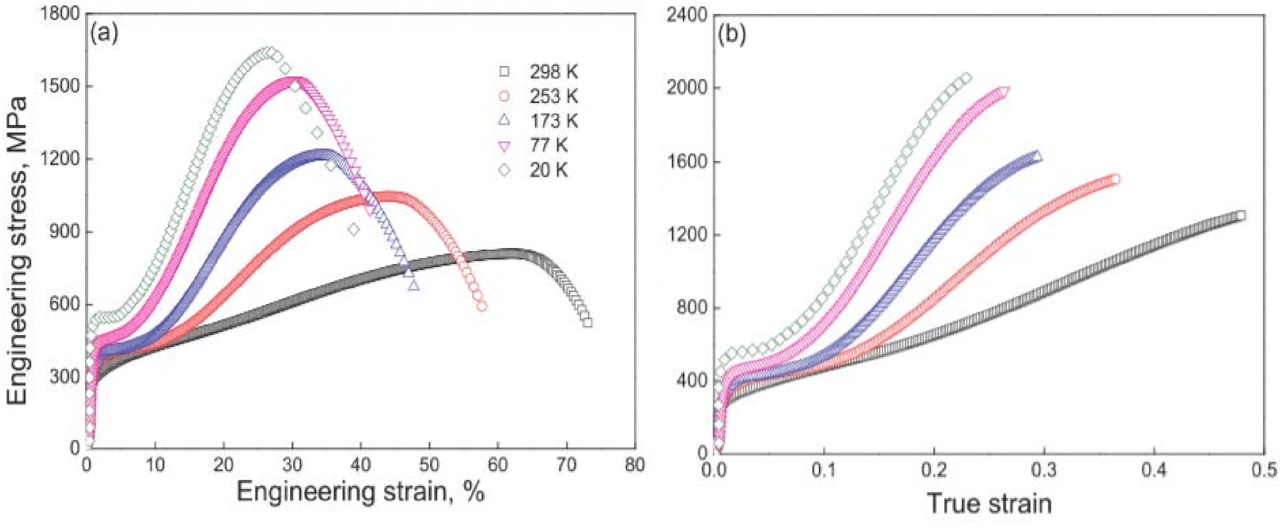
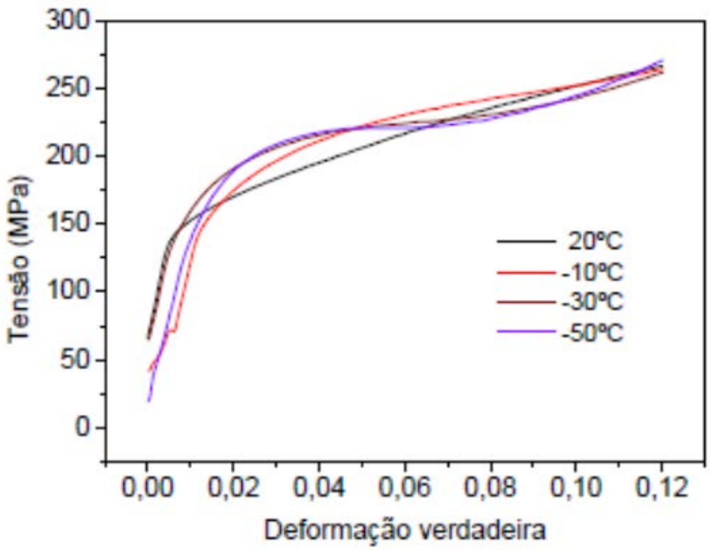


Figure 4. Curve Tension σ - true strain ε of stainless steel AISI 304, with deformation true up to 0.12 at different temperatures (Santos and Andrade, 2008).



Analyzing the Fig. 5 obtained from Essoussi (2019), it is noticed that the temperature exerts a direct influence on the hardness of the material. The hardness plot as a function of temperature demonstrates that the higher the temperature, the lower the supported voltage, but with a decrease in temperature, there is an increase of the UTS. This influence of heat on the mechanical properties of stainless steel AISI 304 was also observed by Antunes and Antunes (2007) and Santos and Andrade (2008).

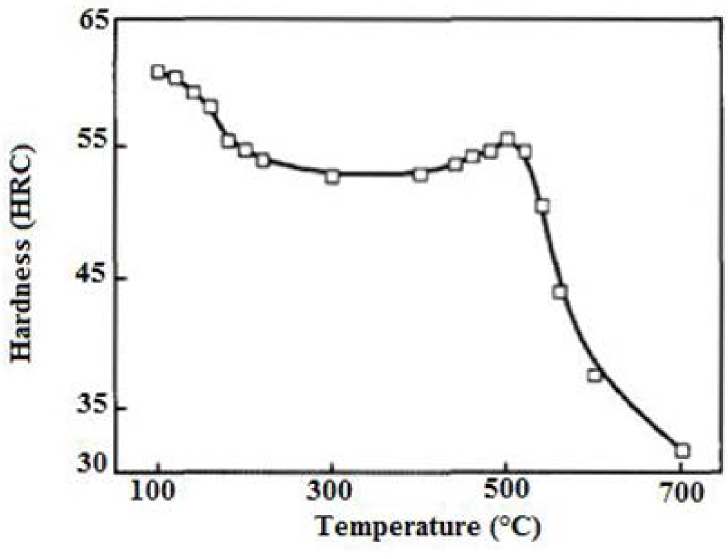


Figure 5. Temperature-hardness graph of a stainless steel (Essoussi et al., 2019).

4. CONCLUSIONS

The present paper had as main objective the evaluation and quantification of the mechanical properties of the austenitic stainless steel AISI 304 as well as the interpretation of information obtained through the traction test. The AISI 304 sample proved to be reactive when imposed at low and high temperatures. Further, it could be seen that depending on the temperature, the hardening levels of the material were visible. Some articles analyzed had disagreement with velocities, and this was also analyzed in order to make the article more complete since it is a literature review.

Additionally, from the analysis of the articles, the following conclusions can be reached:

- Due to the interpretation of the σ-ε curve, the AISI 304 showed good toughness since its minimum variation was around 500 and 600 MPa, and presented higher values than conventional graphs;
- Comparing all the graph curves (σ-ε) of the studied works, it was observed that the austenitic stainless steel and its resilience zone were almost parallel to the Y axis, demonstrating that its elastic and low deformation capacity. The modulus of elasticity is measured by the area below the elastic zone graph and we can say that its modulus of elasticity is low, indicating its low stiffness and high deformation;
- The material is characterized by good ductility due to engineering deformations of 70 to 60%, but when evaluated in a true curve. It was observed deformations in the range of 12 to 50% with values of tension between 250 and up to 100 MPa;
- The AISI 304 presented opposite curves when exposed to high and low temperatures, when it suffered cold deformation, the AISI 304 creates martensitic phases increasing its tensile capacity and reducing its deformation, but when the low temperature is kept constant, the material continues to deformation;
- How much the direction your lamination, the material is strongly anisotropic, that is, its mechanical properties change according to the direction of its lamination, altering its UTS, YL, and its deformation;
- Regarding the different velocities of the test or velocity of plastic deformation, it was noticed that there were not so many changes in its properties when they are not critical, but it was observed that with the increase of velocity of the test, the material possessed increasing regions of non-uniformity contributing to a deformation of uncontrolled form;
- AISI 304 stainless steel only behaved unusually when the value reached critical indexes, drastically reducing its plastic deformation. When submitted to critical velocity, its plastic deformation became heat, dissipating throughout the body region, causing the thermal softening and reducing its hardening.

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