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THE INFLUENCE OF SPECIMEN SURFACE ROUGHNESS ON TENSILE TEST RESULTS

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Abstract. *The tensile testing is performed to predict the behavior of a material under a uniaxial tension load. Many factors can affect the tensile test results, such as the specimen preparation. Therefore, the surface of the specimen, especially such gauge length, should be free from scratches or other damage that can act as stress raisers and cause early failure. Accordingly, the aim of this paper is to study the influence of the specimen surface roughness in tensile test results, using the ABNT/SAE 1020 steel. The specimens were manufactured in the CNC machine in accordance with ASTM E8 and ISO 6892-1, with five different speed rotations 1500, 2000, 2500, 3000 and 3500 rpm. The roughness of the specimens was evaluated by the Ra, Rq and Rz parameters. However, the Ra outcomes were taken as the main response of roughness. The tensile test results were assessed by observing the stress-strain curve behavior, and the tensile strength and percent elongation values. The Ra parameter results for the adopted rotation range varied within 1.134 µm to 1.967 µm and their smallest values were obtained with a 3000-rpm rotation. In contrast to the observed in the pre-tests realized by conventional machining, there was a small variation of the Ra roughness, between the best and the worst specimens 'surface finish conditions, which was not sufficient to affect the tensile strength. The tensile strength variations were small and close to the expected value for the ABNT/SAE 1020 steel.*

Keywords: *Surface finish, tensile test, roughness parameters, ABNT/SAE 1020.*

1. INTRODUCTION

One of the most common mechanical stress-strain tests is performed in tension. The tensile test is used to determine several mechanical properties of materials that are important in a component design, such as yield strength, tensile strength and ductility. In this test, a specimen is deformed, usually to fracture, with a gradually increasing tensile load that is applied uniaxially along the specimen longer axis (Callister Jr, 2007).

A tensile specimen is a standardized sample that has enlarged ends or shoulders for gripping and a reduced gauge section, which is the most important part of it. The cross-sectional area of the gauge section is reduced, relative to that of the remainder of the specimen so that deformation and failure will be located in this region (ASM International, 2004).

Improperly prepared specimens are often the reason for unsatisfactory and incorrect tensile test results. Therefore, it is important to be cautious in the preparation of the specimens, particularly in the machining, to maximize precision and minimize bias in the results. So, the reduced sections of the prepared specimens should be free of cold work, notches, chatter marks, grooves, gouges, burrs, rough surfaces or edges, overheating, or any other condition which can deleteriously affect the properties to be measured (ASTM E8/E8M, 2012).

The ISO 6892-1 (2009) specifies the method for tensile test of metallic materials at room temperature. Within its recommendations, there are the specimen dimensions and characteristics. Despite of some materials being very sensitive to specimen preparation, such as surface finish, the ISO 6892-1 does not provide any roughness parameter values for its manufacturing. Thus, the aim of this paper is to study the influence of the specimen surface roughness in tensile test results. For this, it was utilized a round specimen of ABNT/SAE 1020 steel.

2. TENSILE TEST AND FUNDAMENTALS OF FRACTURE

A tensile test involves mounting the specimen in a machine and subjecting it to tension. The specimen, that is fixed by its ends into the holding grips of the testing apparatus, is normally deformed to fracture. The tensile testing machine is designed to elongate the specimen at a constant rate, and to continuously and simultaneously measure the applied load and the resulting elongations. In the conventional tensile test, a stress-strain curve is constructed from the load-elongation measurements.

Engineering stress is defined by Eq 1, where F is the tensile force and A_o is the initial cros-sectional area of the gauge section, and engineering strain is calculated by Eq 2, where L_o is the initial gauge length and ΔL is the change in gauge length ($L – L_o$).

$$\sigma = \frac{F}{A_o} \tag{1}$$

$$\varepsilon = \frac{\Delta L}{L_o} \tag{2}$$

As reported by ASM International (2004), the advantage of dealing with stress versus strain rather than load versus elongation is that the stress-strain curve is independent of specimen dimensions. However, the shape and magnitude of the stress-strain curve of a metal depend on its composition, heat treatment, the strain rate and temperature, for example.

From the stress-strain curve of a metal, it makes possible to obtain important mechanical properties of the material such as the tensile strength, yield strength, percent elongation and reduction in area. The first two are strength parameters and last two indicate ductility.

For engineering materials, two fracture modes are possible: ductile and brittle. This classification is based on the ability of a material to experience plastic deformation. Ductile materials typically exhibit plastic deformation with high energy absorption before fracture. On the other hand, there is few or no plastic deformation with low energy absorption accompanying a brittle failure (Callister Jr, 2007). Since this research focuses on a ductile material analysis, the failure explanation will be limited to the ductile mode.

For ductile materials, the fracture process occurs following some steps. First, after necking begins, small cavities form in the interior of the cross section. Next, as deformation continues, these small cavities enlarge and coalesce to form an elliptical crack, which has its long axis perpendicular to the stress direction. Finally, fracture ensues by the rapid propagation of a crack around the outer perimeter of the neck. Sometimes a fracture having this characteristic surface contour is termed a cup-and-cone fracture because one of the mating surfaces is in the form of a cup, and the other like a cone (Callister Jr, 2007).

3. ROUGHNESS PARAMETERS

Surface roughness evaluation is very important for it can affect the function of mechanical components. Such assessment can be done by calculating different kinds of roughness parameters. Each of these parameters indicate a property of the surface and should be used for a certain application. So, it is common to evaluate more than one roughness parameter at the same time, because it provides a more accurate description of the surface. This section presents the definition and the mathematical formulation for only the three roughness parameters used in this research: the arithmetical mean value (Ra), root mean square roughness (Rq) and mean roughness depth (Rz).

According Gadelmawla *et al* (2002), the Ra is the most universally used roughness parameter for general quality control. It is defined as the average of the absolute values of the profile deviations from the mean line over the evaluation length. This parameter is easily measured, but it does not give any information about the wavelength and is not sensitive to small changes in profile. It can be calculated as follows

$$R_a = \frac{1}{n}\sum_{i=1}^{n}|y_i|. \tag{3}$$

The Rq parameter represents the standard deviation of the distribution of surface heights, therefore it is an important parameter to describe the surface roughness by statistical methods. It is also more sensitive to large deviation from the mean line than the Ra parameter (GADELMAWLA *et* al, 2002). The Rq mathematical definition is defined as

$$R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} y_i^2}. \tag{4}$$

The Rz parameter denotes the mean value of the five Rzi values from the five sampling lengths within the evaluation length (ln). The Rzi consists of the sum of the height of the highest profile peak and the depth of the deepest profile valley, relative to the mean line, within a sampling length (lr) (MITUTOYO, 2016). The Rz parameter is calculated by

$$R_z = \frac{Rz_1 + Rz_2 + Rz_3 + Rz_4 + Rz_5}{5} \tag{5}$$

Figure 1 illustrates the Ra and Rq parameter definitions and Fig 2 shows the Rzi and Rz descriptions. In Fig 1 and Fig 2, it can also be seen the sampling length (lr) and the evaluation length (ln) concepts.

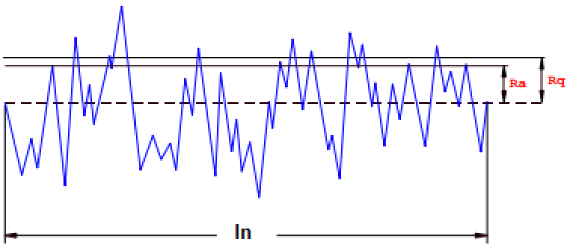

Figure 1.Ra and Rq parameter definitions (MITUTOYO, 2016).

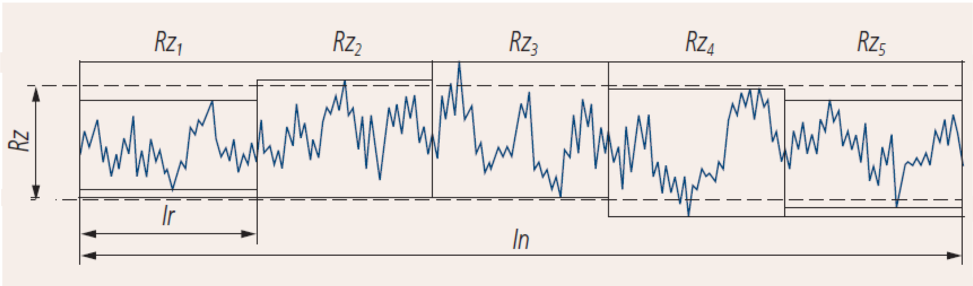

Figure 2. Rzi description and Rz parameter definition (MITUTOYO, 2016).

4. EXPERIMENTAL PROCEDURES

This section presents the experimental part of the paper. First, the selected raw material will be described as well as the manufacturing process. Next, the procedure for roughness assessment will be explained, and, finally, which parameters were used in the tensile test.

In this research, a low-carbon steel, the ABNT/SAE 1020, whose standard chemical composition is presented in Tab.1, was studied. According to MATWEB (2017), the tensile strength for a ABNT/SAE 1020 laminated bar is 450 MPa.

Table 1. Chemical composition of ABNT/SAE 1020 steel (SAE J 403, 2014)

% C	% Mn	% Si	% P	% S	% Fe
0,180 – 0,230	0,300 – 0,600	< 0,030	< 0,030	< 0,050	Balance

The tensile specimens were manufactured in a proportional size from a bar with 12,7 mm in diameter, respecting the ISO 6892-1 (2009) recommendation, which establishes

$$L_o = 5{,}65\sqrt{S_o}. \tag{6}$$

In the Eq. 6, L_o consists of the original gauge length and S_o is the original cross-sectional area of the parallel length. Based on the Eq. 6, the specimens' final dimensions were A= 48mm, G = 40mm; D=8mm, R=8mm, as shown in Fig. 3. The specimens' total length was 128mm and, since its gripping sections were not machined, its shoulder diameter remained the same as the original bar.

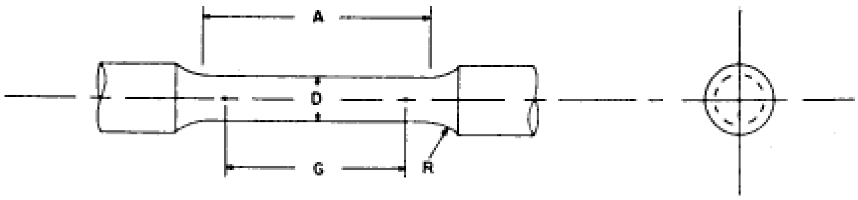

Figure 3. Tensile specimen dimensions (ASTM E8/E8M, 2012)

Fifteen tensile specimens were produced in CNC machining process on five different conditions of surface finishing, being three specimens produced for each condition. These conditions came as result from a change in the machine rotation, whose values were 1500, 2000, 2500, 3000 and 3500 rpm.

By using a portable surface roughness tester, aided by a height gage, as illustrated in Fig 4, the surface finish from the gauge length of the specimens was evaluated. As results, the Ra, Ry and Rz roughness parameters were obtained. For this, the specimens were turned 120º and, for each rotation, the surface finishing was assessed twice in different parts of the gauge length. Therefore, six evaluations were done per specimen. The main goal of adopting this procedure was to obtain, by arithmetical average, a roughness value that described the entire surface finishing of the specimen gauge length.

Figure 4. Roughness assessment procedure

The tensile test was carried out on a universal tester, by using the test speed of 10mm/min. The output of such test was recorded on a computer as force versus elongation, and such results were correlated to the obtained roughness. Finally, the research outcomes were compared with the ones achieved by Kikuchi *et al.* (2017), who studied the influence of surface roughness on the tensile test by using ABNT/SAE 1020 steel specimens machined in a conventional mechanical lathe. Kikuchi *et al* (2007) results represent the pre-tests of this research.

5. RESULTS

The explanation for the results will be done in three subsections. In the first one, it is presented the roughness parameter values, which were measured in the specimen's gauge section. In the second one, the tensile test results are described. In the last one, a correlation between both results is realized.

5.1 Roughness parameter results

Table 2 and Tab.3 present the roughness parameters obtained on the fifteen specimens' evaluation. These results represent the roughness mean value of the specimen gauge length and its respective standard deviation, which is indicated between parenthesis. As it is observed, the Ra parameter results for the adopted rotation range varied within 1.134 µm to 1.967 µm and their smallest values were obtained with a 3000-rpm rotation.

Table 2. Roughness values for each machining rotation (1500, 2000 and 2500 rpm)

Rotation	1500rpm			2000rpm			2500rpm		
Specimen	1A	1B	1C	2A	2B	2C	3A	3B	3C
Ra	1.632 (0.027)	1.681 (0.040)	1.724 (0.039)	1.963 (0.076)	1.967 (0.136)	1.933 (0.040)	2.084 (0.035)	1.370 (0.231)	1.402 (0.105)
Rq	1.882 (0.052)	1.962 (0.070)	2.038 (0.052)	2.472 (0.096)	2.303 (0.174)	2.368 (0.071)	2.614 (0.048)	1.706 (0.303)	1.695 (0.122)
Rz	7.577 (0.607)	8.050 (0.561)	8.759 (0.509)	10.761 (0.784)	9.784 (0.965)	10.053 (0.706)	10.953 (0.723)	7.952 (1.649)	7.496 (0.506)

Table 3. Roughness values for each machining rotation (3000 and 3500 rpm)

Rotation	3000rpm			3500rpm		
Specimen	4ª	4B	4C	5ª	5B	5C
Ra	1.134 (0.069)	1.273 (0.090)	1.199 (0.049)	1.375 (0.097)	1.332 (0.146)	1.337 (0.141)
Rq	1.356 (0.089)	1.544 (0.100)	1.453 (0.058)	1.666 (0.127)	1.627 (0.206)	1.622 (0.189)
Rz	5.808 (0.450)	6.862 (0.298)	6.240 (0.282)	7.286 (0.763)	7.215 (0.907)	6.746 (1.133)

By relating the Ra results with the rotation machining in the Fig.5, it is observed a nonlinear behavior of the roughness values. In theory, it is expected that an increasing in the machine rotation speed improves the surface finishing. However, as it can be seen in Fig. 5, this situation did not occur, which indicates that other variables had influenced the manufacturing process.

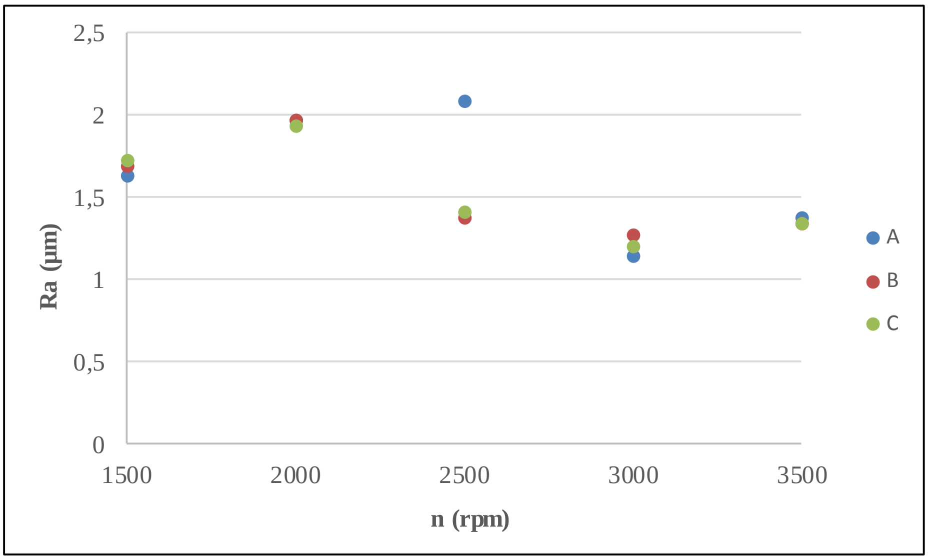

Figure 5. Behavior of Ra roughness parameter for each rotation speed

Analyzing the Fig.5, there is a raise of the Ra values for all specimens produced under 2000 rpm, and also for one from the group produced under 2500 rpm. These unexpected values could be explained because of an interaction between the tool and the work piece during the machining, such as chip adherence in the cutting edge of the tool. This phenomenon increases the machine vibration and results in a worse surface finishing of the piece.

The NBR 6152 used to recommend the international tolerance IT 09 as the maximum deviation for the assessment of widths along the entire gauge length of the specimen. Since the specimen gauge diameter is within the range of 3 mm and 18 mm, according to the established tolerance, the Ra parameter for the gauge length should be around 5 µm. Thus, even presenting some roughness deviation, all the specimens studied in this paper (Fig. 5) have their surface roughness values in agreement with this recommendation.

However, once the NBR 6152 is no more valid and have been replaced for ISO 6892-1 (2009), these values are not more officially use. But, since the ISO 6892-1 (2009) does not mention any roughness parameter value for tensile specimen, these ancient's values were used in this research only for a manufacturing guideline.

5.2 Tensile test results

Figure 6 to Fig.10 illustrate the stress-strain curves obtained in the tensile test, respectively for the specimens produced with 1500 to 3500 rpm-rotation. Observing all these graphs, it is possible to verify that the elastic-plastic transition is clearly defined and occurs abruptly in what is termed a yield point phenomenon. For metals that exhibit this effect, the yield strength is taken as the average stress that is associated with the lower yield point, since it is well defined and relatively insensitive to the testing procedure.

After yielding, the stress necessary to continue plastic deformation increases to a maximum, represented by the highest point of the stress-strain curve. This point, named tensile strength, is the maximum stress that can be sustained by the material in tension and such values are described in table 4.

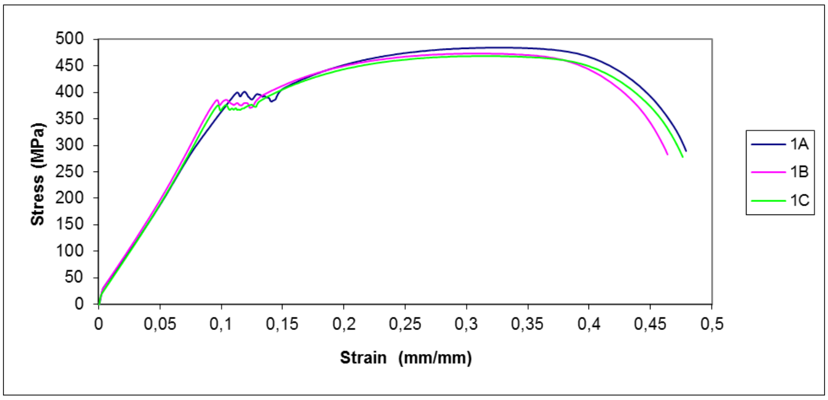

Figure 6. Stress-strain curve for machined specimens with 1500 rpm-rotation

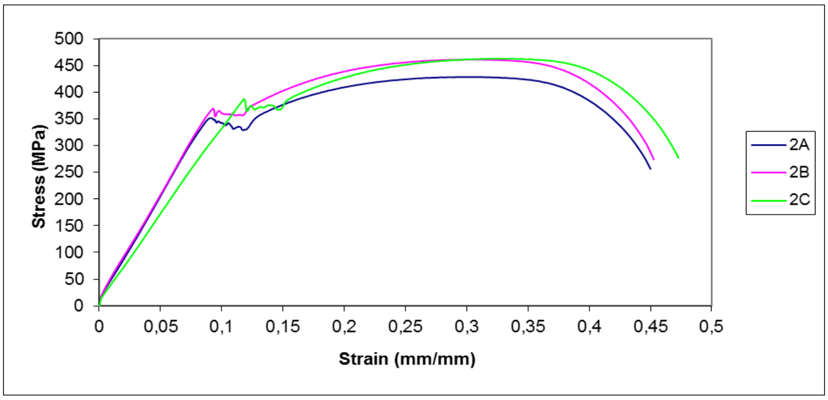

Figure 7. Stress-strain curve for machined specimens with 2000 rpm-rotation

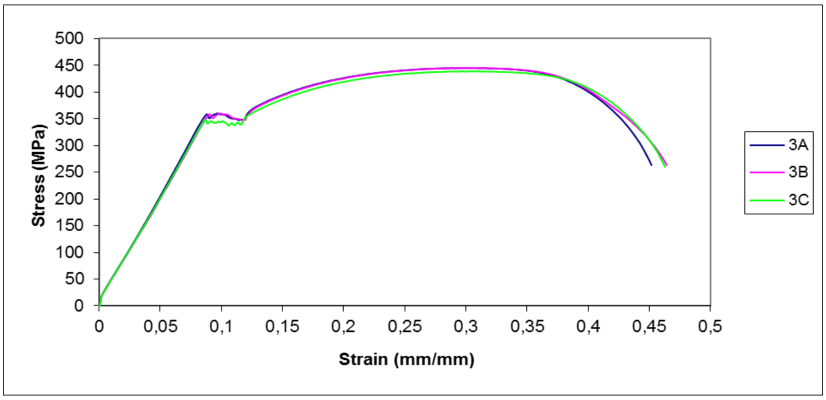

Figure 8. Stress-strain curve for machined specimens with 2500 rpm-rotation

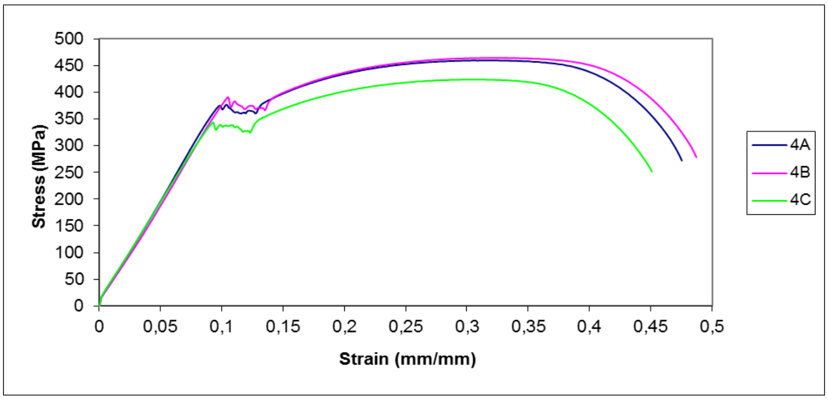

Figure 9. Stress-strain curve for machined specimens with 3000 rpm-rotation

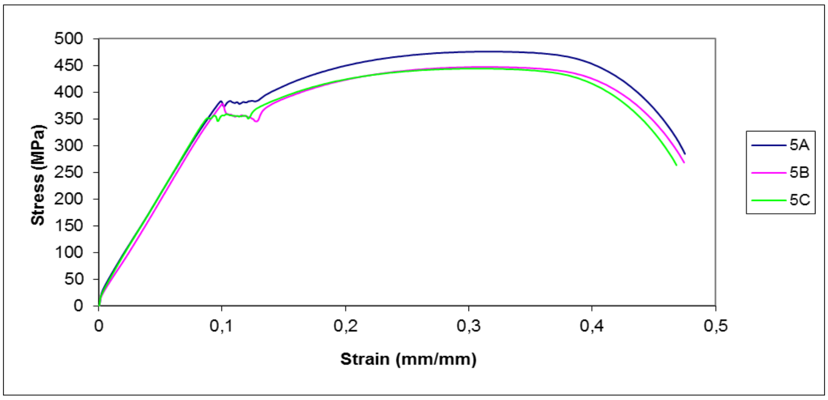

Figure 10. Stress-strain curve for machined specimens with 3500 rpm-rotation

By Fig. 6 to Fig 10, it is remarkable that the test material experienced a large plastic deformation at fracture, which demonstrates its high ductility. This property is quantitatively expressed by percent elongation (EL%), whose values are shown in Tab. 4. Both tensile strength (UTS) and percent elongation presented in Tab. 4 are mean values, that represent each group of specimens, categorized by machining rotation.

Table 4. Mechanical properties of the specimen's groups

Rotation (rpm)	1500	2000	2500	3000	3500
UTS (MPa)	473.77	449.71	442.58	451.26	454.91
EL (%)	38.50	36.33	37.00	37.17	37.15

The UTS and the EL (%) values (Tab. 4) are in accordance with the expected for the ABNT-SAE 1020 steel. However, the specimens manufactured with 1500 rpm-rotation presented a slightly higher tensile strength than the others, which can be explained by a possible strain hardening caused by a machining parameters' combination.

The high EL (%) observed in Tab.4 is a characteristic of ductile steels, such as the one studied here. All the specimens experienced a high plastic deformation until fracture as can be seen in Fig 11, which indicates a cup-and-cone fracture.

Figure 11. Cup-and-cone fracture of the specimen

By analyzing the values of Tab.2, 3 and 4, none direct correlation between the mechanical properties and surface roughness could be done. For the selected machine rotations, there was a small Ra roughness variation (0.833µm) between the best and the worst surface finish condition, which was not sufficient to affect the tensile strength of the studied material.

In contrast, Kikuchi *et al.* (2017) showed that for ABNT/SAE 1020 tensile specimens, whose Ra roughness values varied between 2 µm to 5.28 µm, there is a tendency of tensile strength reduction when the Ra value gets closer to 5 µm. Kikuchi *et al.* (2017) also verified that a better surface finish leads to a higher tensile strength, which can be attributed to the specimen' surface integrity. These results are illustrated in Fig. 12.

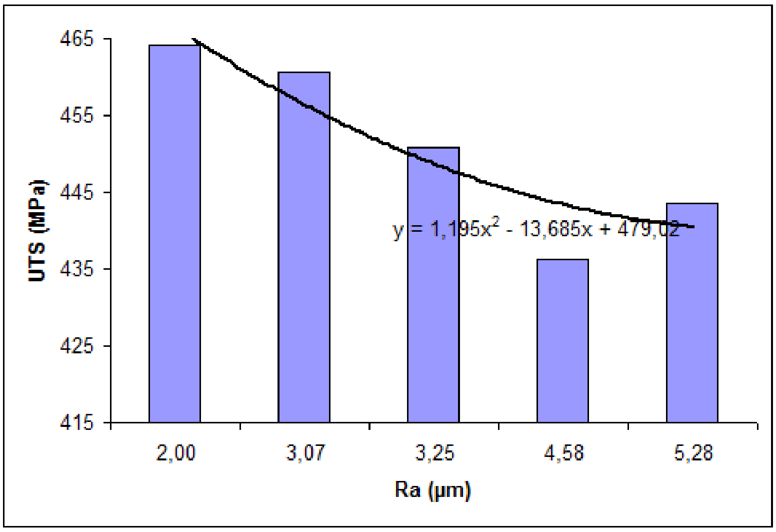

Figure 12. Tensile strength values for each surface roughness condition (KIKUCHI *et al*, 2017)

In Kikuchi et al. (2017), the specimens were produced in a conventional mechanical lathe and the Ra roughness variation between the best and the worst case was 3.28 µm, as can be seen in Fig. 12. This bigger variation made possible to observe different mechanical behaviors in the material since the increment of the peaks and the valleys of the roughness profile acts as stress raisers.

6. CONCLUSION

The tensile test is performed to ascertain several mechanical properties of materials, such as tensile strength and ductility. However, many factors can affect such results as specimen preparation, which includes surface finish and dimensional accuracy for example.

Regarding these factors, this paper studied the influence of the specimen surface roughness in tensile test results. The specimens were manufactured in a CNC machine, utilizing the ABNT/SAE 1020 steel, with five rotation speeds: 1500, 2000, 2500, 3000 and 3500 rpm. However, this change in the machine rotation did not cause a representative modification on the specimen surface finishing, as expected. Therefore, the roughness range, which was evaluated by the Ra parameter, was narrow and only varied between 1.134 (0.069) µm and 1.967 (0.136) µm. Such small Ra variation reflected on a uniform specimen gauge length, with small changes in roughness profile, which characterized a good surface finishing.

Thus, for the studied roughness, just a small variation in the tensile strength was observed. Such values remained close to the expected one, which is 450 MPa for the ABNT/SAE 1020 in the laminated state. The stress-strain curves demonstrated that the results were typical of a ductile material, which could also be seen by the high percent elongation value, around 37%, and by the cup-and-cone fracture aspect.

In conclusion, the influence of the roughness in the tensile strength was more perceptible in the pre-tests, showed in Kikuchi *et al* (2017), whose specimens were produced in the conventional mechanical lathe. In these experiments, the roughness variation was bigger than the studied here and, consequently, it acted as stress raisers, which contributed to the crack propagation. It is remarkable that specimens produced in a conventional way have higher roughness variation since the operator dependency and the instability of the equipment are bigger than in the CNC process.

7. ACKNOWLEDGEMENTS

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