https://dx.doi.org/10.22161/ijaers.74.45 ISSN: 2349-6495(P) | 2456-1908(O)

The influence of heat treatments in the shear force during the machining of the SAE 4320 Steel

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***Abstract*— *The steel have a wide range of applications in the industry, being of extremely importance in any manufacture process. The SAE 4320 steel is used in a lot of ways, some of them are the transmission systems like gears and pinions. The heat treatments are used to improve some properties of the steel like, hardness, ductility and impact resistance. There are many different types of heat treatment. In this article it was made the tempering process in water and oil, and the quenched process was done in the samples. The purpose of this activity is to do the heat treatments, that were mentioned before, in the SAE 4320 steel, and then analyze with tests the mechanical property variation in the shear force during the machining, with the objective of verifying if there is any correlation between these parameters and if the shear force is also influenced by this modification of the microstructure. Some parameters, like the time that the sample was in the austenitization temperature and the machining parameterswere fixed. After the heating treatments some analysis of the microstructures and hardeningwere made.*

***Keywords*— SAE 4320 Steel; Heat Treatment; Hardness; Shear Force.**

I. INTRODUCTION

The study of thermal and thermochemical treatments, as well as mechanical analysis after certain treatments are of great relevance to optimize the machinability of a given material. The SAE 4320 steel, which is widely used in the manufacture of pins, gears and elements requiring high surface hardness, is still of few use in the range of products available on the market. This report has the objective to broaden the knowledge already acquired in relation to steel, contributing to its applicability. Using different thermal treatments it was evaluated how these processes influence the machining of a part made of SAE 4320 steel, allowing the choice of the ideal processes according to the application of the material.

The concepts and knowledge developed in the machining of hardened steel are applied to obtain desired surfaces and production in the shortest time possible, eliminating future operations, mainly rectification [1]. The choice of the appropriate tool and application of the cutting parameters can contribute not only to obtaining the specified surfaces but also to the execution of the operations with lower costs [2]. Machining is of fundamental importance to other manufacturing processes, being the most widely used in the industry, turning into chips about 10% of all metal production, employing tens of millions of people worldwide [3]. It also accounts for more than 15% of the total value of processed products, whether mechanical or not.

By comparing the machining forces (Fu) of thermally treated samples, it is expected to determine which variables should be used in order to optimize the manufacturing process of parts made of 4320 steel. It is also expected that the work will contribute to the determination of the heat treatment variables of the steel under study, in order to offer results that will show which type of treatment is most suitable for obtaining certain mechanical characteristics such as hardness.

Among the main objectives to be taken into account, one highlight is the heat treatment of 4320 steel, as well as the metallographic analysis that evaluates how such treatments can change the machinability of the material. In this way, to see if the results obtained were satisfactory for the applicability of SAE 4320 steel in the variety of materials available in the market of mechanical and structural elements.

Among the range of materials available in the market, the SAE 4320 is still a poorly exploited material for mechanical analysis when compared to other materials such as SAE 1020, 1045 and 4340 steel. Although it is a low carbon steel (0.2 %), the material presents good temperament because it contains molybdenum (Mo) in its composition.

SAE 4320 steel has high surface hardness and is mainly used in parts such as pins, crowns and gears [4].Thus, processes such as thermal and thermochemical treatment are operations that aim to further optimize the properties of this material, being able to contribute with the metalworking industry, in addition to providing amplification in the application of this material. Chandler *et al*. [4] concluded that SAE 4320 steel has high surface hardness and is mainly used in parts such as pins, crowns and gears. Thus, processes such as thermal and thermochemical treatment are operations that aim to further optimize the properties of this material, being able to contribute with the metalworking industry, in addition to providing amplification in the application of this material.

Materials from the same family, such as the SAE 4340 alloy, have a considerably larger range of information, where SAE 4320 is somewhat under-researched. Therefore, the activity developed had as foundation to also contribute to the literature and assist those who seek a material of high hardness, good temperability and low percentage of carbon. Among the mechanical analyzes it is noticed that the machining is very important to generate the final cost of a part. Thus the research contributes to the optimization of this process in the studied material, since the forces involved in the machining of this steel will be analyzed, having or not being submitted to different types of thermal treatments.

II. MATERIALS AND METHODS

This work had as main goal the accomplishment of thermal treatments in the steel SAE 4320 and to verify its changes, and what those changes can interfere in the process of machining and in its shear forces. Samples of the steel under study were submitted to various types of thermal treatments, from which they provided alterations in the microstructures of the pieces, where these were analyzed with the Metallographic Test. In order to verify the influence of the treatments on the machinability of the material, shear tests were performed. Then the collected data were analyzed and treated in order to generate primordial graphs for the discussion of the results.

In each type of treatment, three (3) samples were used, in order to improve the collected data. Prior to the repeatable tests, pre-tests were performed. The pre-tests contributed with the training and experience of the researchers, which reduces possible failures in the studies ahead, besides leaving the machines and tools already prepared and adjusted for the later actions of this research.

2.1 Sample Preparation

To obtain the samples to be worked, it was necessary to segment the pieces. Thus, a steel bar with a diameter of 1 inch (25.4mm) was used, and with the use of the Horizontal Band Saw of the brand “FRANHO” and model "FM-900", the parts were produced with approximately 30mm of length (for the machining force test).

Before the start of the experimental procedures, the characteristics of the parts were determined according to Table 1, where each sample was destined for the machining test. Respecting that, 3 pieces of each sample were used.

Table 1. Sample Description.

Sample 1	Tempering in water
Sample 2	Tempering in oil
Sample 3	Quenched from the tempering in water
Sample 4	Quenched from the tempering in oil
Sample 5	No Treatment

All steps to be described are set forth in Figure 1 which represents the procedures in which the 30 mm long samples were submitted for the determination of the machining force.

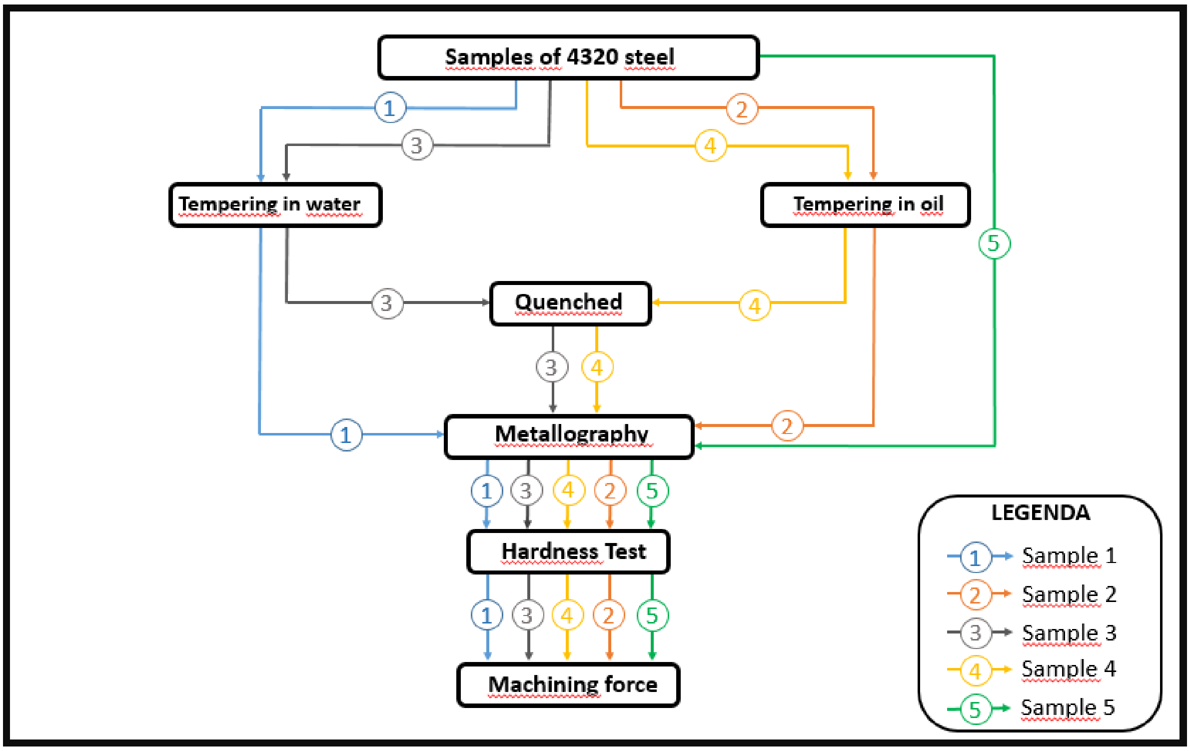

Fig. 1. Complete chart with the activities for the machining force analysis.

2.2 HeatingTreatments

2.2.1 Tempering

Chandler *et al.*[4] concluded that the austenitizing temperature of SAE 4320 steel is 850 ° C. Thus, the pieces were taken to the Oven (EDGCOM 3P) until they reached the described temperature at a rate rising level of 15 ° C per minute. Before being withdrawn, the samples were left in the oven at their austenitization temperature (850 ° C) for 30 minutes [4]. Cooling is an essential part of tempering, of which the type and speed plays a key role in its outcome. So for this study, water and oil were used for this stage.

2.2.2 Quenching

Fig. 2. EDGCOM 3P (MC-2) Oven

Quenching is done shortly after tempering, and consists of reheating the part at a temperature below that of the material's austenitizing temperature. Thus, some of the "tempered" specimens 25 were returned to the oven (Figure 2), warming them to the quenching temperature (150ºC), and the samples were held at that temperature for 30 minutes before being cooled in Water. [4]

2.3 MetalographicPreparation

To get a properly regular and flat piece prepared for metallographic analysis, sanding is very important. After the use of the saw and successive heat treatments, the samples were taken to the sander (ORATEC APL-4D), and with the use of 80, 180, 240, 320, 600 and 1200 sander with water, the pieces were prepared for polishing. To observe the phases present in steel, the sample is polished until "mirrored", followed by the use of an appropriate chemical reagent. One of the most commonly used chemical reagents for carbon steels is nital, which consists of a mixture of 0.5 to 6% nitric acid in ethyl alcohol. [5]

After the sanding, the specimens were taken to PolitrizMetalgraphic Sander (PL 02 ET), where they were prepared to receive the chemical attack and later analysis under the microscope. The pieces were polished using Alumina 0.5 µm (aluminum oxide). Before the metallographic test, the chemical attack was carried out, in order to provide the visualization of the grain contour and the phases of the microstructures. The agent used was Nital 4% (solution of nitric acid in ethyl alcohol 96° GE), and

https://dx.doi.org/10.22161/ijaers.74.45 ISSN: 2349-6495(P) | 2456-1908(O)

the polished pieces looked "opaque" after the attack and were cleaned and taken for analysis of the microstructure. All samples, except for the samples for the traction test, went through the metallographic preparation stage, since their microstructures need to be studied, even the "Sample 5", which are the pieces that did not receive any type of thermal treatment, but are essential to make comparisons and define what each treatment has changed in the steel structure.

2.4 Metallographic Analysis

In order to verify the microstructural changes, the samples, including those not treated thermally, were submitted to metallographic analysis. In this step the Optical Microscope (Olympus BX51M) connected to a computer was used, where the parts were positioned and focused on magnifying glasses for visualization. Samples for the machining strength test, whether or not heat treated, sanded and polished, were subjected to chemical attack with nital.

The softwares“analySIS ®” and “PixelLINK Capture ®” were of main importance. The samples 1, 2, 3, 4 and 5 were analyzed microscopically in three (3) regions with two (2) lenses (500x and 1000x magnification), to obtain more coherent results and better visualization.

2.5 Hardeness Test

After verification of how the heat treatments modified the microstructure of the material, the samples were submitted to the Vickers microhardness test, to also highlight how the same treatments influenced this mechanical property. According to Budynas (2011), [6] the hardness property of a material (in the Vickers microhardness test) is related to the penetration resistance of a sharp tool.

The method used consists of a square base diamond penetrator with an angle of 136° between the opposing faces. Thus, the impression when visualized with an optical microscope is in the form of a rectangular diagonal "L" diamond. The test has relation to the applied area and the area of the faces printed on the material. It is a suitable process for tempering and carburizing. The voltage unit of this test can be used as HV, Kgf / mm² or N / mm² and is calculated according to Equation 1. [7]

$$HV = \frac{1.8544*P}{L^2} [1]$$

The microdriometer "HM 102" was adjusted to apply a load of 1kgf, using a Pyramid Indentador with diamond tip. Five (5) measurements were made, always from the center to the end of the pieces, so that the first one is in the center (reference point), and the other ones distancing 2, 4, 8 and 10mm respectively, according to the representation of Figure 3.

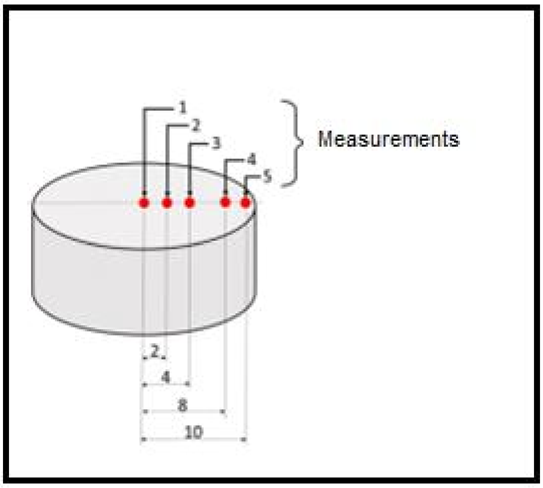

Fig.3. Measurements points of microhardness Vickers (dimensions in mm)

2.4 Shear force

In order to know the influence that the described heat treatments have under the machining force of the SAE 4320 steel, it is important to do tests that evaluate the shear forces associated to the machining of the samples. Through the top milling, and using the CNC Milling Machine (Petrus 50100R), shown in Figure 4, and an 80 mm milling cutter with seven (7) carbide inserts (490R-140408M-PM 4240), the shear forces of each test were analysed.

Fig.4. CNC Milling PETRUS 50100R – DIPLOMAT.

The samples were fixed in a bench vise attached to the Kistler Dynamometer (model 9265B), which by means of the deformation of their "sensors" quantifies the force exerted by the cutting tool on the "x", "y" and "z" axes. The data then acquired at a speed of 2000 dots per second, and in text file format, were stored and analyzed. Each test was performed separately in each of the samples

https://dx.doi.org/10.22161/ijaers.74.45 ISSN: 2349-6495(P) | 2456-1908(O)

(and their replicates) with machining parameters (depth, feed and rotation) set according to Table 2, so that the final results are better compared.

Table 2. Parameters used in the machining of the samples during the shear force test.

Cuttingdepth[ap]	Rotation[n]	Feed[f]	Cuttingspeed[Vc]	Mill diameter[df]
1(mm)	300 (RPM)	75 (mm/min)	75,4 (m/min)	80 (mm)

A low cutting depth and feed were used in order to minimize tool wear, and for greater depths it could not be affirmed that the tool would be in contact with the altered microstructure material (the treatments are more effective on the surface of the piece).

Top milling was done on the samples in a way that they were centered relative to the cutter and positioned with a wooden block (so that all samples are machined in the same position) according to the illustration in Figure 5. Cutting fluid was not used, and tool wear was not considered to generate the final resultsof machining force calculations.

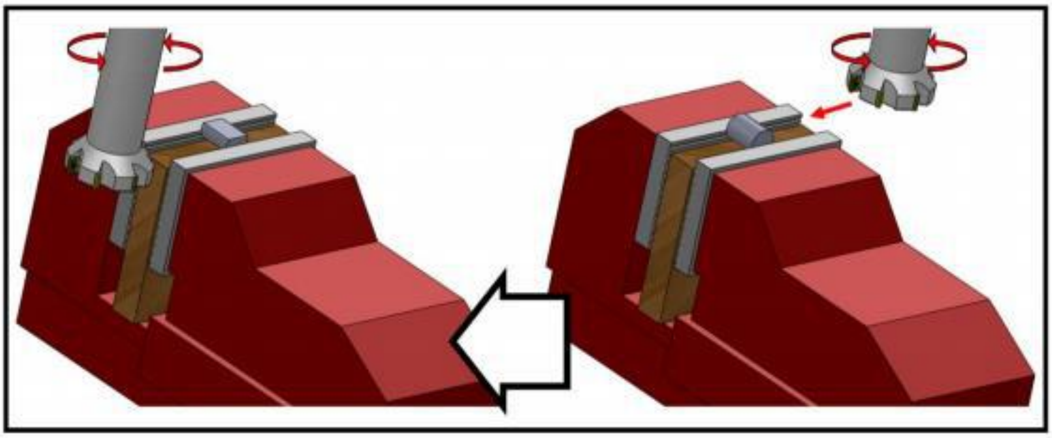

Fig.5. Representation of the way that the machining of the samples were made during the shear force test.

III. DISCUSSION AND RESULTS

3.1 Hardness Test

In order to obtain a better visualization of the data, Table 3 was created, it shows, in a summarized form, the average of all the samples treated. The average of each position of the samples was calculated, allowing the construction of the graph of Figure 6, which shows how the hardness of the piece at each point varied. The activity in question was made with three (3) samples for each treatment.

Table 3–Average of the values of microhardness Vickers (HV) of the replicates in relation with the position it was measured.

MEASUREMENTS AVERAGE IN EACH ONE OF THE POSITIONS					
Distance [mm]	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**
Center	464.3	389.7	400.3	305.7	251
2	453.7	324.3	424.7	295.3	236
4	480.0	362.0	436.3	323.7	264
8	443.0	353.0	445.3	341	225
10	453.3	315.0	455.0	320.7	243
Total Average	**458.9**	**348.8**	**432.3**	**317.3**	**253.8**

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According to the Table above, it is verified that Sample 1 (tempered and cooled in water) obtained a greater hardness in comparison to the other samples, thus confirming the formation of martensite, adifusional phase of high hardness. In agreement, the Sample 3 that was also cooled in water, but with the process of quenching, was placed second in terms hardness, evidencing that the cooling in water, because it is faster, facilitates the formation of martensite. The quenching process alleviates martensite tensions, which may reduce its hardness a little (due to the precipitation of iron carbides).

On the other hand, samples 2 and 4, due to having undergone oil cooling, obtained lower hardness. Agreeing to what has been said previously, that hardness is related to cooling speed.

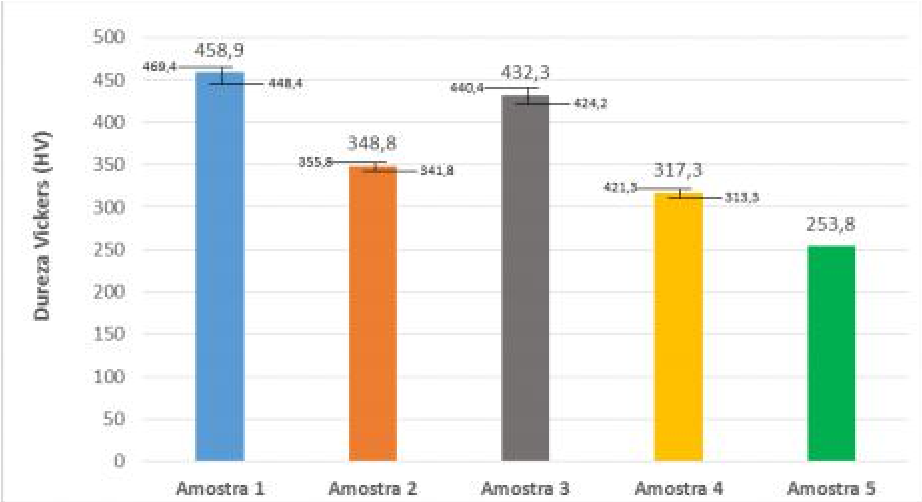

Fig. 6. Hardness Average Graph (Total Average and Standart Deviation) between the replicates of each kind of sample.

The graph of Figure 6 indicates that even with the standard deviation made in Table 3, it can be seen that the water-tempered piece (Sample 1) had the highest hardness average, especially in relation to the untreated piece (Sample 5), thus proving the proportional relationship between hardness and tempering/quenching.

3.2 Machining Force

With the dynamometer properly fitted and adjusted to the CNC milling machine, the top milling of SAE 4320 Steel was machined in a single pass (Figure 7), in which each sample was subjected to the same machining parameters (Table 2), in order to obtain greater comparability between them. The dynamometer collected 2000 data per second and these data were computed with the aid of the software "Scilab ®". Therefore, fifteen (15) test bodies were machined, and the graphs referring to the shear forces (of each process) were plotted with the aid of the "Scilab ®" Software.

The Figures 7, 8, 9, 10 and 11 show how the shear force behaved on the three (3) axes during the tests, and the RMS value of the forces is shown in the graphs by the line perpendicular to the vertical axis.

https://dx.doi.org/10.22161/ijaers.74.45 *ISSN: 2349-6495(P) | 2456-1908(O)*

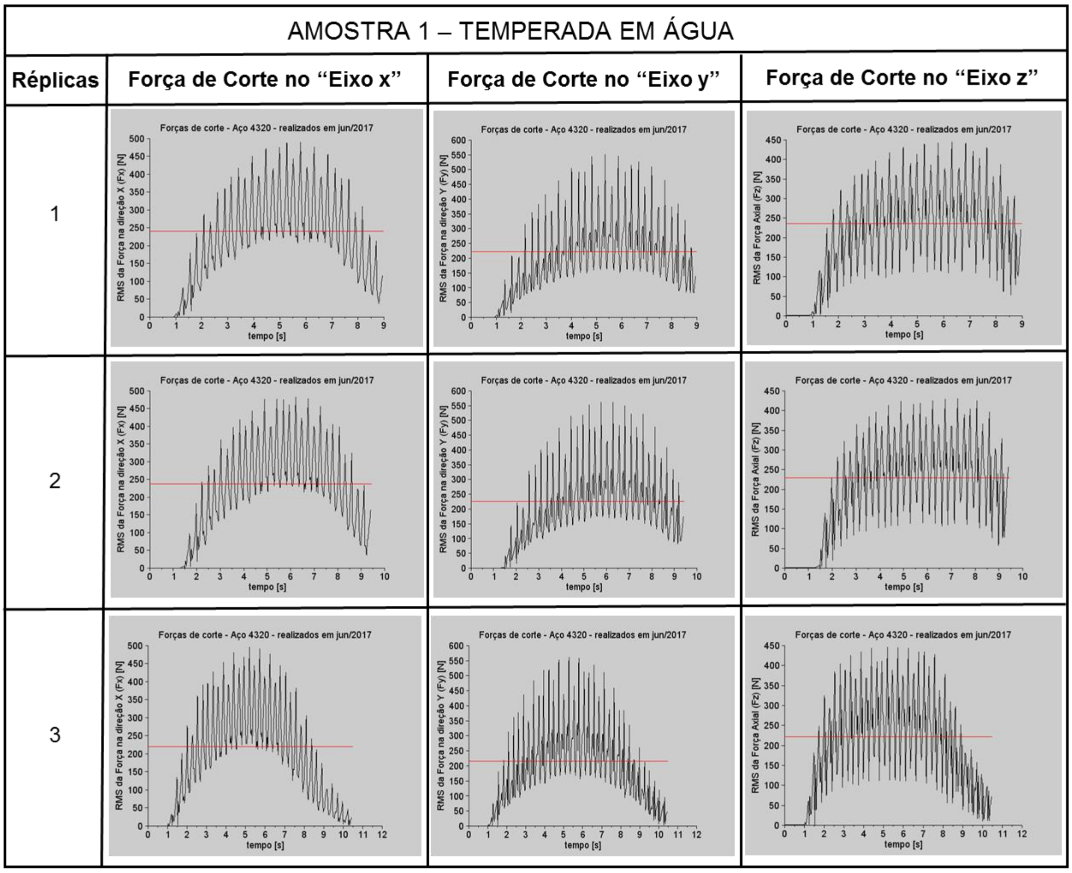

Fig. 7. Graph referring to the machining force tests of Sample 1 and its replicates.

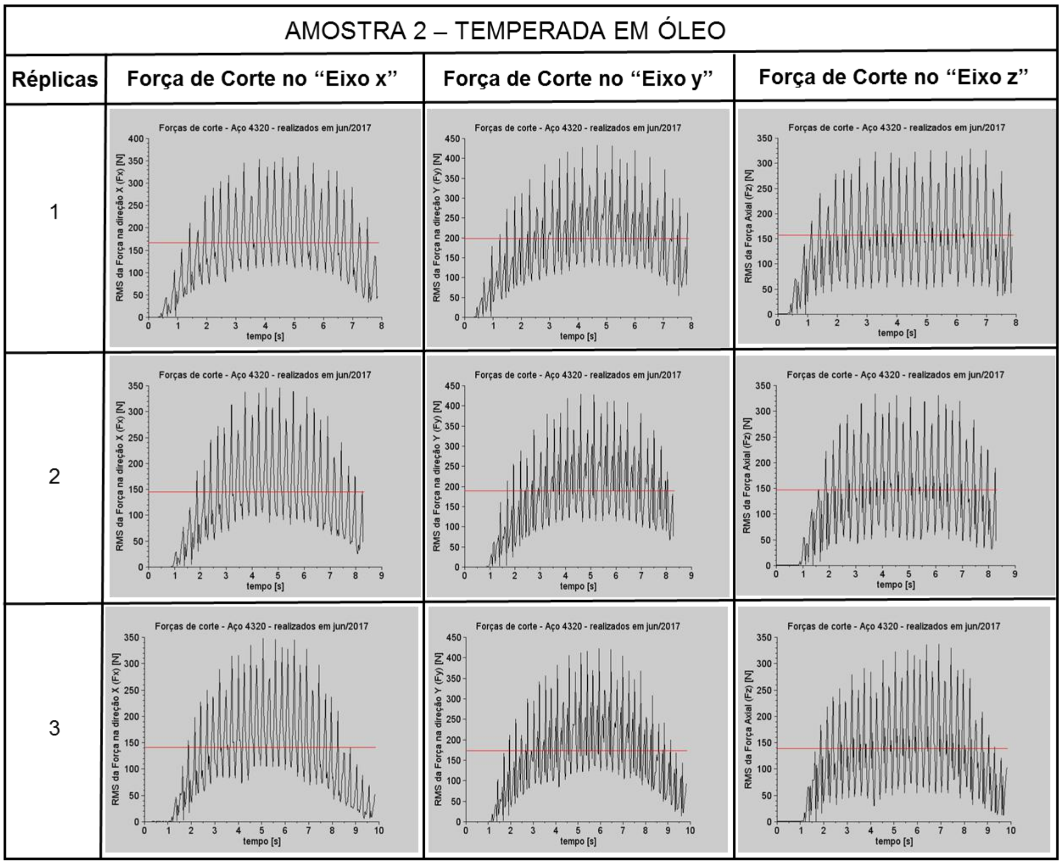

Fig .8. - Graph referring to the machining force tests of Sample 2 and its replicates.

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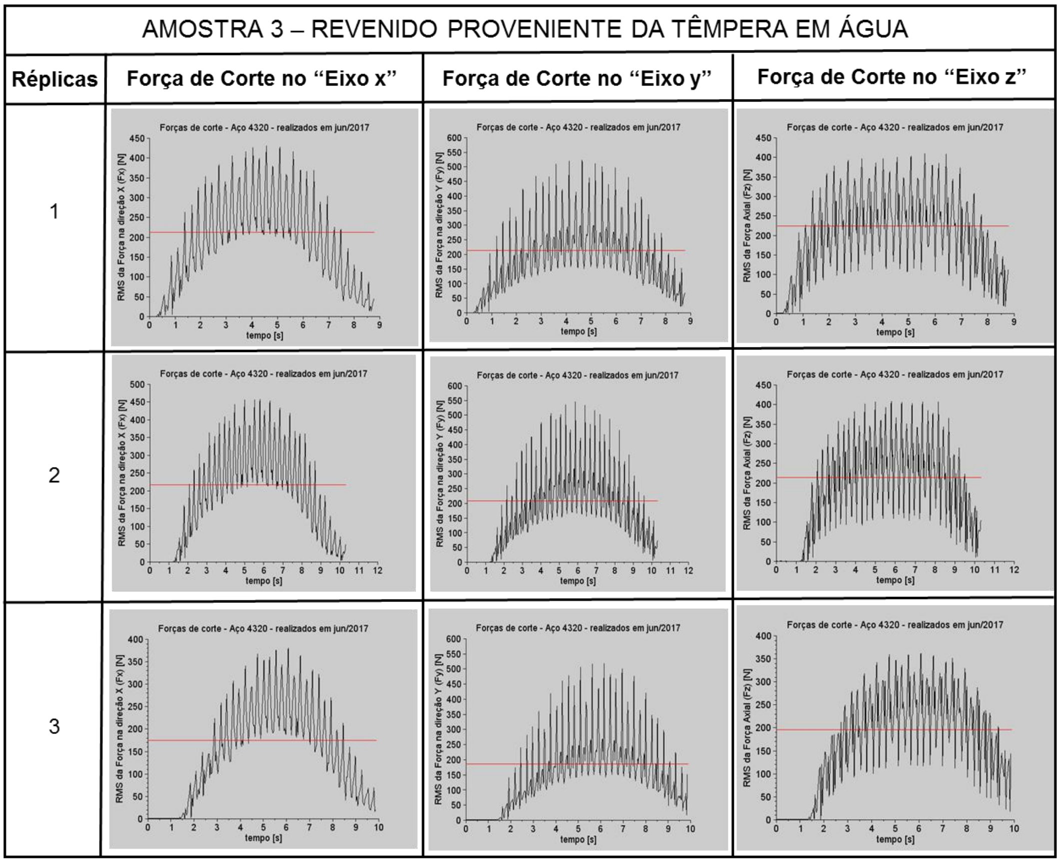

Fig 9. -Graph referring to the machining force tests of Sample 3 and its replicates.

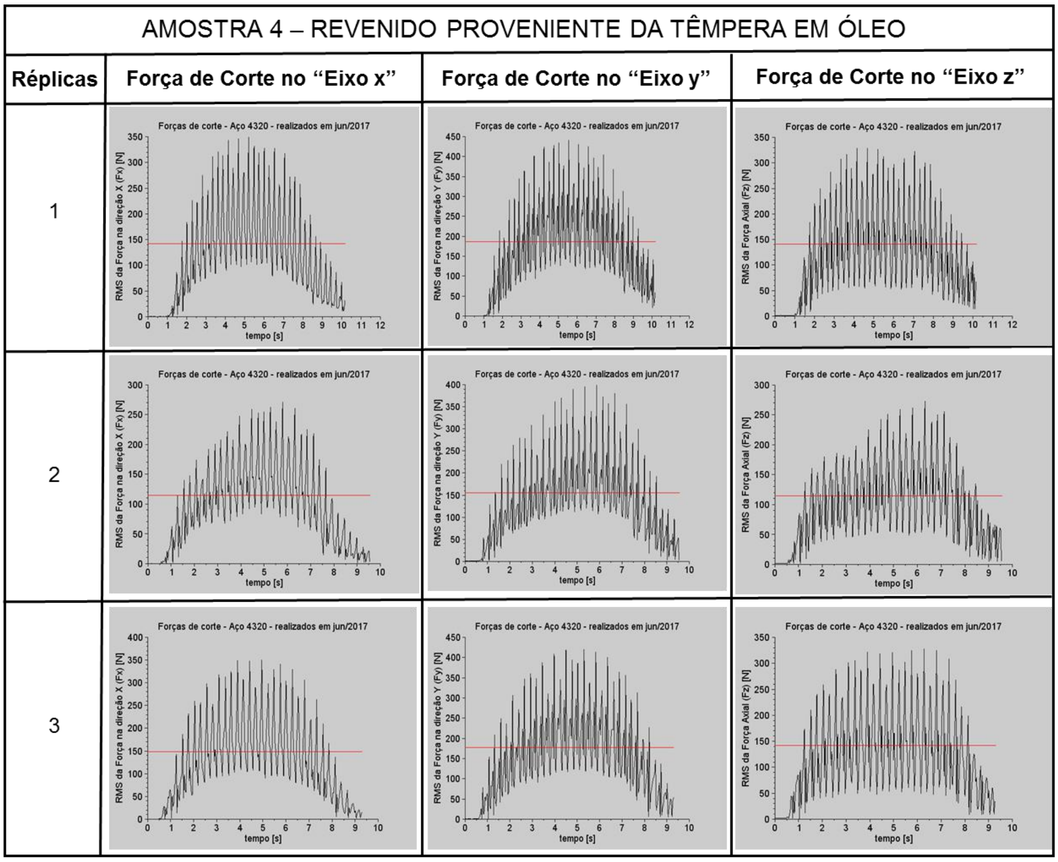

Fig.10.Graph referring to the machining force tests of Sample 4 and its replicates.

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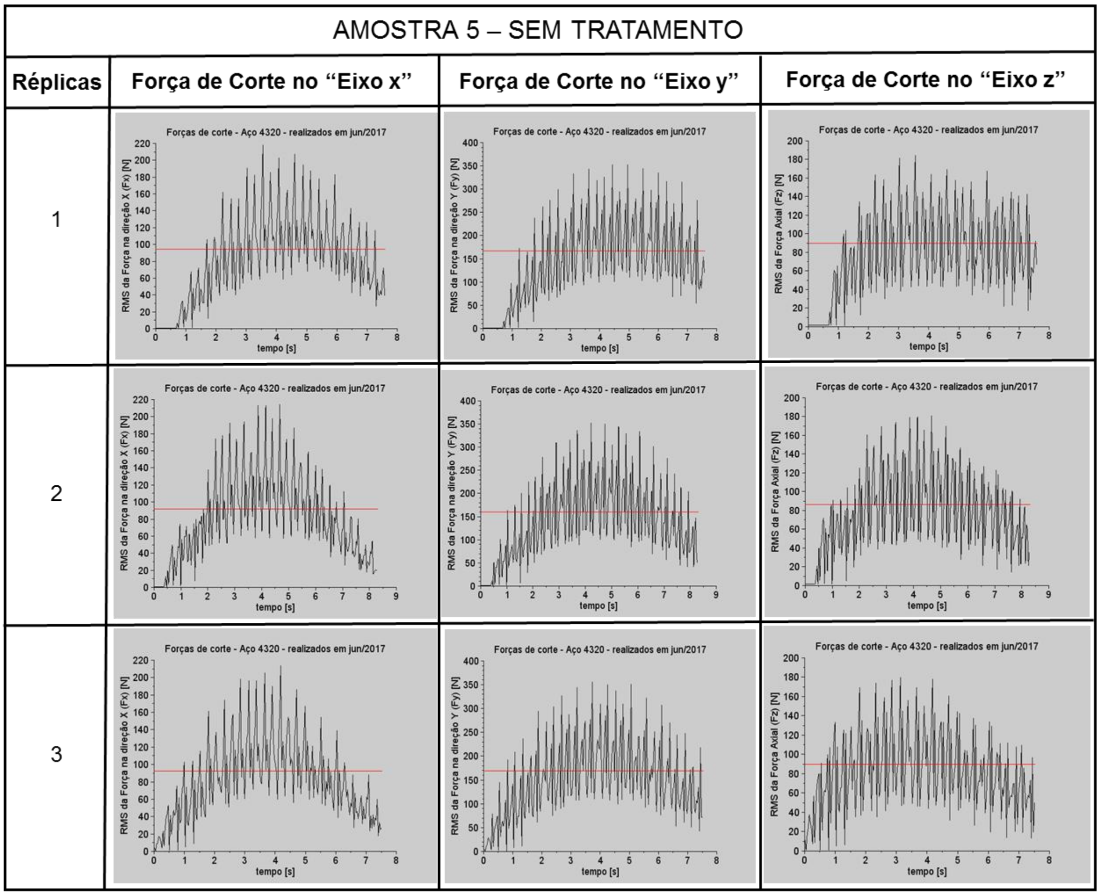

Fig 11.Graph referring to the machining force tests of Sample 5 and its replicates.

Using the software "Excel ®", the force data on the "x", "y" and "z" axes of each test sample were collected, and it was possible to calculate the resulting force "Fu" for each case. It is necessary to emphasize that the machined area did not remain constant during milling, as shown in Figure 5, which explains the behavior of the plotted graphs, where with the tool advance to the center of the part, the shear force increases, and from then on it decreases to the other end of the piece, precisely because of the change in the depth of cut provided by the way that the samples were positioned. Tables 4, 5 and 6 show all values (RMS) obtained in all tests, as well as the average of the replicates, and the machining force.

Table 4- RMS Values obtained in the machining force test and its replicates, samples treated with water.

Shear Force[N]	Tempered (1)				Quenched (3)			
	R1	R2	R3	**Average**	R1	R2	R3	**Average**
Fx	239.99	237.78	232.41	236.73	212.41	217.82	175.58	201.94
Fy	223.09	225.68	228.37	225.72	214.01	208.29	186.89	203.06
Fz	237.77	229.42	233.95	233.05	224.77	213.45	196.42	211.55
Fu	403.68	400.14	401.12	**401.65**	376.08	369.31	323.01	**356.13**

Table 5 - RMS Values obtained in the machining force test and its replicates, samples treated with oil.

Shear Force[N]	Tempered (2)				Quenched (4)			
	R1	R2	R3	**Average**	R1	R2	R3	**Average**
Fx	167.15	144.64	140.79	150.86	141.76	114.75	148.66	135.06
Fy	198.65	189.09	173.56	187.10	186.75	155.42	177.45	173.21

Fz	157.16	146.95	138.83	147.65	141.22	115.11	141.94	132.76
Fu	303.48	279.77	263.09	**282.12**	273.71	224.89	271.54	**256.71**

Table 6 - RMS Values obtained in the machining force test and its replicates, samples without treatement.

Shear Force [N]	**WithoutTreatament (5)**			
	R1	R2	R3	**Average**
Fx	94.61	91.98	92.51	93.03
Fy	167.22	159.88	169.24	165.45
Fz	89.66	86.58	99.73	91.99
Fu	212.02	203.76	217.13	**210.97**

It should be noted that the force for the removal of material was higher in the pieces that were treated in water (Samples 1 and 3), thus also confirming that the increase in hardness influences the shear force. According to that, the sample that did not undergo any heat treatment, which presented less hardness due to the absence of the martensite structure, was the one that the milling occurred with greater ease. Then, it is seen that the "Fu" of the tempered samples increases noticeably, with Sample 1 having the highest of all the pieces, with a 90% increase when comparing with Sample 5. Sample 4, that had a lower "Fu" (between heat treated samples), an increase of 21.7% was obtained when compared with a sample without treatment. Analyzing Tables 4, 5 and 6 with table 3 it is verified that the results are coherent, since the machining force increased as the hardness increased between the samples.

For a more satisfactory and simple analysis, a graph was created from the tables presented, which shows the average of the machining force of the samples according to Figure 12, which also provides a direct comparison between the values obtained in each of the tests.

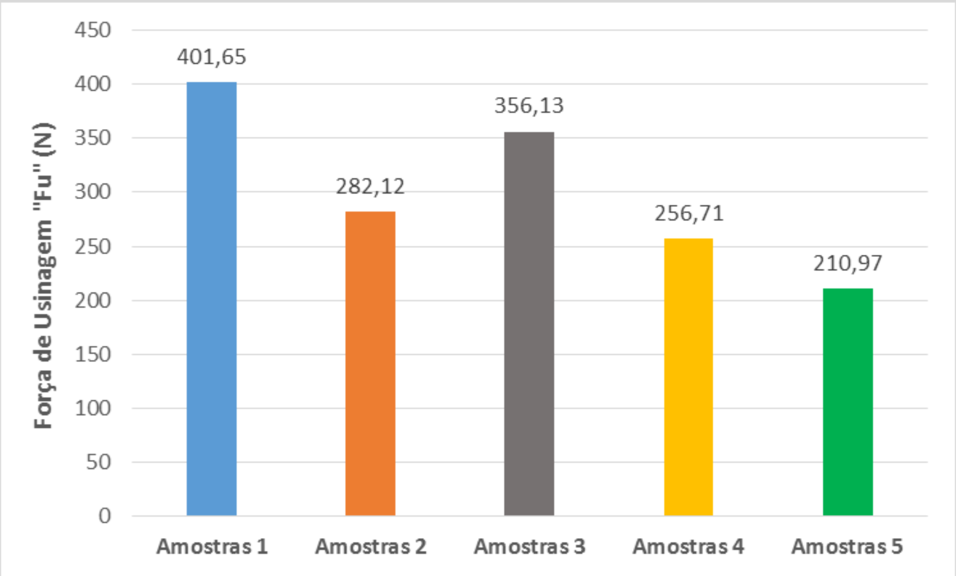

Fig.12. Average graph of the machining forces of each sample.

IV. CONCLUSION

With the results obtained, a great correspondence of the data was verified. At first, processes such as heat treatment and hardness testing proved the existence of martensite and thus the increase in hardness of the samples, whose best case (Sample 1) obtained a 109% increase in relation to the untreated piece (Sample 5).

Subsequently, the machining (milling) delimited that with the increase of the hardness harder is the removal of material, in which Sample 1 had an increase in machining force of 90% and the Sample 4 (lower hardness) an increase of 21, 7%.

Therefore, it should be noted that the activity in question contributed in some way to the metal/mechanical industry, where the range of SAE 4320 steel information is still scarce. Thus, temperability is a variable which can further improve the properties of a material, especially the alloy in question, specifically contributing to parts requiring high surface hardness, such as gear, crowns and pins.

ACKNOWLEDGEMENTS

I would like to thank stomy parents and my friends by financial support to this project.

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