CHARACTERIZATION OF HIGH MANGANESE STEEL (FE27MN1SI) SUBMITTED TO ABRASION WEAR TEST AND SOLUTION HEAT TREATMENT

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Abstract. High manganese steel has been increasingly studied due to its applications in cryogenic temperatures. These steels are mainly formed by carbon and manganese, with manganese being used as austenite stabilizer. One of the most important characteristics of these steels is their resistance to wear. Its great use for parts subjected to wear is due to the properties of surface hardening provided by work and toughness. There are two transformation mechanisms that occur in this alloy, the transformation induced plasticity (TRIP), in which the martensitic transformation occurs and the twinning induced plasticity (TWIP), in which mechanical twinning occurs. The present work aims to characterize the Fe27Mn1Si alloy when submitted to the abrasion wear test with different loads and to compare the martensite formation between samples solution heat treatment at different temperatures. Five samples were used, one as received, two solubilized at 800 ° C and two solubilized at 1100 ° C. In the wear test, two different loads, 46.8 and 192.9 kg, were used and tested on the universal wear test machine. The samples were weighed before and after wear test to calculate the mass loss. To verify the martensite formation, optical microscopy was performed in five samples. Finally, the samples passed the vickers microhardness test. The samples that were solubilized at 800 ° C showed greater resistance to wear. High manganese steel samples showed greater wear resistance for the wear test with a 192.9 kg load. Optical microscopy showed the martensite formation in the worn out samples with 46.8 kg load. Observing the results of the microhardness test, it is noted that there was hardening of the material in relation to as received sample. The results obtained in the vickers wear and microhardness test were compared with the results obtained in the 304 stainless steel samples studied in literature.

Keywords: high manganese steel, wear test, TRIP effect, austenite, transformation mechanisms

1. INTRODUCTION

Over the years, the search for more sustainable energy sources has become increasingly necessary, a less polluting alternative is natural gas. Natural gas is transported in a liquid state, so it needs to be at very low temperatures. Recent studies have discovered the potential of high manganese steel for applications at cryogenic temperatures and the manufacture of tanks feasibility for storing and transporting these gases.

Austenitic manganese steel was discovered by Sir Robert Abbott Hadfield in 1882 and called Hadfield steel. The steel developed by Hadfield had 1.2% carbon and 12% manganese. At room temperature, this steel has an austenitic

structure, combining high toughness and ductility. Its great use for parts subjected to wear is given by the surface hardening properties provided by the work and toughness.

There are two transformation mechanisms that occur in this alloy, the transformation induced plasticity (TRIP), in which martensitic transformation occurs, and the twinning induced plasticity (TWIP), in which mechanical twins occurs. TWIP and TRIP high Mn steels (15-30% by weight) have typically metastable austenite matrix. The deformation mechanisms of these steels are strongly dependent on the temperature and the stacking fault energy(BENZING, JT, et al., 2018).

TWIP high manganese steels are highly ductile, high strength austenitic steels characterized by a high work-hardening rate resulting from deformation. The addition of Si and Al helps to achieve a stable fully austenitic microstructure with low SFE, in the range of 15-30mJ/m² (FERREIRA, 2019 apud DE COOMAN, 2011). TRIP steels undergoes the austenite to martensite transformation during the deformation process and the stacking fault energy has values below 20mJ/m². These steels have attracted interest due to their high strength characteristics, good formability and high energy absorption capacity.

All machine elements are subject to wear, so this is the most worrying phenomenon of metal destruction. Wear can be defined as a "surface phenomenon that consists of the gradual mechanical deterioration of metal surfaces in contact, through the extraction of particles by friction" (SUBCOMMITTEE ON WEAR OF METALS, 1948, p. 128)

The main factors influencing wear are divided into two categories, those related to the material, which are: hardness, toughness, surface finish, constitution and structure, and those related to service conditions: pressure, movement speed, temperature, lubrication and corrosion (CHIAVERINI, 1986).

In the present work, the properties of Fe27Mn1Si high manganese steel alloy, which have been studied for cryogenic application, subjected to wear, were studied. The alloy was subjected to solution heat treatments at temperatures of 800°C and 1100°C. The solubilized alloys were submitted a wear testing to verify the loss of mass and martensitic transformation. A microstructural analysis of the parts was performed using an optical microscope. Finally, a Vickers microhardness test was carried out to verify the mechanical hardening of material in its different working conditions. Thus, it can be verified in the laboratory, the results brought by literature.

2. EXPERIMENTAL PROCEDURE

2.1 Materials

The material used to carry out this work was a high manganese steel alloy (Fe-Mn-Si-C), its chemical composition is shown in Table 1.

Table 1. Chemical composition of the studied alloy

High Mn Steel	Mn	C	Si	Ni	Cr	Fe	
	27	0,027	1,0	0,19	0,41	Bal.	(%p)

A total of 5 samples were produced. The first sample of rectangular shape and dimensions 19x9x10mm, was used in as received condition. This material was obtained from a tube manufacture by the centrifugal casting process.

Four samples were also produced with a cylindrical shape with a 10 mm diameter, which were solution heat treated.

2.2 Solution heat treatment

The 4 cylindrical samples were solubilized so that the precipitates formed during the solidification process were dissolved. The furnace used was muffle type, heating took place for 2 hours. According to Lima (2018) the temperature range in which the studied alloy is 100% austenitic is from 500 to 1380ºC, the samples were solution heat treated at 800 and 1100ºC temperatures.

2.3 Wear test

The wear test was performed on the 4 cylindrical samples that were solution heat treated. The test was carried out on a universal machine for wear tests, with an 0.55 kW energy power and a 1415 RPM rotation speed, located in the mechanical testing laboratory of the Federal University of Piauí. The machine has a frequency inverter and an ammeter that relates electric current to friction, so the greater the current shown, greater the friction will be. Using two different loads, 192.9 kg and 46.8 kg.

The universal wear testing machine has a system of levers and a counterweight that help load application. To perform the test, the samples were fixed in the sample holder and the counterweight was fixed on the lever according to the desired load. The time chosen was 4 seconds.

Before and after the wear test, the samples were weighed on a semi-analytical precision scale with a 0.001g 8-digit resolution hood, brand Marte, model AD330, with a maximum capacity of 330g, located in the metallography laboratory of Federal University of Piaui. Weighing was performed to verify the mass variation, that is, to verify the mass worn during the test.

After weighing the samples, a cut was made in the cross-section of the parts at the place where the wear occurred, then the part was prepared for optical microscopy.

2.4 Optical microscopy

For optical microscopy, the samples were sanded with 100, 220, 360, 600 and 1200 mesh sandpaper and then polished using a Skill Tec model PSK 2V polisher with 1μm alumina water solution to the polishing cloth. After preparing the piece, chemical attack was performed to reveal the microstructure of the sample. The chemical attack was carried out using 5% Nital. After a few attempts, it was found that the best time was 80 seconds.

Optical microscopy was performed to analyze the microstructure of the 5 samples used. The microscope used was the microBel Photonics model MTM-1, with the aid of the Scop Image 9.0 software, located in the mechanical metallography and testing laboratory of the mechanical engineering course at the Universidade Federal do Piauí.

2.5 Vickers Microhardness

The microhardness test was performed on the 5 samples using the microhardness tester INSIZE, model ISH-TDV 100 A-B, located in the mechanical testing laboratory of the mechanical engineering course at Universidade Federal do Piauí. The load used for the test was 100 gf for 15 seconds. In the sample as received, the test was performed on 5 points of the piece chosen randomly and on samples that underwent heat treatment, the test was performed on 10 points, being 5 points on the worn edge and 5 points on the center of the piece.

3. RESULTS AND DISCUSSIONS

3.1 Wear test

The wear test was performed on the 4 cylindrical samples that were solution heat treated, the 192.9 kg highest load was used in samples 1 and 3 and the 46.8 kg lowest load in samples 2 and 4. The mass loss results are shown in Table 2 below:

Table 2. Comparison of masses before and after wear test

Sample	Before wear mass (g)	After wear mass (g)	Wear (g)	Mass difference(%)
Sample 1	9.360	9.316	0.044	0.47
Sample 2	9.264	9.259	0.005	0.05
Sample 3	10.142	10.092	0.050	0.49
Sample 4	9.245	9.236	0.009	0.09

Comparing the results, it can be seen that for the same temperature, wear was greater where the greatest load was applied. For samples solubilized at 800°C (1 and 2), the percentage wear was almost 10 times higher in the sample worn with the highest load. For samples solubilized at 1100°C (3 and 4) the result was similar, with 0.49% wear for the 192.9 kg load and 0.09% wear for the 46.8 kg load.

In Graph 1 below, a comparison will be made with stainless steel 304 from the works carried out by Guimarães (2019) and Bezerra (2018).

Graph 1. Comparison of the worn mass
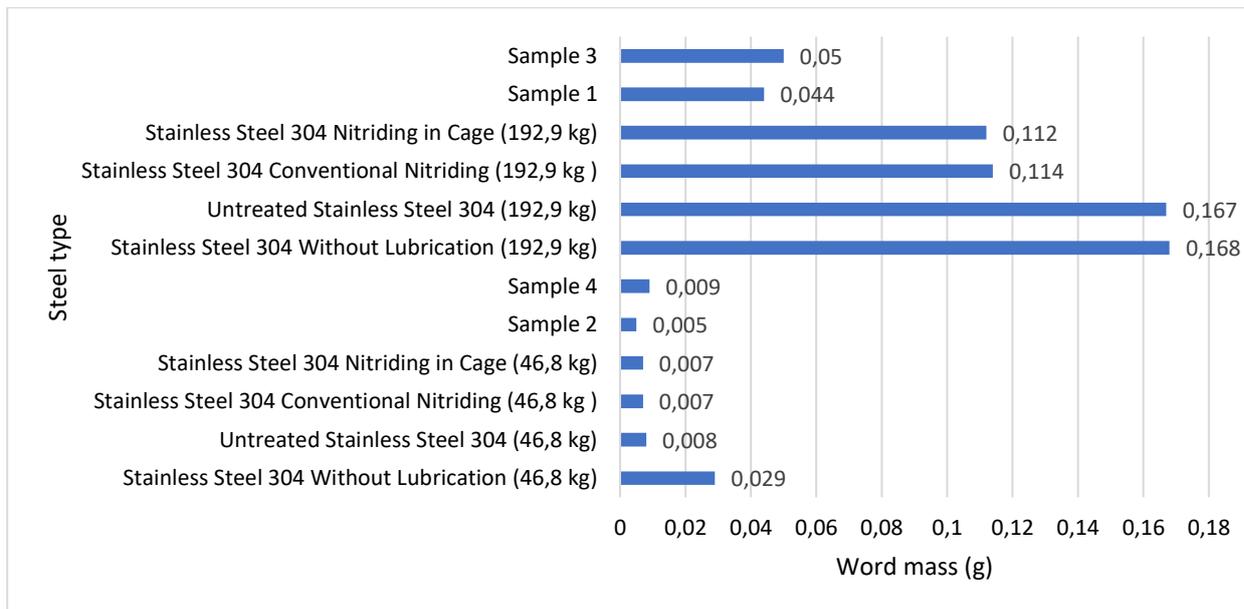
For the results obtained in the wear test with a load of 46.8 kg, the stainless steel without lubrication suffered a wear of 0.029, a value considerably higher than the wear of other samples in the same load. For 304 stainless steel sample without treatment, the wear was 0.008g for lowest load. The 304 stainless steel sample with conventional nitriding at 400°C suffered a wear of 0.007g. And finally, the cage nitride sample at 400°C suffered a wear of 0.007g for the load of 46.8 kg.

In the wear test with 192.9 kg load, the wear for stainless steel 304 without lubrication was 0.168g. The untreated 304 stainless steel sample had a wear of 0.167 for the highest load. For the 304 stainless steel sample with conventional nitriding at 400°C, the wear was 0.114g. And finally, the sample nitrided in a cage at 400°C suffered a wear of 0.112g for 192.9 kg load.

For 192.9 kg load, the high manganese steel sample obtained better results in the test, being more resistant to wear. As for 46.8 kg load the results obtained were similar, with the exception of the stainless steel sample without lubrication, which lost the greatest mass in test and, therefore, has the lowest wear resistance.

As mentioned before, the universal wear testing machine has a frequency inverter and an ammeter coupled to it, where it is possible to measure the electric current value during the procedure. For comparison of electric current values, the results are distributed in Table 3 below:

Table 3: Maximum electric current reached in the wear test for each sample

Sample	Electric Current (A)
Sample 1	4.2
Sample 2	2.6
Sample 3	3.8
Sample 4	2.4

The relationship between the applied load and the friction in the test is directly proportional, that is, the greater the load applied in the wear test, greater the friction and consequently greater the maximum electric current reached. As can be seen in Table 3, the samples in which the 192.9 kg load was applied (1 and 3) had electric current values greater than that achieved in samples tested in which the lowest load of 46.8 kg (2 and 4).

For better comparison, graph 2 below shows the electric current values achieved in the wear tests of stainless steel samples 304 studied by Guimarães (2019) and Bezerra (2018) for each applied load.

Graph 2. Comparison of the maximum measured current
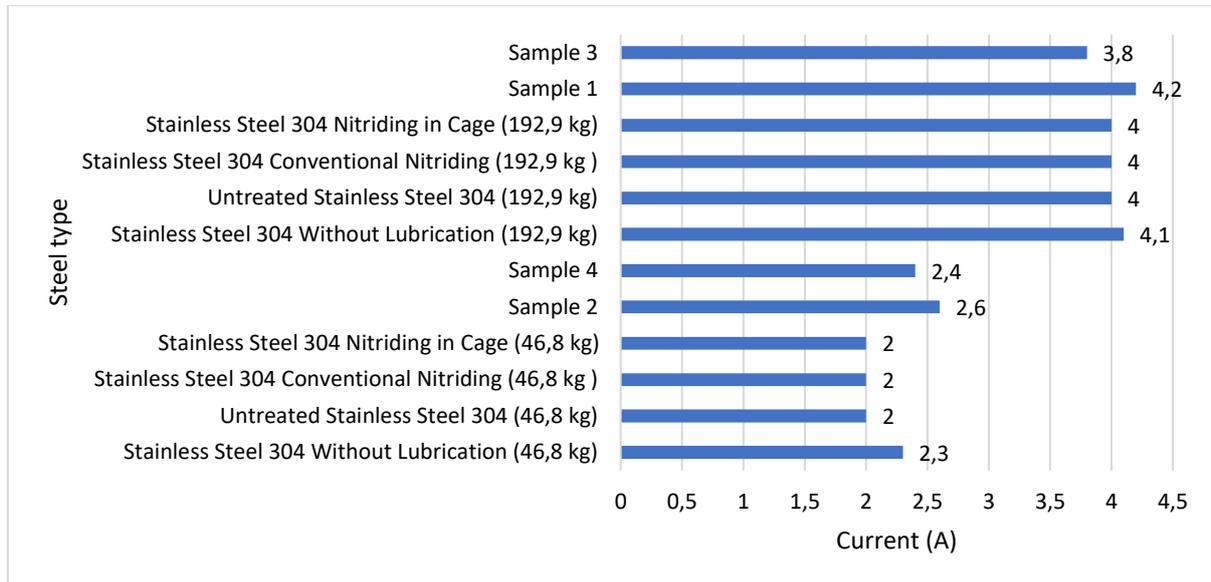
For the load of 46.8kg, the electric current and the friction values were higher for high manganese steel samples than for 304 stainless steel samples. In the test with the highest load of 192.9 kg, however, sample 1 (solubilized at 800°C) had a higher electric current value than stainless steel, but sample 3 (solubilized at 1100°C) had a lower result than all the other samples.

3.2 Optical microscopy

Optical Microscopy was performed for a better comparison of samples that received solution heat treatment at the highest and lowest temperature (1100 and 800°C) and between samples that received the highest and lowest load (192.8 and 46.8 kg) in wear test, being possible to observe the gradual appearance or not of ε martensite with these parameters variation.

Below we have the microscopy results. Figure 2 shows the sample micrograph as received:

Figure 2. Sample As Received in the center region, grain contour – 200x magnification (A and B), 500x magnification (C).

In this sample we already have the presence of ε martensite, figure 2A shows two grains, one with a much greater presence of martensite. Figure 2B, on the right, is a grain with only total presence of ε martensite. Note also the presence of dendrites from the casting process and a significant presence of impurities due to polishing with 0.3µm alumina, which did not have the desired quality. Therefore, in the following samples, polishing was done only with 1µm alumina.
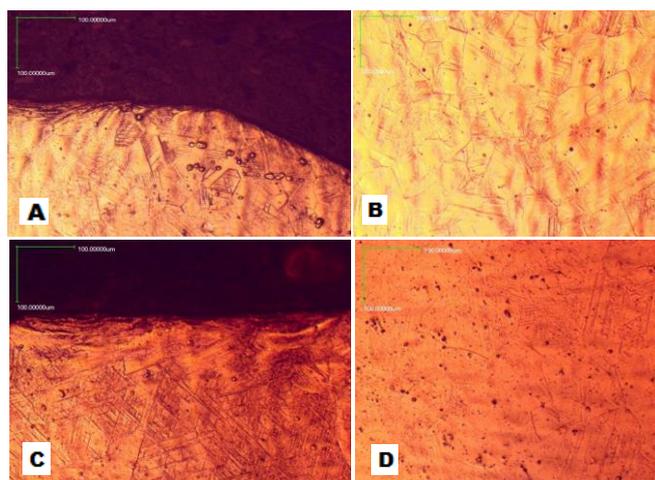
Figure 3. Samples solubilized at 800º C with 200x magnification. (A) Sample 1 in the worn edge region with a load of 192.9 kg (B) Sample 1 in the worn edge region with a load of 192.9 kg (C) Sample 2 in the worn edge region with a load of 46.8 kg (D) Sample 2 in the central region worn with a load of 46.8 kg.

For sample 1 (Figures 3A and 3B) there is a decrease in impurities, but there was no significant difference in ε-martensite amount between the edge and center. Note also the presence of lamination bands. Sample 2 (Figures 3C and 3D) was solubilized at 800°C and its wear test was carried out with the lowest load (46.8 kg). In this sample there was a greater formation of ε-martensite and the difference between edge and center is more noticeable than in sample 1.
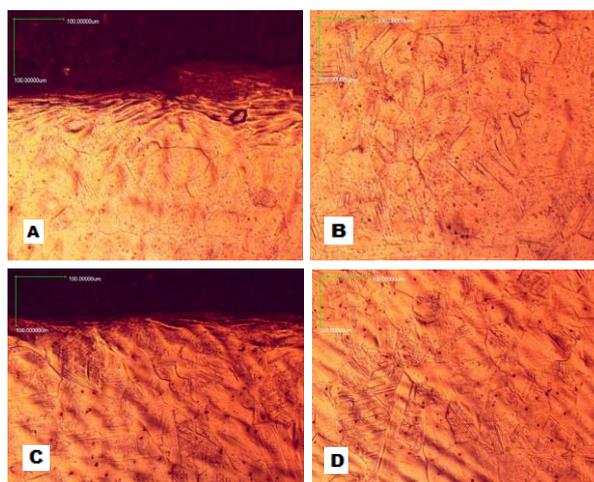

Figure 4: Samples solubilized at 1100°C – 200x magnification (A) Sample 3 in the edge region, worn with a load of 192.9 kg (B) Sample 3 in the central region, worn with a load of 192.9 kg (C) Sample 4 in the edge region, worn with a load of 46.8 kg (D) Sample 4 in the central region, worn with a load of 46.8 kg.

Sample 3 (Figures 4A and 4B) was solubilized at 1100°C and the test load was 192.9 kg. As in sample 1, in sample 3 there was no significant difference in the formation of ε-martensite between edge and center. Sample 4 (Figures 4C and 4D) was solubilized at 1100°C and passed the wear test with the lowest load (46.8 kg). In this sample, there was a more significant difference in the formation of ε martensite between edge and center. In micrographs, the presence of dendrites is noted.

3.3 Vickers Microhardness

Initially, the Vickers microhardness test was performed on the sample as received at 5 randomly chosen points. The results can be seen in Table 4 below:

Table 4. Vickers microhardness values of the sample as received

Print No	Vickers Microhardness value (HV)
1	243.79
2	230.31
3	224.95
4	223.57
5	300.54*
Average value = 244,63	
Standard deviation = 28,85	

*Microhardness performed in martensite lath.

Then, the test was carried out on the samples that were solution heat treatment. The microhardness test was performed at 10 different points in each sample, the first 5 being on the worn edge and the last 5 in the center of piece. The results are distributed in table 5 below:

Table 5. Vickers microhardness for solubilized samples

Print No	Sample 1	Sample 2	Sample 3	Sample 4
1	291.3	284.9	265.8	323.6
2	314.2	275.3	243.1	303.5
3	294.2	334.3*	250.1	332.3
4	395.3*	317.0	481.5*	301,4
5	301.8	251.7	311.9	364.3*
6	238.2	226.3	282.1	265.0
7	351.5	240.6	256.4	230.8
8	247.2	264.3	262.2	298.8*
9	256.1	290.9*	264.3	286.9
10	282.1	254.1	267.2	221.3
Average value:	**297.2**	**273.9**	**288.5**	**292.8**
Standard deviation	**48.1**	**33.7**	**70.4**	**44.2**

*Microhardness performed in martensite lath.

To calculate the standard deviation of the hardness of each sample, the maximum and minimum values were disregarded.

The purpose of the microhardness test performed after solubilization and the wear test was to compare the effects of solubilization temperature and wear test load variation on final hardness of the material and compare with the initial hardness of part to check if there was work hardening in the material.

Graph 3. Vickers microhardness average values for each wear test load
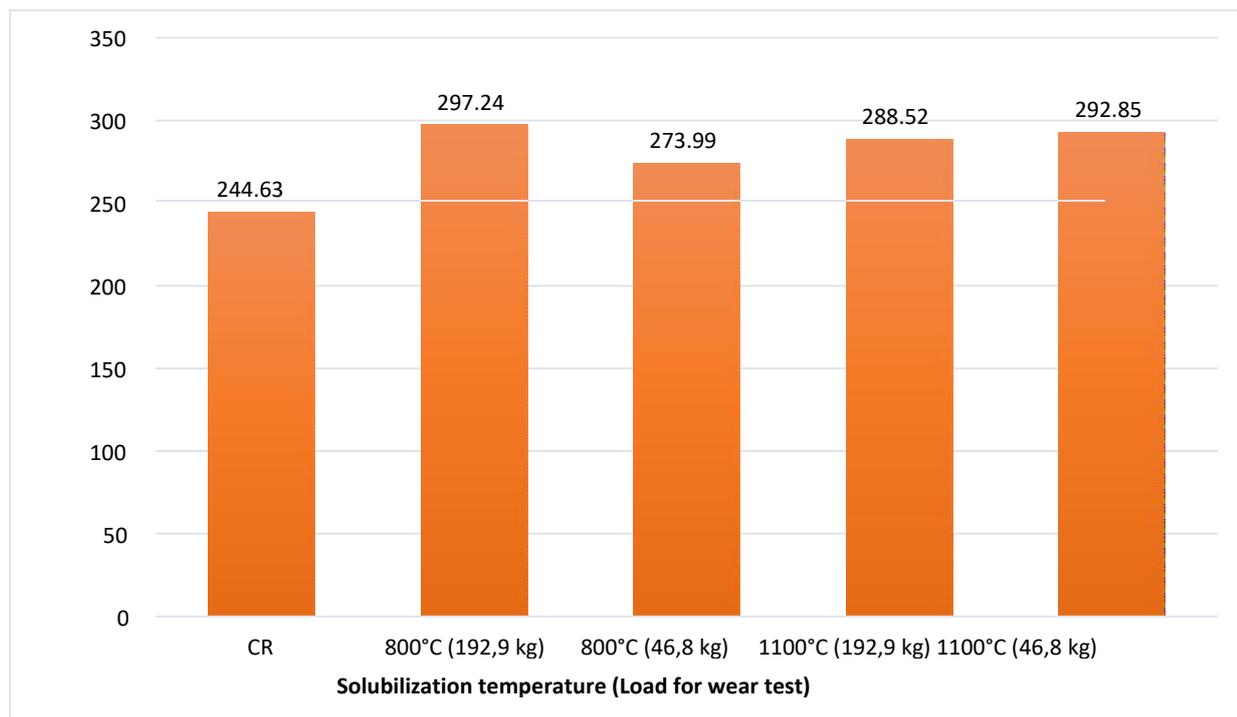
Comparing the results of the solubilized and worn samples with the result of as received sample, it is possible to notice a significant increase in hardness. For samples solubilized at 800°C, an increase in hardness is noted with increasing load. In the samples solubilized at 1100°C, the result was the opposite, the highest average hardness was obtained in sample worn at a lower load. This result can be explained because the wear test of sample 4 had two impressions obtained in martensite laths, which have greater hardness, and in sample 3 only one impression was on martensite, as can be seen in table 5.

4. CONCLUSION

From the studies carried out and the results obtained and discussed in this work, and based on the objectives of carrying out the wear and vickers microhardness tests and obtaining the micrographs, it can be concluded that:

• In the wear test, the mass loss was significantly greater in the samples where the highest load of 192.9 kg was used. Making the comparison in relation to temperature, it can be seen that the mass loss was greater in the samples solubilized at 1100°C. Samples that were solubilized at 800°C showed greater wear resistance.
• Compared to 304 stainless steel, for the wear test with 46.8 kg load, 304 stainless steel without lubrication had a much higher wear, while the other samples obtained relatively close results. As for the wear test with 192.9 kg load, the samples of high manganese steel had a much lower mass loss than stainless steel, showing a higher wear resistance for this load.
• In microscopy, it was possible to observe the formation of martensite in samples worn with 46.8 kg load, where a greater difference was observed between the worn edge and the center of samples, while in the samples worn with a higher load, they became more uniform . This result contradicted what was expected, but can be explained by the fact that the higher load removed part of transformations obtained at the edge of piece.
• Observing the results of the microhardness test, it is noted that there was hardening of the material in relation to the As-Received sample. The highest hardness was in sample 1, which was solubilized at 800°C and which passed the wear test with 192.9 kg load.

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