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NORMALIZING HEAT TREATMENT EFFECT ON BARKHAUSEN MAGNETIC NOISE IN AISI 1020 STEEL SURFACE GRINDING PROCESS

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Abstract. *The grinding process is widely used to improve the parts machined accuracy by other manufacturing processes and heat treated. The grinding process result depends on the cutting conditions, which incorrectly selected, can cause microstructural changes that prevent the use of the machined component. In addition, there is a lack of information about grinding damages in carbon steels due to the high costs of non-destructive methodologies for checking microstructural changes, such as the Barkhausen noise (BN). The AISI 1020 steel has plasticity and excellent weldability, and is widely used in the mechanical industry. The aim of this work is to analyze normalizing heat treatment influence and the surface grinding on AISI 1020 steel grinding process results. Different grinding process conditions and a conventional grinding wheel were used in the AISI 1020 steel surface grinding. BN was measured in all samples, varying magnetic excitation frequencies of 10 Hz and 50 Hz. The roughness and hardness machined samples evaluations complement the study. An inverse relationship between normalizing heat treatment and BN results was observed.*

Keywords: *surface grinding process, AISI 1020 steel, normalizing heat treatment, Barkhausen noise*

1. INTRODUCTION

Grinding is a cutting process of great importance to obtaining demanding shape and dimensional tolerances. Additionally, as grinding normally is the last material removal process, an adequate choice of grinding wheel and cutting parameters is essential to ensure a high-quality part, considering dimensions and energy consumption, and temperatures that do not affect the part's properties (Garrido *et al*., 2021). It is one of the most widely applied machining manufacturing processes in the industry (Bianchi *et al*., 2012; Spirito, 2018), and can be used for machining all types of materials, ranging from soft metals to hardened steels and non-metallic materials, such as ceramics (Groover, 2017).

AISI 1020 steel stands out about ferrous metals, widely used in industry, as it combines mechanical resistance, availability, and low cost compared to other materials. Its main applications are in automotive plates, such as gears, shafts, crankshafts, structural profiles, plates for tube production and civil construction, pins (heat treated), gear rings (heat treated), columns, ratchets, covers (Drehmerl, 2013; Rodrigues *et al*., 2014). When being grounded, machined steel can suffer grinding damage (burning) and increased residual stresses. To improve machinability and changes in residual stresses, normalizing heat treatment can be done (Raimar, 2015).

The thermal damage verification or microstructural changes caused by the grinding process is usually carried out by indirect methods, such as determination of hardness, residual stresses, and metallographic attack. One possibility that has been used frequently is Barkhausen noise (BN), also called Barkhausen magnetic noise. This technique is based on the physical phenomenon that occurs in ferromagnetic materials during magnetization (Garstka, 2008). In simple terms, a BN measurement system has a probe composed of an electromagnetic yoke (which produces an alternating magnetic field on the sample) and a coil (which detects the BN signal). The effective voltage (root mean square value) of the generated signal is a strong function of the microstructure and the residual stress state of the material. For this reason, the BN technique is ideal for detecting grinding burns, as thermal damage will result in decreased hardness and more residual stresses, both of which will result in an increase in BN (Wotjas *et al*., 2011; Benini, 2017).

Several works addressed the AISI 1020 steel machining. Machado (2018) evaluated the feed influence on the surface roughness of turned 1020 steel using four different feed values (0.07; 0.12; 0.17 and 0.22 mm/rev), while the other cutting parameters were constant. Roughness Ra decrease with feed increased from 0.07 mm/rev to 0.12 mm/rev was observed. Another's grinding condition had no significant change in the Ra parameter. Homero (2011) studied the influence of cutting speed, feed per tooth, depth of cut, and coolant on the residual stresses after annealed AISI 1020 faced milling. Feed and coolant were the variables that statistically affect the residual stress (low feed per tooth values and coolant application provided lower residual stresses). Cutting speed and cutting depth was not considered statistically significant. Feitosa (2007) investigated the intrinsic relationships between the surface quality of AISI 1020 steel parts, acoustic emission signals behavior, and cutting power for surface grinding using artificial neural networks. Surface burning, roughness and microhardness were evaluated. Artificial neural networks use in the surface quality characterization obtained satisfactory results.

Likewise, there are BN applications in the grinding process. Benini (2011) used the BN to evaluate thermal damage after the external cylindrical grinding process of 100Cr6 steel, varying Sol-gel type aluminum oxide percentages in the conventional grinding wheels composition. Sol-gel abrasives percentage increase in the grinding wheels had no significant influence on the BN results. De Melo (2019) used BN to identify microstructural changes in AISI 1020 steel sample regions affected by the welding process BN behavior using the RMS (root mean square) curves was measured. Grain boundary length, the possible bainitic microconstituents, and the dislocation density were significantly influenced RMS curves, mainly in the amplitude and position of BN main peaks. Benini *et al*. (2021) evaluated the annealing and quenching influence on microstructural changes in AISI 1045 steel surface grinding using BN. Quenching generated de lowest BN values, inversely proportional to the Vickers hardness values compared to the annealed samples. BN behavior using RMS (root mean square) curves was measured. Quench treatment provides the lowest BN results, which were inversely proportional to the Vickers hardness values compared to the samples annealed.

Despite these studies, is a clear need for further studies involving the flat grinding process of AISI 1020 steel, analyzing the heat treatment influences on the machining result. The aim of this work is to evaluate the normalizing influence on AISI 1020 steel microstructural changes after surface grinding process.

2. EXPERIMENTAL SET-UP

The material chemical composition used is shown in Table 1.

Table 1. AISI 1020 steel chemical composition with elements (% wt) (NBR NM 87/2000).

C	Mn	P (máx)	S (máx)
0.18 – 0.23	0.30 – 0.60	0.040	0.050

Sixteen samples were prepared (Figure 1): eight samples were not heat treated. Other samples were normalized at 850 ºC for 50 min. Sixteen samples were used in 8 different conditions (2 replicas). It is important to highlight the samples originated from extruded bars, the samples were machined by the milling process and 8 samples were heat-treated. After, all samples were machined by the surface grinding process. The grinding was carried out on the Benner RVK-4515 surface grinding machine (Figure 1). Two feed speeds (v_w), 11.4 m/min and 18.6 m/min, and two infeed (or depth of cut) (a_e), 0.1 mm and 0.05 mm, were used (Table 2). The cutting speed (v_c) 37.5 m/s was constant. In Table 2, the column ‘sample’ indicates each condition has a replica (the mean value of two samples tested under the same conditions is considered).

Cutting tool was an aluminum oxide (Al_2O_3) grinding wheel form 1, Sol-gel, grain size 80, grade K, bond vitrified, 205 x 13.5 x 31.8 mm. Coolant biodegradable oil HYDRIA-EP (5%) was applied. The grinding wheel was dressed with a single-point diamond dresser (performed before the samples grounded), using dressing overlap ratio (U_d) 5 and dressing depth (a_{ed}) 0.05 mm.

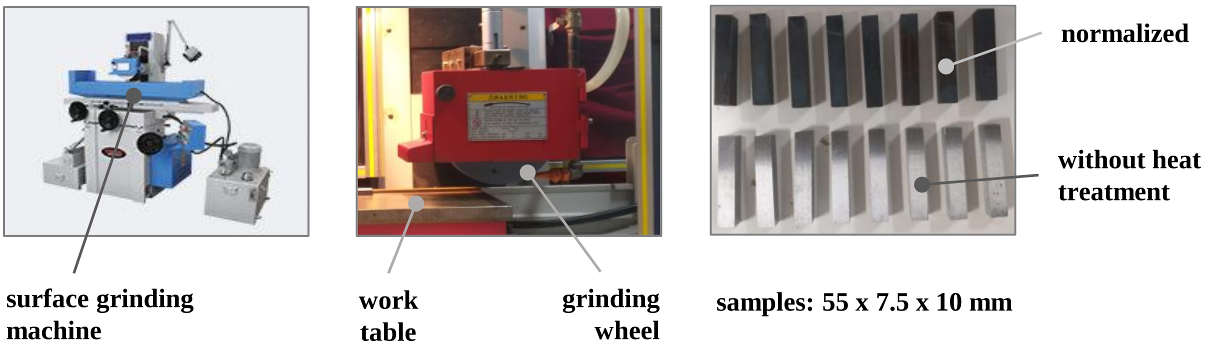

Figure 1. Benner RVK-4515 grinding machine, Al_2O_3 grinding wheel, and AISI 1020 steel samples.

Table 2. Conditions and grinding parameters to each AISI 1020 steel sample.

Heat treatment	Sample	Infeed (a_e)	Feed speed (v_w)	Heat treatment	Sample	Infeed (a_e)	Feed speed (v_w)
Without	1	0.10 mm	18.6 m/min	Normalized	5	0.10 mm	18.6 m/min
	2	0.05 mm	18.6 m/min		6	0.05 mm	18.6 m/min
	3	0.10 mm	11.4 m/min		7	0.10 mm	11.4 m/min
	4	0.05 mm	11.4 m/min		8	0.05 mm	11.4 m/min

BN signals were measurements with equipment *Barktech* developed by the University of São Paulo (USP), which is not available for commercial use. This equipment is responsible for generating and controlling the excitation current, for acquiring and filtering the voltage signals generated by the BN sensor, which are acquired and amplified with certain gain values. The total control of the system was carried out by the BarkView *software*. The adjustment parameters were used for all configurations, in which the system excitation frequency was 40 Hz and the sampling frequency was 350 MHz.

Considering the sample shapes, three BN measurements were performed on each sample, varying the magnetic excitation frequencies (f_{ex}) of 10 Hz and 50 Hz. The sampling frequency of 350 kHz and 1 V excitation voltage amplitude were used. BN Measurements were performed with an equipment probe, totaling 96 measurements. Subsequently, after being treated by its own algorithm, these 96 measurements result in a single value, represented by the statistical parameter RMS (root mean square). The BN RMS millivolts (mV) are obtained directly on the equipment display after signal stabilization. The BN measurements equipment, BN probe, and measurement points are shown in Figure 2.

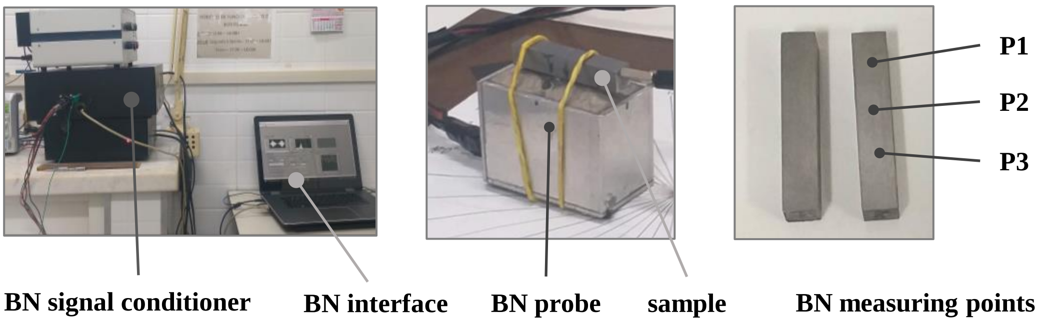

Figure 2. BN equipment overview and sample measuring points.

The Rockwell B hardness tests used the Wilson Hardness Durometer Rockwell 2000, with a 1/16" Ball Penetrator, 10 kg initial load and 100 kg major load. Three distinct points were measured in each sample, totaling 48 measurements. Roughness evaluation using Taylor Hobson Surtonic S25 rugosimeter (Figure 3c) by mean roughness (Ra) and average value over assessment length (Rz) was done. It should be considered that Ra value determination does not take into account the profile irregularity shape. For this reason, Rz was measured in this study. Roughness parameter Rz allows for a slightly more comprehensive interpretation. It is the arithmetic mean value of the single roughness depths of consecutive sampling lengths. Rz is the sum of the height of the highest peaks and the lowest valley depth within a sampling length.

Rugosimeter calibration with DNC001 standard Type 112-1502, from the same manufacturer, was applied. Left, center, and right roughness measurements of the sample were taken. Durometer is showed in Figure 3(a) and (b). Roughness evaluation using Taylor Hobson Surtonic S25 rugosimeter by mean roughness (Ra) and average pick-to-valley

(Rz) was done. Rugosimeter calibration with DNC001 standard Type 112-1502, from the same manufacturer, was applied. Left, center and right roughness measurements of the sample were taken. Evaluation length (l) 4.0 mm and sampling length (*cut off*) 0.8 mm were used. Roughness parameters was carried out with a diamond cone-spherical probe tip 5 μm, with 0.01 μm resolution.

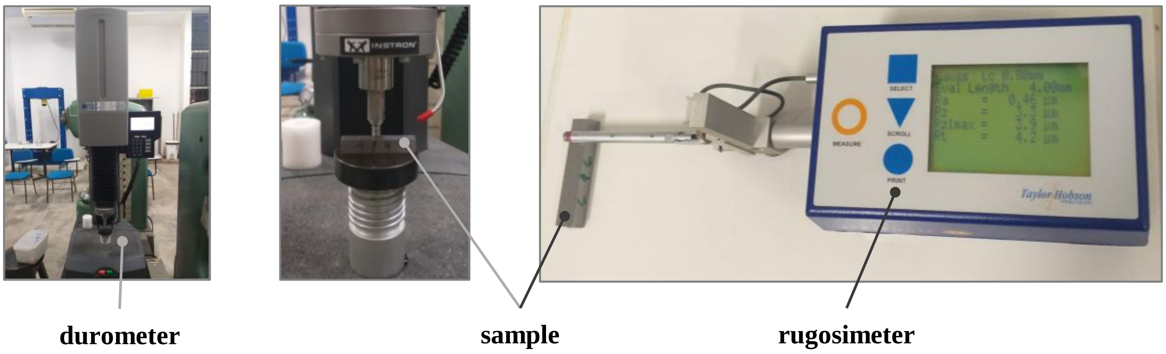

Figure 3. Durometer and rugosimeter overview.

3. RESULTS AND DISCUSSION

3.1 Barkhausen noise results

The BN results measured in machined samples with excitation frequencies (f_{ex}) of 10 Hz and 50 Hz are shown in Table 3.

Table 3. BN measurements average in the machined AISI 1020 steel samples.

Sample		f_{ex} = 10 Hz average (mV)	f_{ex} = 50 Hz average (mV)	Sample		f_{ex} = 10 Hz average (mV)	f_{ex} = 50 Hz average (mV)
Without heat treatment	1	226.049	709.586	Normalized	5	33.825	235.973
	2	213.087	692.301		6	35.334	225.949
	3	200.531	645.654		7	54.207	345.365
	4	218.370	655.013		8	29.379	194.679

Graphic representation of the BN means values, measured with f_{ex} = 10 Hz, in the grounded AISI 1020 steel samples are shown in Figure 4. As seen in Figure 4, observed samples set without heat treatment had the highest BN values for the excitation frequency used in comparison to the normalized samples. These results are related to the fact that normalization heat treatment altered the material microstructure, causing more anchorage points. This behavior is explained by the domain movement mechanism under the influence of low-intensity magnetic fields. As the field increases, the domain walls reach enough energy to overcome the anchor points, corroborating with Moorthy *et al*. (2015).

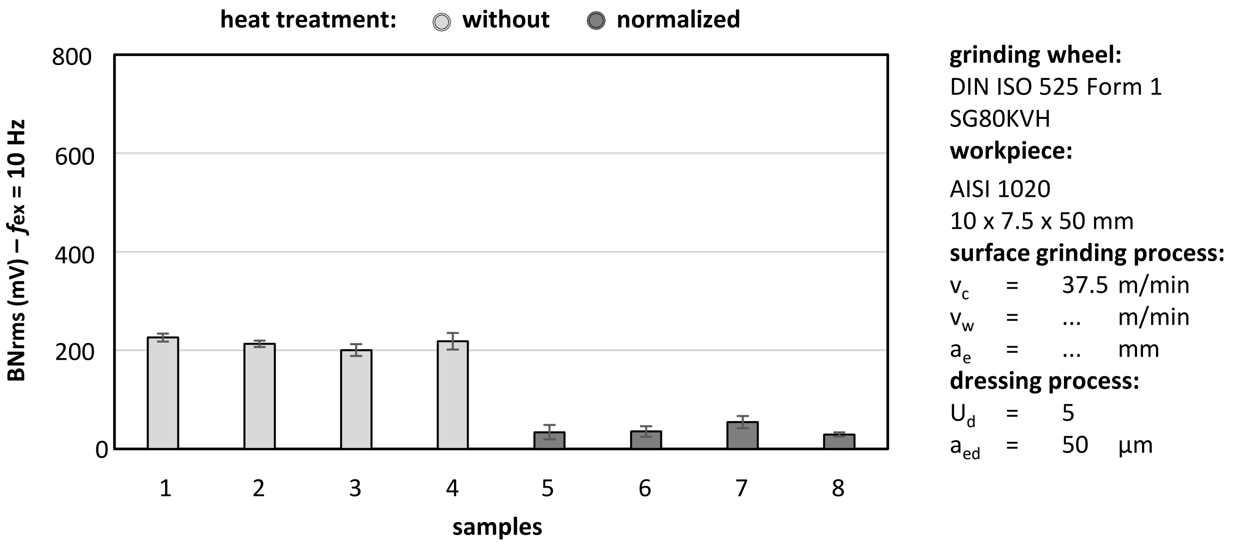

Figure 4. BN results measured with f_{ex} 10 Hz in AISI 1020 steel samples machined by the surface grinding process.

Figure 5 shows BN results evaluated with f_{ex} = 50 Hz in the AISI 1020 steel samples grounded. Again, BN values in the normalized samples were lower compared to samples without heat treatment.

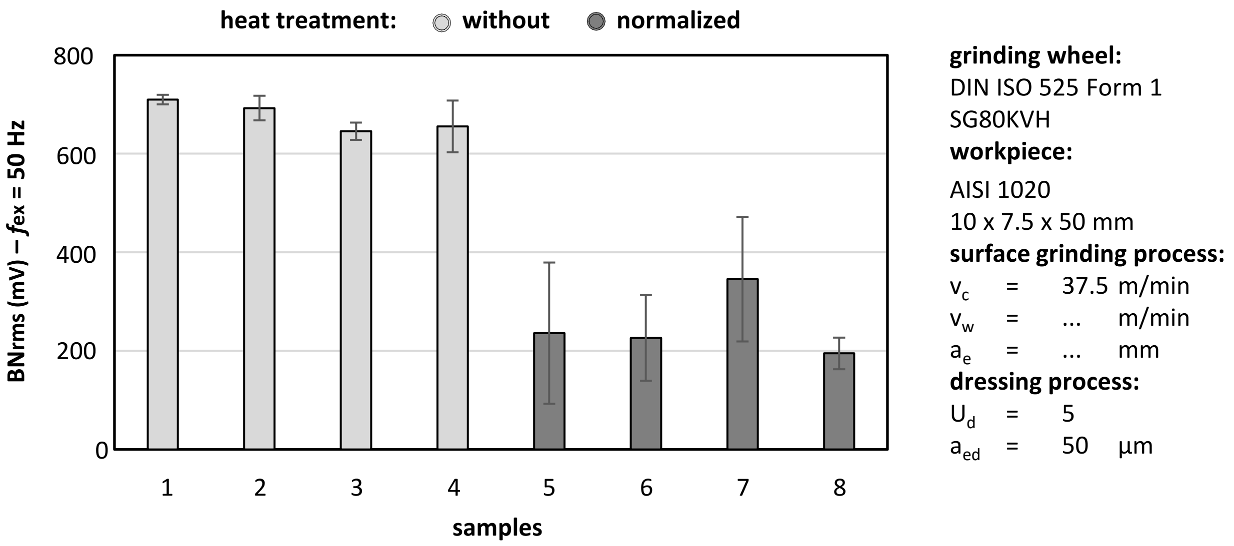

Figure 5. BN results measured with f_{ex} 50 Hz in AISI 1020 steel samples machined by the surface grinding process.

Regarding the grinding conditions, feed speeds (v_w) and infeed (a_e) had no influence on the BN activity measured with the f_{ex} = 10 Hz. However, BN results measured with f_{ex} = 50 Hz in the normalized samples were observed a more accentuated variation considering grinding conditions evaluated in this study (v_w and a_e). This leads to asserting normalized samples have more microstructural changes pointed out by the BN compared to samples without heat treatment. According to Cheng *et. al* (2018), as microstructural variations influence the BN, the change in the RMS is due to heat treatment.

Comparing Figure 4 with Figure 5, it is verified BN results were higher when measured with f_{ex} = 50 Hz. This occurs because the domain hops number per time unit and signal amplitude increase with increasing magnetic excitation frequency. These results are consistent with Chen *et al*. (2018), that performed an analysis using a bandpass filter with an interval of 5 kHz to understand the behavior of each frequency band in the BN signal. High magnetic excitation frequencies are suitable for measuring magnetic properties close to the component surface. Thus, it can be stated that the high BN values measured with f_{ex} = 50 Hz indicate that the residual stresses generated by the grinding process are closer to the sample's surface.

The study of roughness is important because the BN is sensitive to microstructural changes, mechanical stresses and plastic deformations, therefore, the surface quality must be adequate so that these sensitivities do not affect the measurement, according to Chen *et al*. (2018).

3.2 Rockwell B hardness

Rockwell B (HRB) hardness analyzes results are shown in Figure 6. Hardness values obtained in the normalized samples were on average 10% higher than the hardness values in the samples without heat treatment. This indicates normalizing influenced the Rockwell hardness values in the AISI 1020 steel samples machined by the surface grinding process. According to Callister (2002), normalizing leads to grain refinement. Average grains are reduced and the grain size distribution becomes more uniform. Grain refining is associated with increased hardness in AISI 1020 steel samples.

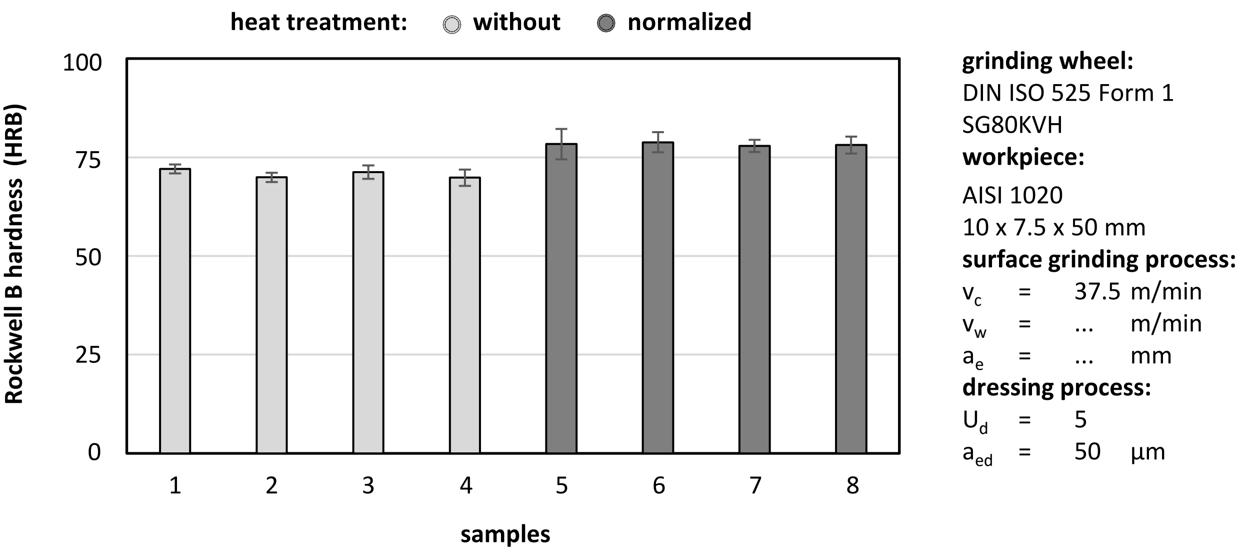

Figure 6. Rockwell B hardness of samples machined by the surface grinding process.

An important correlation was observed between the BN results (Figure 5 and 6) and the Rockwell hardness results (Figure 7). As the hardness results increase the BN results decrease, corroborating with Raja *et al*. (2018) studies, indicates hardness influences the BN results. It is verified the normalized samples had their hardness values increased and registered lower BN signals in comparison with samples without heat treatment. These results corroborate with Ting *et al*. (2006), which states materials with hardened surfaces typically have compressive stresses, which results in low magnetic parameters. Once normalization treatment aims at microstructure refinement, and BN energy jumps are related to anchor points, grain boundaries, disagreements, and micro constituents, it is possible to obtain direct BN noise relationships with these parameters. According to Deng *et al*. (2018), a more refined microstructure acts as an anchor point in magnetization.

3.3 Micrographics analysis

Sample 6 (without heat treatment) metallographic analysis is shown in Figure 7. Figure 7(a) with 10X magnification, a microstructure with polygonal morphology near the machined surface edge is observed. Micro constituents of ferrite (light grains) and pearlite (dark grains) are also identified. In Figure 7(b) fine pearlite agglomerates are identified.

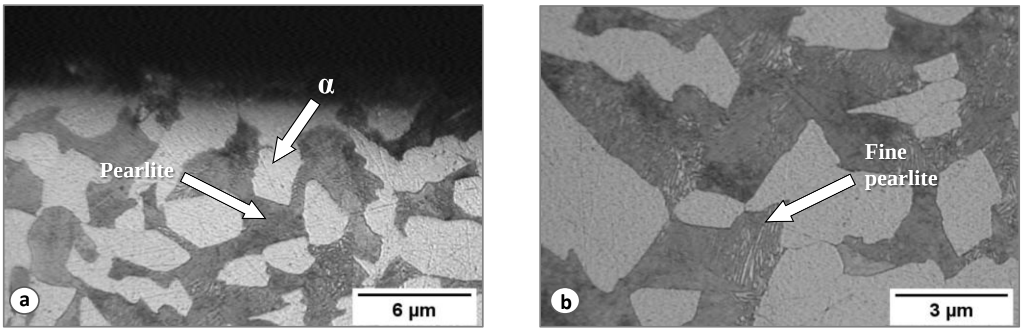

Figure 7: AISI 1020 steel microstructure near surface machined edge without heat treatment with (a) 20X and (b) 40X.

Sample 14 (normalized) microstructure is shown in Figure 8. After normalization heat treatment followed by slow cooling in the furnace (Figure 8a) the microstructure generates is uniform with fine grain. Due to exposure to high temperature, there is an increase in pearlite grains and a reduction in ferrite grains (α) making the microstructure more homogeneous (Figure 8b).

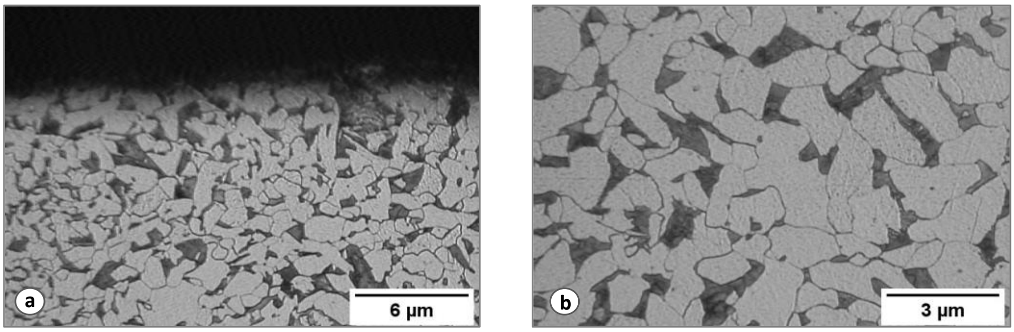

Figure 8: AISI 1020 steel microstructure near surface machined edge normalized with (a) 20X and (b) 40X.

According to Drehmer (2013) hardness values below 200 HV are equivalent to approximately 91 HRB, correspond to a ferrite + pearlite microstructure. Hardness values obtained are consistent. However, there is a small increase in normalized sample hardness results compared to samples without heat treatment. This is due to carbon redistribution in the matrix, which is evidenced by the volumetric ferrite fraction of 79.3% for the sample n° 6 and 73.8% for the sample n° 14 (normalized), as a result of volumetric fraction increase of fine pearlite. According to Callister (2002), normalizing leads to grain refinement. Average grains are reduced and the grain size distribution becomes more uniform. Grain refining is associated with increased hardness in AISI 1020 steel samples.

Correlating BN results (Figure 5) with micrographs (Figures 6 and 7), these results are in accordance with Costa *et al*. (2014), who evaluated BN in AISI 1020 samples with different microstructures. Costa *et al*. (2015) claim the domain wall movement is difficult in such fine structure. On the other hand, in ferrite, the domain walls can move freely. For this reason, in the present study, BN values were higher in samples without heat treatment compared to a refined microstructure obtained by normalizing heat treatment.

3.4 Roughness Ra and Rz results

Roughness results of the AISI 1020 steel samples after the grinding process are shown in Figure 9. Regarding grinding parameters, feed speeds (v_w) had not significantly influenced the roughness parameters in the samples without heat treatment. This can be verified by comparing samples 1 with samples 3, and comparing samples 2 with samples 4 (all without heat treatment, where only v_w is varied). Considering normalized samples, there was a trend in the decrease of Ra and Rz values with the decrease of feed speeds (v_w) – comparing samples 5 with samples 7; as well as with samples 6 with samples 8 (Figure 9). Roughness decrease with decreasing feed speeds is reported by Konig (1989), Klocke (2009) and Marinescu *et al*. (2007). According to these authors, the decrease in feed speeds (v_w) results in less machine tool vibration and, consequently, in low roughness values.

Considering the infeed (a_e) in the samples without heat treatment, the infeed reduction resulted in the decrease of the roughness parameters Ra and Rz. This can be seen by comparing samples 1 with samples 2; samples 3 with samples 4, where only infeed (a_e) was varied. This decrease was expected, as roughness generally decreases with infeed (Konig, 1989). An increase of infeed increases grinding forces and thermal stress. The workpiece surface roughness decreases with a higher number of engaged cutting edges of the grinding wheel (Marinescu *et al*., 2007).

Concerning normalized samples, the decrease infeed (a_e) not lead to a decrease in roughness results considering the feed speeds (v_w) 16 m/min – comparing samples 5 with samples 6. Unexpected roughness Ra and Rz values in sample 6 are observed in Figure 9. It was expected that with decreasing infeed (comparing samples 5 and 6) sample 6 would present a lower roughness. This random result cannot be explained, and further investigations are recommended to clarify the origin of the roughness to remain at the same value even with the infeed reduction. This result can have several origins, the most likely source was normalization heat treatment that changed the material hardness. Grounded surface roughness is influenced by several factors, such as workpiece material properties (especially with high hardness), coolant, process kinematics, dressing conditions, and especially due to the random abrasive grain's distribution on the grinding wheel (Malkin and Guo, 2008).

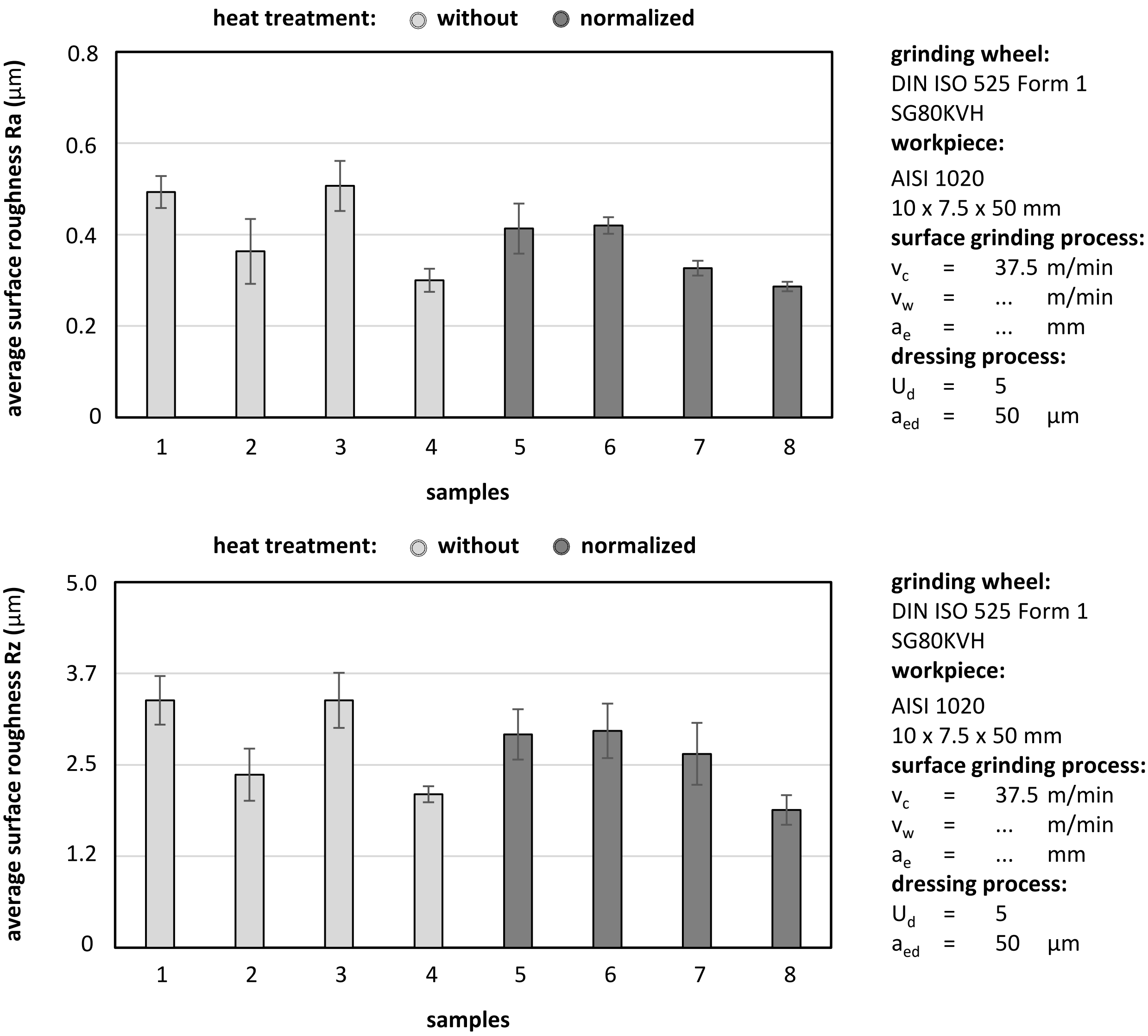

Figure 9. Roughness parameter Ra and Rz results of AISI 1020 steel samples machined by surface grinding process.

According to Lima (2016), the increase in the abrasive grains contact area with the machining component raises the temperature in the cut region. Depending on the heat intensity that goes to the component, may occur component softening at the region in contact with the abrasive grain due to component mechanical resistance shear and abrasion decrease. In some cases, will be plastic deformation without shear. Deformed workpiece materials and chips may enter the grinding wheel pores and compromise abrasives cutting action, impairing the surface finish.

4. CONCLUSION

Normalizing influence on microstructural changes in the AISI 1020 steel surface grounded in this study was analyzed. Barkhausen noise (BN), hardness, and roughness parameters were evaluated. With the results, it is concluded:

- BN results in normalized samples were lower than BN results in samples without heat treatment. Both magnetic excitation frequencies, 10 Hz and 50 Hz, detected changes in the hardness mechanical property, establishing the BN technique can become a powerful tool for microstructural characterization derived from the normalization treatment in AISI 1020 steel. This can microstructural variations influence the BN, the change in the RMS is due to heat treatment;
- Micrographs revealed that matrix homogenization through normalization heat treatment provided the volume fraction of pearlite (ferrite + cementite) increase, causing a slight increase in hardness and a reduction in BN values, due to the consequent increase in lamellar cementite (a non-magnetic micro constituent) in pearlite;

- Normalizing treatment increased 10% hardness results compared to samples without heat treatment. However, the hardness increase was not significant to cause wear on the grinding wheel, which, as a consequence, would increase the roughness parameters values;
- The infeed reduction contributed to the decrease roughness values in most results achieved. On the other hand, the feed speeds variation does not contribute to the decrease in the roughness parameter values.

5. ACKNOWLEDGEMENTS

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