23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

BARKHAUSEN NOISE EVALUATION ON AUSTEMPERED DUCTILE IRON GRADE 3 MACHINED BY CONVENTIONAL SINTERED GRINDING WHEELS WITH DIFFERENT NORTON HARDNESS

Lucas Benini
Walter Lindolfo Weingaertner
Federal University of Viçosa - UFV, Departamento de Engenharia de Produção e Mecânica - DEP, Campus Universitário, Avenida Prof. Peter Henry Rolfs, s/n, 36.570-900, Viçosa, Brasil
Federal University of Santa Catarina - UFSC, Laboratório de Mecânica de Precisão - LMP, Caixa Postal 476-EMC, 88.010-970, Florianópolis, Brasil
lucas.benini@ufv.br, w.l.weingaertner@ufsc.br

Abstract. *The purpose of this paper is to verify the Norton Hardness influence of conventional grinding wheels on the Barkhausen Noise results from austempered ductile iron (ADI) Grade 3 samples. The Barkhausen Noise parameters on these samples was measured and compared. Also magnetization frequency influence, as well the microhardness results, were analyzed. The impact of different frequency magnetization was pointed and related with samples Vickers hardness results, since the Barkhausen noise and microhardness are associated with material subsurface state. The results indicate the magnetization frequency of 125 Hz is the more applicable for the ADI Grade 3 Barkhausen noise evaluation as compared with the another magnetization frequency employed in this research. Original value of this paper is the first time the ADI Grade 3 machined by cylindrical external grinding process is analyzed with different magnetization frequencies through Barkhausen Noise methodology.*

Keywords: *austempered ductile iron, grinding process, Barkhausen noise, conventional grinding wheels*

1. INTRODUCTION

The austempered ductile iron (ADI) has properties desired in the actual manufacturer context, where strength-to-weight ratio and mechanical resistance are demanded. It is due to properties such as high strength and wear resistance, substantial ductility and toughness (Yang and Putantuda, 2005; Klocke *et al*., 2007; Cakir and Isik, 2008; Murthy *et al*., 2009). Another important feature of this material is its weight, 10% lighter compared to steel and therefore allowing considerable weight reduction in the automotive industry (Martins *et al*., 2008).

The conventional grinding wheels employment is an economically viable alternative on austempered ductile iron (ADI) grinding. The machining of this iron is in most cases performed with superabrasive grinding wheels, requiring machine tools with higher costs. The ADI grinding with conventional grinding wheels can produce work results comparable to the superabrasive grinding wheels, followed by lower costs and flexibility in profile grinding, since these wheels can be easily re-profiled.

These results are possible due to new technological developments in materials: new alumina abrasive forms were created. An example is the microcrystalline Al_2O_3 abrasive grains, also known as Sol-Gel abrasives. This type of abrasive is obtained by the sintering process from a solution in gel form. The result is a polycrystalline grain whose crystals have diameters between 0.5 µm and 3 µm with purity of 99.6% (Jackson, 2008) providing an abrasive sharp microcrystalline grain.

The grinding process requires a lot of energy per unit volume of material removed. Much of this energy is converted into heat, the layers being concentrated near the surface of the material after the grinding process, which can lead to residual stresses and thermal damage on the workpiece (Ting, 2006). The thermal damage determination caused by the grinding process is usually made by conventional methods: hardness, residual stress and the nital etch. There is also the alternative method nominated magnetic Barkhausen noise (MBN).

This technique is applicable to ferromagnetic materials, which are composed of small ordered magnetic regions called magnetic domains. The Barkhausen noise method is based on inductively detecting a noise like signal generated by ferromagnetic materials submitted to an alternating external magnetic field. Magnetic domains walls forced to move back and forth by the exciting magnetic field, will pin to crystal lattice defects and dislocations only to jump further once forced by sufficient excessive energy of the magnetizing field. Each jump will generate a pulse in a coil placed near the surface of the sample. Pulses generated in a finite volume of material close to the coil will add to a noise like signal called magnetic Barkhausen noise. The intensity of this signal is further used to characterize the integrity of the stress state and the microstructure of the ground surface (Wojtas *et al,*. 1998; Ting *et al*., 2006; Garstka 2008; Gür *et al.,* 2008).

The effective voltage (RMS) of the generated signal, also referred to as MP (magnetoelastic parameter), is a strong function of the microstructure and residual stress state of a material, making the Barkhausen Noise methodology ideal for detecting grinding abuse. Wojtas *et al.,* (1998) found in his work an increasing behavior of the Barkhausen Noise as a consequence of the increasing grinding damage, though performing experiments in special conditions. The increase in the Barkhausen Noise was most likely due to an increasing residual stress and a decreasing hardness on the workpiece.

D'amato *et al*., (2003) made the ADI characterization thought MBN. They found a good correlation between MBN signal parameters and ADI heat treatment parameters, indicating that MBN is also quite sensitive to fine evolutions of the microstructure of ADI. MBN peak position is especially sensitive to the type of bainite, whereas peak amplitude is linked to the progress of the bainite reaction. Hence MBN measurements appear to be a powerful tool to assess some important microstructural features of ADI castings.

The aim of this work is to verify the Norton hardness influence of microcrystalline conventional grinding wheels on the Barkhausen Noise results from ADI grade 3 samples. Detailed information concerning finishing processes on ADI are so far barely known, and the current literature presents ADI machinability researches in most cases on turning processes (Diniz *et al*., 2000; Seker and Hasirci 2006; Cakir and Isik, 2007; Martins *et al*., 2008; Avisan *et al*., 2009; Akdemir *et al*., 2012; Das *et al*., 2012). However, the finishing turning process is time consuming in comparison with grinding processes and in most cases, it is difficult to perform or not possible a finishing turning process in components with complex geometries or contours, unlike the grinding process. Information's about Barkhausen methodology of ADI characterization can boost non-destructive method utilization in machined ADI components through grinding process.

2. EXPERIMENTAL SET-UP

Specimens preparation. The ductile iron (Tab. 1) was produced in round bars forms through continuous casting and machined by turning process until a final diameter of 90 mm (d_w) and 250 mm length. Heat treatment of the bars was performed aiming the production of ADI Grade 3 (ASTM A897M), consisted of austenitizing at 900 °C for 180 min and followed by austempering at 290 °C in a salt bath furnace. Afterwards, the bars were machined into rings of external and internal diameters of 90 mm and 60 mm respectively with length of 25 mm in order to evaluate the cutting forces on a rotating dynamometer at a grinding machine tool (Fig. 1).

Table 1: ADI chemical composition.

	C	Mn	Si	Cr	Mo	Cu	Mg
%	3.1	0.2	2.3	0.03	0.3	0.7	0.04

Grinding conditions. Experiments in external cylindrical grinding were carried out at the universal cylindrical grinder Pf 51, by *Schaudt Mikrosa BWF GmbH*. The grinding machine tool is equipped with a rotating cutting force dynamometer and offers high stiffness and accuracy as well as a powerful spindle driver. Two different conventional grinding wheel compositions were evaluated, as described in Tab. 2. A 5% solution was used as coolant.

Table 2: Grinding wheel specifications.

Wheel	Microcrystalline Al_2O_3	White fused Al_2O_3	Norton Hardness
30%J	30 %	70 %	J
30%K	30 %	70 %	K

The experiments were executed in a two-stage plunge grinding process. In the roughing phase the bulk of the material stock was ground with a high removal rate. Afterwards, a finishing process was conducted to adjust the surface quality. The grinding wheels were conditioned with a diamond dressing disc before each test series. No dressing took place neither before the finishing process nor between the several workpieces, so the impact of the increasing material removal could be evaluated. The grinding conditions are specified in Tab. 3.

Table 3: Grinding conditions.

Grinding Parameters	
Cutting speed v_c [m/s]	35
Roughing specific material removal rate Q'_w [mm³/mm.s]	10
Finishing specific material removal rate Q'_{w*} [mm³/mm.s]	0.5
Speed ratio q [-]	-60
Dressing parameters	
Dressing overlap ratio U_d [-]	3.7
Dressing depth a_{ed} [mm]	0.015

Speed dressing ratio q_d [-]	0.8
Grinding wheels	
Geometry [mm³]	490 x 30 x 203.2
Grit size	F 80
Norton hardness / Structure	J 6
Bond type	Vitrified
Workpiece	
Material	ADI Grade 3
Hardness [HRC]	37
Diameter d_w [mm]	89.3

The determination of the RBM was made through non-destructive testing system 3MA II (Micro-Magnetic Multi-Parameter Microstructure and Stress Analyzer), made by the *Fraunhofer Institute IZFP*. This equipment provides RBM parameters such permeability and harmonic analysis of the tangential magnetic field. The measurement system consists of a signal conditioner, a laptop and a probe (Fig. 1). In addition, it was developed a fixture system (clamping device) that enables to position the sensor at 90° from the machined surface.

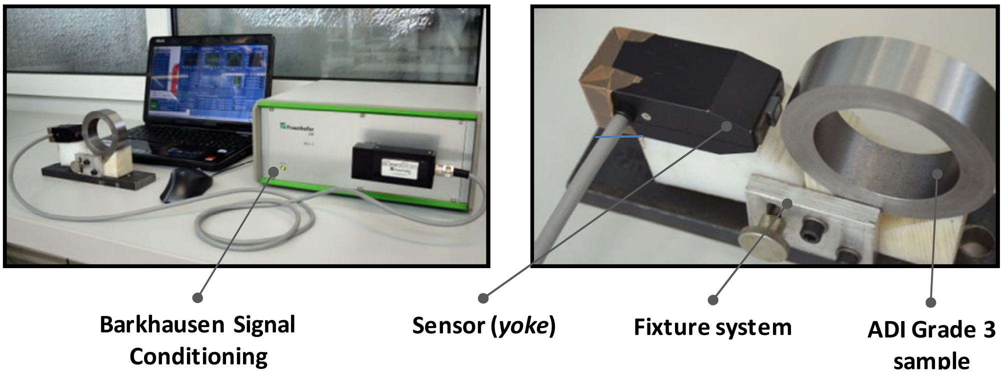

Figure 1. A view of equipments for MBN method

Experimental design. The excitation frequency (f_{EX}) of the sinusoidal magnetizing field is the frequency with which the magnetic field is applied to the material, and presents two important aspects in measuring the RBM: the depth of penetration (depth of the material affected by the magnetic field) and the speed at which measurements they may be performed (scan rate). High excitation frequencies are suitable for measuring the magnetic properties close to the surface. Low excitations frequencies result in greater penetration of the magnetic field, allowing performing measurements at greater depths in the sample. In the researches carried out using systems manufactured by *Stresstech Company*, the more often used for excitation frequency is 125 Hz (Moorthy *et al*., 2003; Lindgren and Lepisto, 2004).

In accordance with Buttle *et al*., (2006) the high frequency excitation are able to generate fields that penetrate to depths of less than 20 micrometers. Moorthy *et al*., (2003) and Moorthy and Shaw (2008) point out in their researches that low frequency magnetic excitation are suitable for determining the magnetic properties at depths greater than 1 mm. The secondary objective was to evaluate the MBN results at different depths of the sample surface, and based on these works, four different excitation frequencies were used, as shown in Tab. 4.

Table 4: Magnetic Barkhausen noise conditions.

Magnetic Barkhausen noise (MBN)		
Low-pass filter	1	[MHz]
High-pass filter	100	[Hz]
Magnetizing amplitude	±40	[A/cm]
Magnetizing Voltage	20	[V]
Sampling rate	256	[ks/s]
Low excitation frequency		
f_{EX}	20	[Hz]
Gain	40	[dB]
High excitation frequencies		
f_{EX}	125; 500; 800	[Hz]
Gain	20	[dB]

In order not to mask any results with magnetic residues, samples were first magnetized with the high frequency magnetic excitation, and subsequently with low frequencies (800 Hz to 20 Hz). It is noted that the experiments with the different frequencies were performed with an interval of more than 24 h in order to demagnetizing the probes (magnetic residues of previous measurements did not affect subsequent tests). For each surface, 5 subsequent measurements were obtained by manually placing the Barkhausen probe on the surface.

The micrograph of ADI Grade 3 samples was performed employing the optical microscope BX 51, by *Olympus* and supported by *Pro Analysis* software, in order to in order to observe any thermal damages caused by grinding process. The samples preparation for micrograph was carried out through the wire electrical discharge machining (WEDM) to not change the mechanical properties of the subsurface.

This process only generates a heat affected layer in the range of a few micrometers - and does not modify the microstructure to eroded material - which is easily removed through sanding and polishing processes the samples already built. Subsequently, the samples was submitted to the nital etch procedure. The nital etch method is able to identify the most thermally affected areas, highlighting them with different colors.

3. RESULTS AND DISCUSSION

The Fig. 2 shows the MBN results along specific material removal V'_w measured with f_{EX} = 800 Hz. The results corresponding to maximum amplitude M_{max} of this figure were not expected, since these have a stochastic nature and are inconclusive.

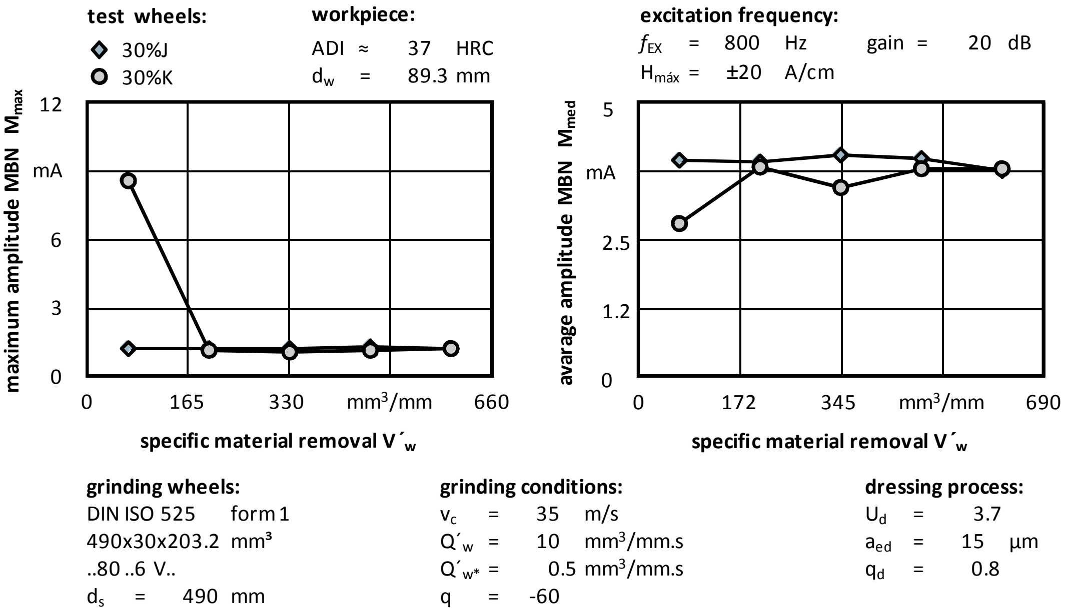

Figure 2. Amplitudes MBN versus specific material removal - f_{EX} = 800 Hz

In the Fig. 3 the MBN results measured with f_{EX} = 500 Hz are shown. Just as occurred in Fig. 2, the maximum amplitude M_{max} results are inconclusive because of the stochastic nature. The average amplitudes M_{med} results, for both excitation frequencies f_{EX} = 800 and f_{EX} = 500 Hz, it is observed similarity curves progression along specific material removal. It is possible to observe in both figures that the grinding wheel 30%J provides highest average amplitudes values.

The MBN results measured with f_{EX} = 125 Hz are presented in the Fig. 4. It is observed that maximum amplitude M_{max} and average amplitudes M_{med} can be considered to take information about the grinding wheel Norton Hardness influence on the MBN results from ADI grinding. It is noteworthy that this magnetic excitation frequency is the most used in the researches reviewed in the literature (Davut, 2007; Gür *et al.*, 2008; Moorthy and Shaw, 2008; Santha-aho, 2012; Buttle, 2013). It is observed in this figure an increase in the maximum amplitudes M_{max} values along the machined specific removal of grinding wheel 30%K in compared with grinding wheel 30%J.

It is important to note the maximum amplitude $M_{máx}$ results showed similar curves in comparing with to mean amplitude results M_{med} with of f_{EX} = 125 Hz utilization. This situation point to prove this frequency is the most suitable for RBM methodology evaluating on ADI samples.

Figure 5 shows the RBM results to magnetic excitation frequency of f_{EX} = 20 Hz. Both curves of this figure and have relatively low values (around M_{max} = 0.7 mA and M_{med} = 0.5 mA) and presented an overlap, making it difficult to analyze the Norton hardness grinding wheel influences identified by the MBN methodology.

The first two points of maximum amplitude M_{max} curves (Fig. 4) suggests that the grinding wheel with Norton hardness ‘K’ generates lower effects on sub-surface since the most MBN values for the grinding wheel 30%K were smaller than the grinding wheel 30%J values. However, the difference between the curves values presented in Fig. 4 is not significant. Basically both grinding wheels generated approximately the same MBN results.

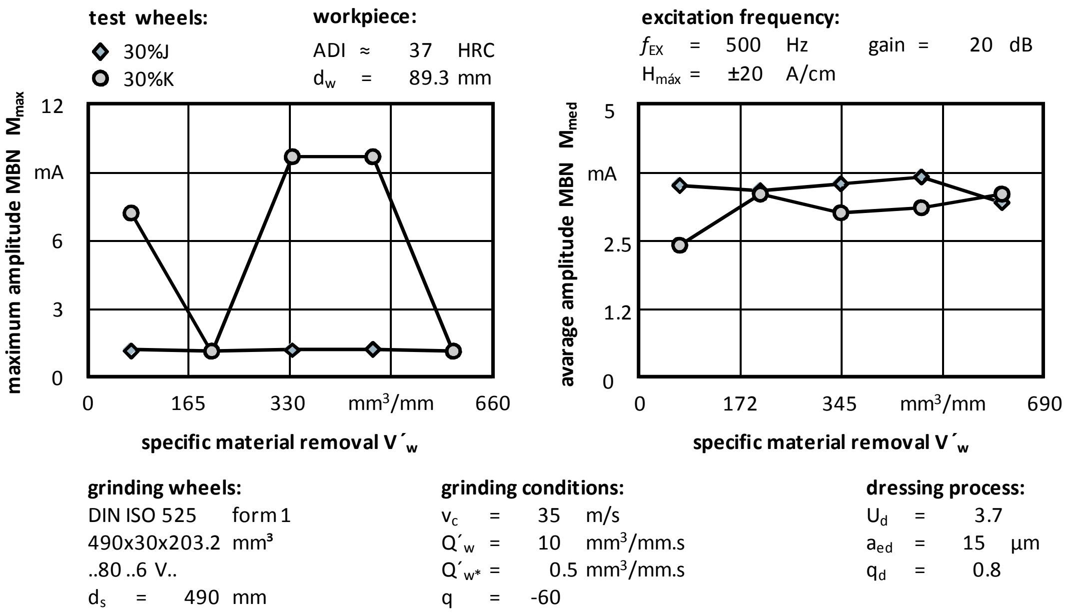

Figure 3. Amplitudes MBN versus specific material removal - f_{EX} = 500 Hz

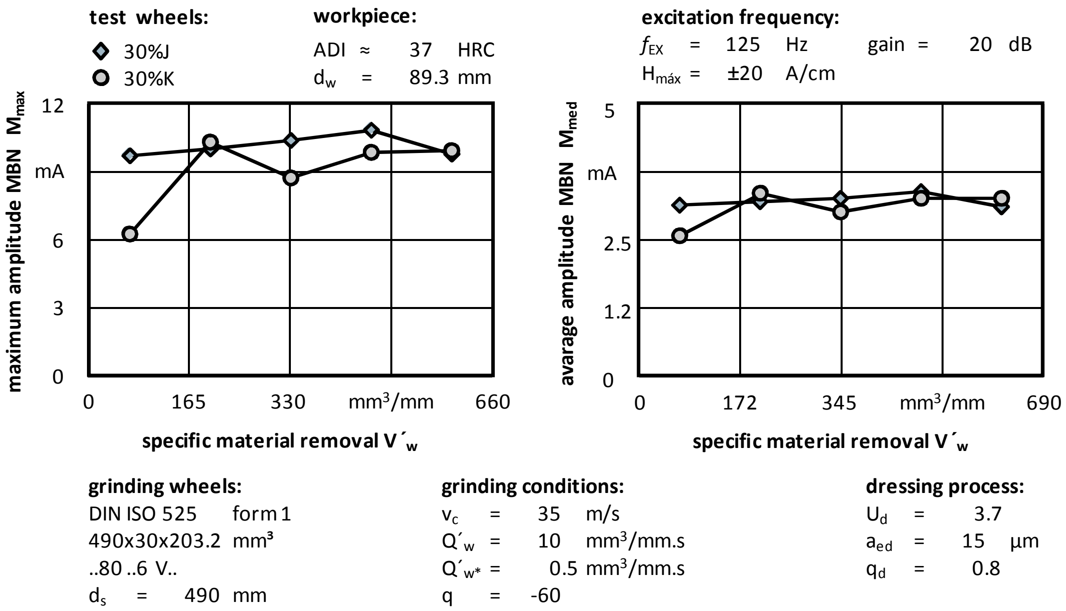

Figure 4. Amplitudes MBN versus specific material removal - f_{EX} = 125 Hz

In Fig. 6 shows the results of ADI Grade 3 microhardness. It is observed in this figure that with the increase of the specific material removal rate curves, the microhardness curves values decrease, i.e., the first sample had higher values of hardness and the last sample values lower.

Therefore, it is evident that the Norton hardness affects the ADI Grade 3 microhardness samples, since the 'J' Norton hardness generated microhardness results that increased over the specific material removal while the 'K' Norton hardness generated microhardness results that decreased with specific material removal increase. Comparing the MBN results obtained with both grinding wheels, it is verifies the wheel 'J' microhardness results showed a curves overlap with progression approximately constant along the specific material removal. This situation not occurred with microhardness results obtained with grinding wheel 30%K, since it is observed high curves dispersion in compare with microhardness results originated of the grinding wheel 30%J.

In the case of the grinding wheel 'K' Norton hardness, the microhardness curves decreased their values along specific material removal and MBN results showed the progression curves increase. This scenario indicates a correlation between the microhardness and the MBN results: these parameters can be considered inversely proportional.

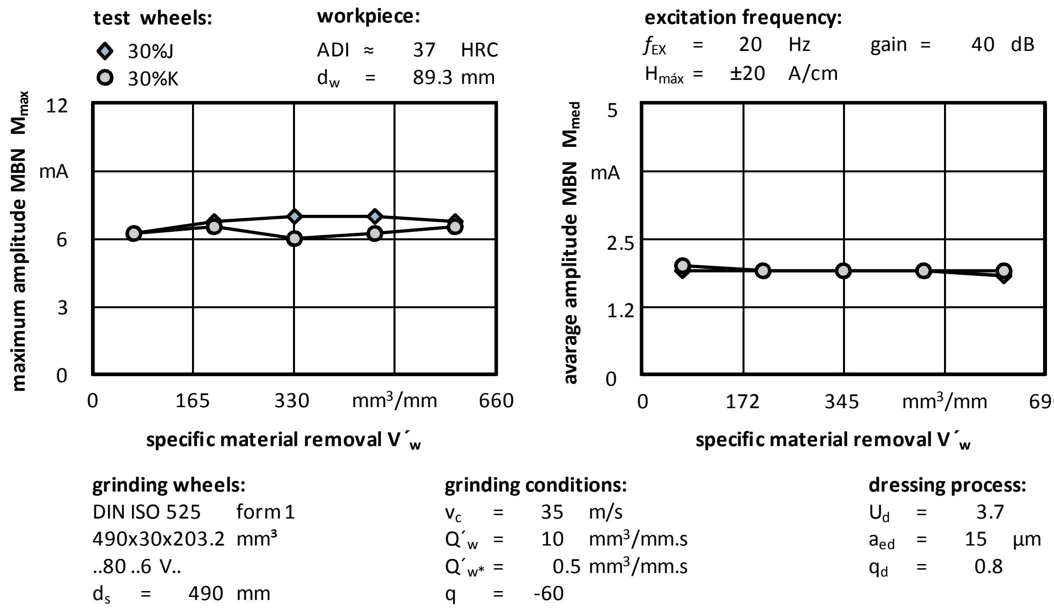

Figure 5. Amplitudes MBN versus specific material removal - f_{EX} = 20 Hz

The Fig. 7 shows the micrographs of ADI Grade 3 samples grounded with grinding wheel 30%J. It is observed in this figure the large amount of graphite nodules (spheroidal graphite) and micro constituents near to samples surfaces. In the magnification 500x of this figure is noted the partial and total graphite spheroidal break out on the samples surface has occurred.

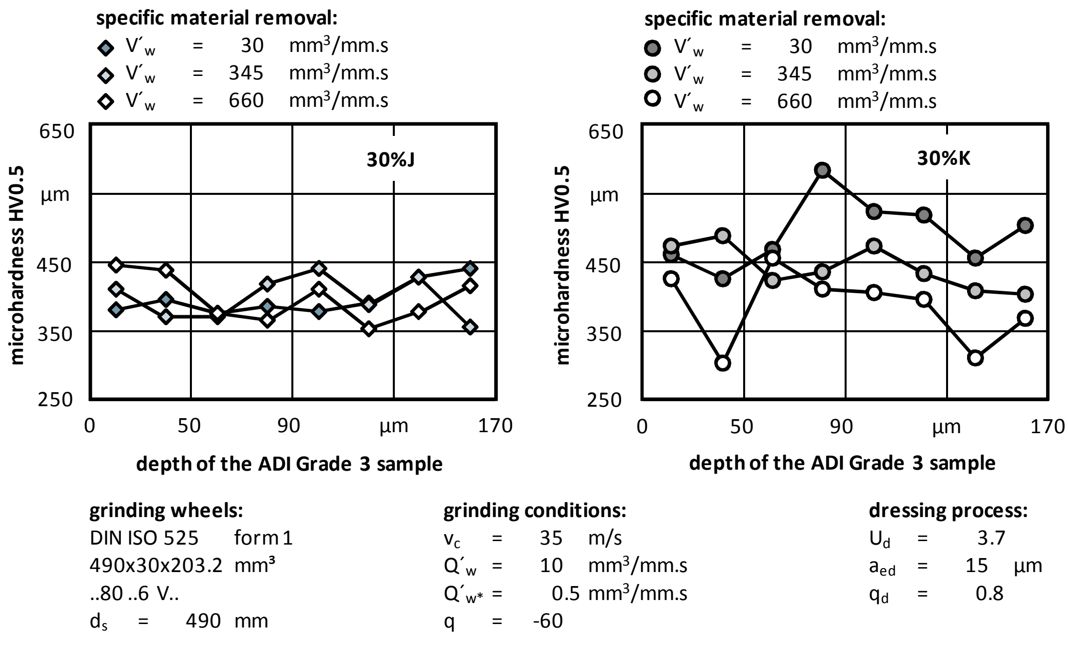

Figure 6. Microhardness HV along depth ADI sample

The micrographs suggest the magnetic parameters values decreasing of the grinding wheel 30%J can be related to the presence of nodular graphite on samples surface. As the ADI Grade 3 microstructure is not homogeneous, the grinding process removed the graphite nodules near the surface. In Fig. 7, it was observed the graphite nodules near the surface will decrease along specific material removal, which may be the cause of decrease of the MBN average along specific material removal. Furthermore, it is not observed thermal damages (or grinding burns) on the samples analyzed.

In Fig. 8 are observed micrographs obtained in ADI Grade 3 samples machined with grinding wheel 30%K. As the same way, in these results not occurred thermal damages on the ADI samples over specific material removal. Comparing the micrographs of the Fig. 7 and Fig. 8, it is observed in both micrographs there is not thermal damage caused by grinding wheels with different Norton hardness. Thus, the employing of these grinding wheel hardness grades is not harmful to ADI Grade 3 in terms of grinding burns.

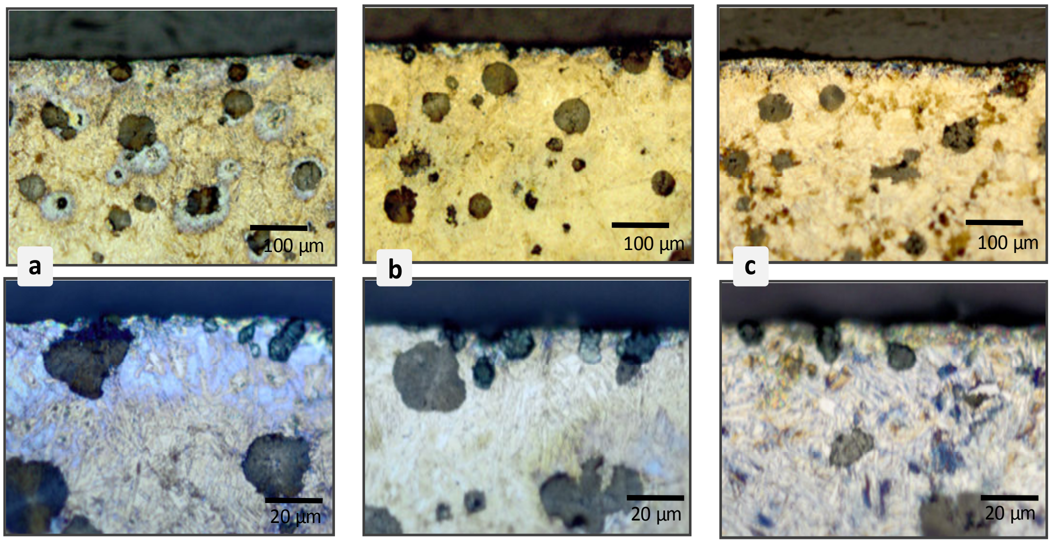

Figure 7. ADI Grade 3 at 200x e 500x: (a) V'_w = 30 mm³/mm.s; (b) V'_w = 345 mm³/mm.s; V'_w = 660 mm³/mm.s – grinding wheel 30%J

Moreover, the 30%K micrograph reveals more subsurface microstructure changes on the samples comparing with the micrographs provides by grinding wheel 30%J. It can be the reason of the high dispersion observed in the MBN 30%K results. The not homogeneity of ADI Grade 3 associated with the grinding wheel hardens contributes to more microstructure changes in the ADI samples, reflected in the MBN results in comparing with MBN results obtained by grinding wheel 30%J.

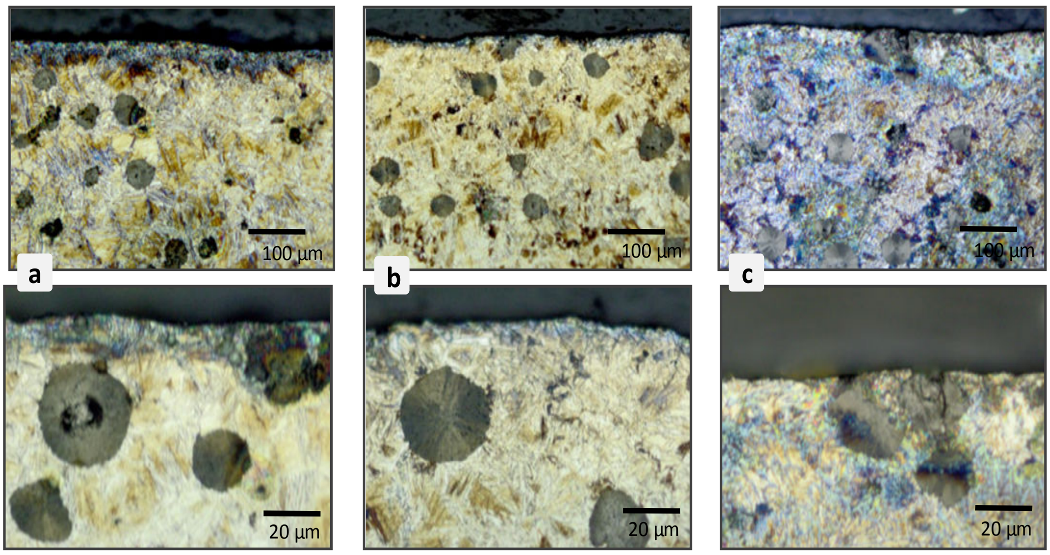

Figure 8. ADI Grade 3 at 200x e 500x: (a) V'_w = 30 mm³/mm.s; (b) V'_w = 345 mm³/mm.s; V'_w = 660 mm³/mm.s – grinding wheel 30%K

4. CONCLUSIONS

Two Al_2O_3 sintered grinding wheels were used in the experiments, varying only the Norton hardness. With the experiments results, it is ascertained:

- The values increase of the average amplitudes MBN curves indicates the thermal damage increase along specific material removal on the ADI Grade 3 samples, caused mainly by grinding wheels wear. The maximum MBN amplitudes results obtained by the excitation frequencies 800 Hz, 500 Hz and 20 Hz were inconclusive because of their stochastic nature and overlay their curves.
- The excitation frequency 125 Hz produced the most consistent results (average and maximum MBN amplitudes), in comparing with other frequencies tested in this work, being the most indicated to evaluate Norton hardness grinding wheels influence on ADI samples by Barkhausen methodology. The amplitudes MBN results for the excitation frequency of 20 Hz did not reveal the influence of Norton hardness on MBN amplitudes evaluated. This reinforces the low excitation frequencies are not preferred to evaluate thermal damage by Barkhausen methodology.
- Considering mean amplitude MBN results (obtained with the various excitation frequencies application) and the microhardness results, it can be concluded these results are inversely proportional to the machining of ADI Grade 3 with microcrystalline conventional grinding wheels.
- The Norton hardness of the grinding wheel has influences on ADI Grade 3 microhardness. The micrographs revealed more microstructures changes in the ADI samples machined with grinding wheel 30%K in compare with grinding wheel 30%J. These changes may be associated with high microhardness values of the samples machined with grinding wheel 30K.
- Considering the results of hardness and micrograph faced with the MBN results it was found that the MBN was sensitive to changes caused by varying the hardness of Norton wheels on machined samples, thus being an appropriate methodology for characterization of rectification work results as a non-destructive method.
- In view of microhardness and micrograph results faced with MBN results, verified that Barkhausen methodology is sensitive to microstructures changes caused by Norton hardness grinding wheels variations on machined ADI Grade 3 samples. Thus, MBN is an appropriate methodology for grinding work results characterization as a non-destructive method.

4. ACKNOWLEDGEMENTS

The authors would like to acknowledge the TUPY S. A. Foundry, for the ADI samples supply, and the financial support from CAPES (Process number: 012.043.133) and from FAPEMIG.

5. REFERENCES

Akdemir, A., Yazman, S., Saglam, H., and Uyaner, M., 2012, "The Effects of Cutting Speed and Depth of Cut on Machinability Characteristics of Austempered Ductile Iron". *Journal of Manufacturing Science and Engineering*, Vol. 134, p. 9.

ASTM A897M – 06, 2011, "*Standard Specification for Austempered Ductile Iron Castings*". Vol. 01-02.

Avishan, B., Yazdani, S. and Vahid. D.J., 2009, "The influence of depth of cut on the machinability of an alloyed austempered ductile iron". *Materials Science and Engineering A*, Vol. 523, p. 93.

Buttle, D.J., Moorthy, V. and Shaw, B., 2006, "Determination of residual stresses by magnetic methods". *Measurement Good Practice Guide*, n. 88, 56 p.

Cakir, M.C. and Isik, Y., 2008, "Investigating the machinability of austempered ductile irons having different austempering temperatures and times". *Materials and Design*, Vol. 29, p. 937.

Das, A.K., Panda, R.K., Dhal J.P., Mishra S.C. and Sen, S., 2012, "Variation of mechanical properties of austempered ductile iron with processing parameters". *International Journal of Current Research*, Vol. 4-8, p. 12.

D'amato, C., Verdu, C., Kleber, X., Regheere, G. and Vicent, A., 2003, "Characterization of austempered ductile iron through Barkhausen noise measurements". *Journal of Nondestructive Evaluation*, Vol. 22, n. 4, p. 127.

Davut, K. and Gür, H., 2007, "Monitoring the Microstructural changes during tempering of quanched SAE 5140 steel by magnetic Barkhausen noise". *Journal Nondestruct Eval*, Vol. 26, p. 107.

Diniz, A.E., Marcondes, F.C and Coppini, N.L., 2000, "*Tecnologia da Usinagem dos Materiais*", Artliber Editora, 2 ed.

Garstka, T., 2008, "The influence of product thickness on the measurements by Barkhausen noise method", *Journal of Achievements on Materials and Manufacturing Engineering*. Vol. 27, n. 1, p. 47.

Gür, H.C., Kilicli, V. and Erdogan, M., 2008, "Investigating the austempering parameters of ductile iron by magnetic Barkhausen noise technique". In *17th World Conference on Nondestructive Testing*, Shanghai, China.

Lindgren, M., Lepistö, T., 2001, "Effect of prestraining on Barkhausen noise vs. stress relation". *NDT&E International*, Vol. 34, p. 337.

Jackson, M.J., 2008, "Grinding technology and new grinding wheels", *Machining*, Springer, p. 249.

Klocke, F., Klöpper, C., Lung, D. and Essig, C., 2007, "Fundamental Wear Mechanisms when Machining Austempered Ductile Iron (ADI)". *Annals of the CIRP*, Vol. 56, p. 73.

Martins, R., Seabra, J. and Magalhães, L., "Austempered ductile iron (ADI) gears: power loss, pitting and micropitting". *Wear,* Vol. 264, p. 838.

Moothy, J.D., Parolini, J.R. and Rundman, K.B., 2003, "On the kinetic of austempered gray cast", In *Proceedings of the Iron annual meeting of the American Foudryments Society*, Milwaukee, USA.
Moorthy, V. and Shaw, B.A., 2008, "Magnetic Barkhausen emission measurements for evaluation of material properties in gears". *Nondestructive Testing and Evaluation*, Vol. 23, n. 4, p. 317.
Murthy, K. N., Sampathkumaran, P. and Seetharamu, S., 2009. "Abrasion and erosion behavior of manganese alloyed permanent moulded austempered ductile iron". *Wear*, Vol. 267, p. 1393.
Santa-aho, S., Vippola, M., Sorsa, A., Latokartano, J., Lindgren, M., Leiviska, K., Lepisto, T., 2012, "Development of Barkhausen noise calibration blocks for reliable grinding burn detection". *Journal of Materials Processing Technology*, Vol. 212, p. 408.
Seker, U. and Hasirci, S., 2006, "Evaluation of machinability of austempered ductile irons in terms of cutting forces and surface quality". *Journal of Materials Processing Technology*, Vol. 173, p. 260.
Ting, L.M., Wah, H., Wong, S., 2006, "Inspection of aircraft landing gear components by Barkhausen noise measurement". *NDT.net*, Vol. 11 n. 6, p. 1.
Yang, J. and Putatunda S.K., 2005, "Effect of microstructure on abrasion wear behavior of austempered ductile cast iron (ADI) processed by a novel two-step austempering process". *Materials Science and Engineering A*, Vol. 406, p. 217.
Wojtas, A.S., Suominen, L., Shaw, B.A., Evans, J.T., "Detection of Thermal Damage IN Steel Components After Grinding using the Magnetic Barkhausen Noise Method", The Open Access NDT Database. 27 Jan. 2011 <http://www.ndt.net/>.

6. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.