Evaluation of Residual Stresses in Grinding by Magnetic Barkhausen Noise

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Abstract— **The effect of residual stresses and the lubricant type in grinding on the characteristics of magnetic Barkhausen noise (MBN) profiles were examined in low alloy steel of the type used for wear-resistant engineering components. A shotpeened and ground in different conditions specimens were tested. MBN measurements showed that the intensity of the signal increases with abusive grinding due to residual tensile stresses and decreases with shot peening due to residual compressive stresses. An increase was seen in wet grinding specimens as compared with the heat-treated specimen. The increase in MBN after grinding was due to local heating with transition from the initial stage of strong martensitic structure, with residual stress of compression, to the following stage of lower hardening with tendency to residual stress of tensile character. In addition, Barkhausen signals from surfaces ground under controlled conditions were found to be dependent on the lubricant type. The decrease in MBN after shotpeening was due to the accumulation of residual compressive stresses introduced to the martensitic structure. The observations are discussed in the light of established models of Barkhausen noise.**

Index Terms: **Grinding, Shotpeening, Residual stresses, Lubrication, Hysteresis, Barkhausen noise.**

INTRODUCTION

Techniques based on the phenomenon of Barkhausen noise are potentially useful for non-destructive evaluation of ferromagnetic materials. For instance, residual tensile stress and over-tempering can be detected in ground-finished surfaces using measurements of magnetic Barkhausen noise. Because of the large number of influential variables, the technique produces only relative comparisons between different material states. For a given alloy, measurements have to be calibrated against a standard microstructural state for that particular alloy [1].

Barkhausen noise is produced by the irreversible movement of domain walls in a magnetisation cycle. Domain walls are pinned temporarily by microstructural inhomogeneities and then released in the increasing magnetic field [2, 3].

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The discrete changes in local magnetisation can be detected as voltage pulses in a search coil or magnetic read head. Precipitates, grain boundaries and dislocations act as effective barriers to domain wall motion. Therefore MBN is sensitive to microstructure and plastic deformation in the material. The influence of magnetostriction on magnetisation also makes emission sensitive to applied or residual stress [4].

The manufacturing processes for gear components include numerous heat treatment operations which are carried out to ensure the proper surface characteristics for components to deal with wear and fatigue. These heat treatments include austenitizing and quenching in air followed by grinding. Grinding is most commonly used as a finishing process to provide good surface, dimensional and geometrical quality. Thermal shock during grinding gives rise to localized surface residual tensile stresses which result in reduced wear resistance and fatigue life during service. As thermal damage is one of the main limitations of grinding process, cooling plays a crucial role in grinding to avoid thermal damage to the workpiece surface. Cooling and lubrication are especially important to ensure workpiece quality in grinding, because of high friction and intense heat generation involved in the process [4].

The MBN technique offers certain advantages such as the greater depth of penetration, faster measurement, portability of equipment, and capability to measure components having complex geometries like gears [5]. Microhardness profile is an important surface integrity characteristic as it may alter the surface properties. Grinding, is a typically, last tooling operation, which defines the surface integrity of a ground component; however, grinding causes variation in microhardness along the depth of the ground sample. Assessment of microhardness profile of ground samples using conventional technique is destructive quite often time consuming. Literature survey indicates that the MBN technique has been successfully attempted for surface hardness assessment of optimized analysis parameters [6, 7].

In grinding, cooling and lubrication fluid type and its application to the work area are crucial factors in determining the quality of the grinding operation. Although some grinding operations are performed dry, most of the high efficiency operations utilize some of grinding fluid delivery. Fluids lubricate the grind zone, reduce fractional heat, cool the wheel and the workpiece in order to reduce thermal damage and clean the particles that load the wheel face and reduce the grinding efficiency. In practice, grinding fluids are classified into categories according to their performance and chemical characteristics. Therefore, the aim of the present work to investigate the effect of lubricant type and surface residual stresses type on MBN emission in gear steel.

MATERIALS AND METHOD

The steel used in the investigation was recently developed for low cost manufacture of wear-resistant machine elements known as Ovako 667. A feature of its utility is that it can be fully hardened by air-cooling from the austenite region. Another feature is that the material is resistant to over-tempering. The composition of the stock material is shown in Table 1. Bars of (10×10×120 mm) machined from the stock were austenitized in vacuum to prevent surface oxidation and air cooled to produce martensite microstructure. The specimens were ground according to the standard operational specifications analogous to that used with gears. All operational parameters were kept constant during grinding except the lubricant medium type. In the first grinding run, one specimen was ground in dry condition and another four specimens were ground in the presence of oil, oil-water mixture, diesel and water with normal flow rate at contact surface. In order to produce compressive residual stresses, one specimen in the quenched state was shotpeened.

Table 1. Composition of Stock Material

Element	Wt %
C	0.67
Mn	1.48
Cr	1.03
Ni	0.11
Mo	0.25
Si	1.46
S	0.007
P	0.016

The MBN measurements were conducted using equipment developed in the author's laboratory [8]. The testing procedure was developed to give a high degree of reproducibility, i.e., to produce minimum variations in a run of tests on the same specimen. To produce a constant rate of magnetic induction in the specimen, the U-shape electromagnetic yoke is fed by a triangular waveform from a bipolar amplifier to take the specimen to near saturation at maximum current. A driving current, amplitude1 A at a frequency of 1 Hz was used to produce a magnetic field strength of 4.5 kA m^{-1}. A relatively low excitation frequency is used to minimize eddy current opposition to the applied magnetic field and to ensure a relatively slow magnetization rate in the sample. Barkhausen emission is detected by a search coil with 1000 turns of 0.01 mm insulated copper wire wound around a narrow plastic cylinder located at the magnetizing yoke. The signal is amplified to 40 dB in both stages.

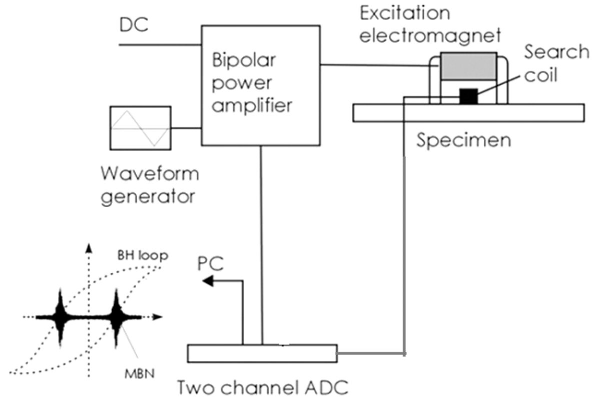


Figure. 1. Schematic Layout of the MBN Measurement Apparatus.

The amplified signal is filtered using a 1–100 kHz band pass filter. MBN emission, to a first approximation, was correlated with the differential permeability of the material. It follows that in a homogeneous material the emission is twice maximum in each hysteresis loop. The intensity of the MBN emission is anticipated to peak at a positive field with increasing energizing current and at a negative field as the state of magnetization of the sample moves around the magnetic hysteresis loop [9].

This was observed in the experiments, but only profiles obtained with a rising current are reported below. An indication of the amplified and filtered output from the search coil is shown in the inset in Figure. 2. It is convenient to smooth emissions in Fig. 2-a to produce a measure of the amplitude of the envelope enclosing the signal. This was done numerically using a Matlab script. The signal was rectified by calculating the local root mean square using a running average of fifteen points. A schematic illustration of the smoothed envelope is shown in Figure. 2-b.

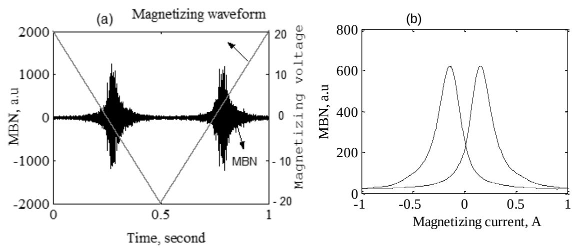


Figure. 2. One Cycle MBN Time Domain Signal of a Complete Magnetizing Cycle (a) and the Corresponding Profile (b) of Oxidized Surface.

RESULTS

Grinding is used in the manufacture of high accuracy components to achieve the required tolerance. Moreover, compared with other machining processes, grinding requires a very large energy input per unit volume of material removed. The majority of this energy is converted to heat, which is concentrated in the surface layers of the material, within the grinding zone. As a result of this, a rapid rise in the localized temperature within the surface can occur. The actual rise in temperature depends on a range of factors, including the type of coolant, method of coolant supply, type of grinding wheel and the speed and depth of cut of the wheel. The heat generated in the process and plastic deformation in the surface layer of the part will produce a considerable amount of residual mechanical stress. Heat treatment and shot peening induce compressive residual stresses in the substrate surface. Presence of a compressive layer is desired to achieve optimal fatigue strength and wear resistance. Grinding is known to often reduce those compressive stresses and sometimes even to turn them into tensile thus representing a risk for early material failure in critical applications such as bearings, axles, shafts and gears etc.

Since the level of the residual surface stresses after grinding has a detrimental effect on the fatigue strength it is important that any of the above-described defects are detected before the component is placed in service. The aim of the work was to investigate the surface residual stresses of ground surfaces in commonly used lubricants. The result is then compared with the two extremes of residual stresses. Residual tensile stresses induced by dry grinding and residual compressive stresses of shotpeening. An example of half cycle MBN profiles from the dry ground surface and the shotpeened surface compared with that of the as quenched specimen are shown in Figure. 3. The result shows that the dry ground specimen has higher MBN output than that of the as heat treated surface and the shotpeened surface.

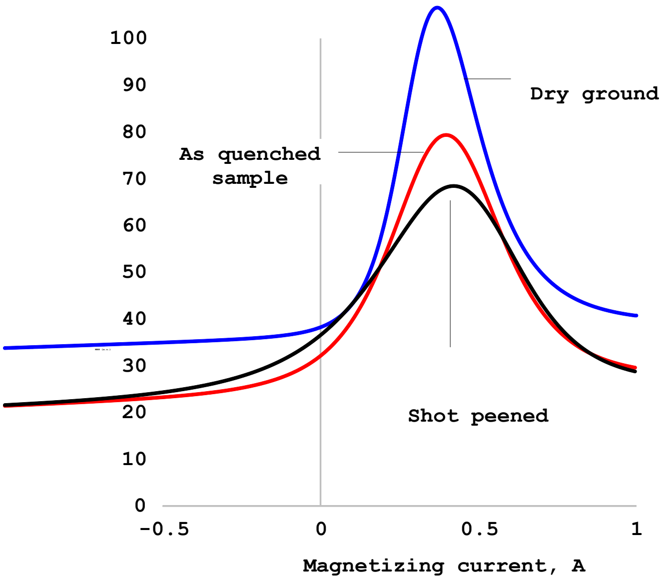
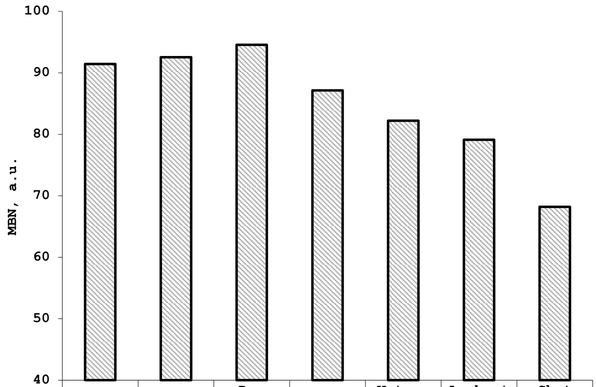


Figure. 3. Half-Cycle MBN Profiles of Different Surface Status

Figure.4 shows a comparable data of MBN peak height (V_p) of all specimens. It can be noticed that dry grinding results in over tempering of the material will have an effect in the development of residual tensile stress as compared with the as quenched surface in which residual compressive stresses are dominant.



	Diesel	Water	Dry ground	Oil	Water-oil mix	As heat treated	Shot peened
Vp	91.449	92.536	94.555	87.138	82.216	79.12	68.21

Figure. 4. MBN Peak Height Variation according to Surface Condition

Residual stress level will affect the MBN in materials with positive magnetic anisotropy like steel. The intensity of the signal will raise with increasing severity of a grinding damage [1]. Presence of residual stresses will affect the MBN shown in Figure 5. A sample under high compressive residual stress will generate a low intensity of the Barkhausen noise (shot peened). With the stress condition changing from high compressive in the as quenched specimen to less compressive, slightly tensile and highly tensile, the measured MBN will show a continuous increase. The main part of stress-MBN will proportionally be reflected on the level of the residual stress in the sample.

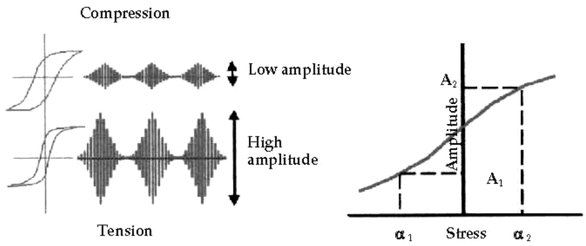


Figure. 5. Barkhausen Noise Amplitude vs. Stress [8]

Coolants plays a significant role in the formation of residual stresses, since surface cooling influences the grinding temperature history and thus alters the phase transformation process. In this experiment, a high cooling rate was implemented to give rise to a lower grinding temperature. The grinding temperature was below the austentizing temperature, so that martensite will not form and the residual stresses in this case were caused only by the conventional thermoplastic deformation without phase change (i.e. with constant material properties).

DISCUSSION

It is generally agreed that the MBN signal detected from steel increases under tensile stress; however, it decreases under compressive stress, as long as the magnitude of the stress does not exceed the tensile strength [1]. In a stress free iron crystal, the magnetic moments are oriented along the [100] directions (easy magnetic axes). When a polycrystalline ferromagnetic specimen is subjected to a tensile stress, because of the positive magnetostriction, the magnetic domains having their magnetic moments parallel to the axis of the applied stress become energetically favorable. Hence, they grow at the expense of the others until the specimen becomes magnetically saturated. In contrast, under a compressive stress, the domains having their magnetic moments perpendicular to the axis of the applied stress become energetically favorable. Thus, when a magnetic field is applied parallel to the stress axis during MBN measurements, in the former case the magnetic microstructure reorganization occurs simply by means of the displacement of the existing 180^o domain walls, while in the latter one the creation and motion of 90^o domain walls is also required to reach the completely magnetized state [9].

The overall MBN signal is expected to be affected by tensile stress in the following manner: Under the influence of residual tensile stress, domains with magnetizations most closely aligned with the direction of residual tensile stress increase in size at the expense of neighboring domains with less favorable orientations. Furthermore, magnetic domains experiencing similar increases in volume are likely to become simultaneously active under an applied field. This increases the MBN response. In addition, there is an increased number of 180^o domain walls in the tensile stress direction [10] which contribute to an enhanced signal. Barkhausen noise is a microscopic phenomenon with a stochastic character [11, 12]. However, Barkhausen noise is modulated by the effect of dynamic magnetic permeability and the presence of stress, which are macroscopic-scale quantities [13, 14]. For instance, when noise is produced by the irreversible movement of domain walls, a peak occurs in the MBN profile in the magnetic cycle because the dynamic permeability also peaks in this way in the course of half a magnetic cycle.

In this sense, the potential usefulness of MBN in non-destructive evaluation arises mainly from the interactive effects of the macroscopic parameters. As with previously reported results [15, 16], the authors believe that the pattern of behavior shown Figure. 3 can to a large extent be rationalized by considering the likely effects of stress and microstructure on the associated BH curves for the material. Jiles [17] has reviewed theoretical models highlighting the connection between MBN and the irreversible component of magnetization, M_{irr}. A basic assumption is that the intensity of noise is proportional to the differential susceptibility $\chi_{irr} = dM_{irr}/dH$, where H, is the magnetic field. For the present discussion, it is convenient to recast this connection in terms of parameters obtained from the standard BH curve. This is not strictly accurate because the standard BH curve includes an element of reversible behavior, but it is convenient to take this approach because the correlations between microstructure, stress and BH behavior is generally known from the literature. Thus, in terms of the BH loop, it is expected that the intensity of noise to be (approximately) proportional to the differential permeability $\mu = dB/dH$. It follows that any changes in modulation of the MBN noise will reflect underlying changes in the BH loop. This can be understood with reference to the schematic diagram in Fig. 6. For instance, if the BH loop becomes narrower whilst retaining the same B value at saturation, one would expect the maximum value of μ to increase along with the peak noise. At the same time, one would expect the value of H at which the peak occurs to diminish along with the width of the MBN envelope. Conversely, if the BH loop becomes broader, the peak noise will diminish while the corresponding H value and profile width will increase.

Conventional shot peening is an important treatment process to obtain beneficial compressive residual stresses in order to annihilate tensile type of residual stresses and to increase the fatigue life of the industrial components. MBN intensity from the shotpeened is very similar to that from the as delivered material. This confirms that the residual stresses in the as delivered material are compressive stresses and the residual tensile stresses as a result of welding are tensile stresses. In addition to the decrease in the intensity of MBN after shot peening, the peaks shift to the higher exciting field values. This can be explained by a reduction of the total 180° domain wall area due to the presence of compressive residual stresses. Due to the loss in motion capability of domain walls, the critical level of the exciting field is increased, so the components start to be magnetized harder [18]. Microstructural changes affect the pinning sites for domain walls, whereas residual stresses affect the area of the domain walls which were specified as 180º and 90º domain walls for steels. It has been proposed that main motion capability of the domains comes from 180º.

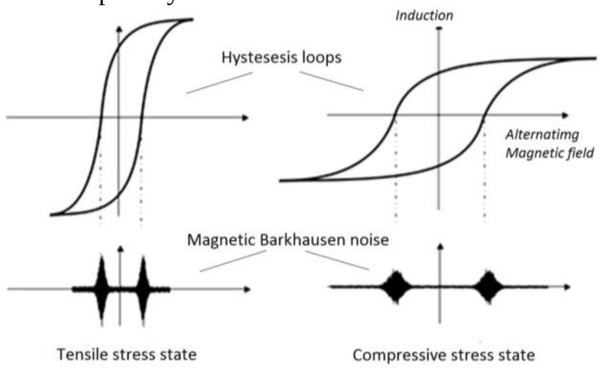


Figure. 6. Magnetic hysteresis loops and the corresponding MBN Signals.

The MBN technique can detect the residual stress differences on the basis of the changing area in these domain walls. While tensile-type stresses increase the area of 180º domain walls by causing an increase in the MBN noise, compressive residual stress has a reverse effect [11]. In the dry ground specimen, it can be seen that the increase in residual tensile stresses increases the peak height and reduces peak position. On the above arguments, this is consistent with the BH loop becoming narrower with increasing tensile stress [19]. This behavior is well known in materials with positive magnetostriction. Sablik and Jiles [20] have given a quantitative account of the interacting factors in their magneto-elastic model. The peak height of MBN envelopes starts to with the reduction of residual tensile stresses and the introduction of residual compressive stresses which is consistent with the idea that the *BH* loop becomes broader when residual stresses become compressive in the as heat treated and shot peened specimens. MBN peak height *V*p varies according to the coolant type in grinding.

CONCLUSION

The magnetic Barkhausen noise method was used to qualitatively study the residual stress state of thermally and mechanically modified surfaces of hardened gear steel. Also, the effect of lubricant type in grinding was investigated. The result of dry ground and shot peened surfaces were considered as a reference in the experiment. The following point can be concluded: -

1. Magnetic Barkhausen noise increases with tensile stresses and decreases with compressive stresses.
2. Coolant type affects the Barkhausen noise intensity. Oil-water mix flow in grinding induces less residual tensile stresses whereas water induces higher level of residual tensile stresses.
3. The development of the MBN technique in assessing residual stress in engineering components could provide a valuable addition to the range of non-destructive techniques.

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