NDT Magnetic Techniques Applied to Degradation Measurement on Rolling Mill Rolls

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ABSTRACT

In rolling mills, rolls or rings represent a very high percentage of the total material costs. Accurate and reliable management of their service life is crucial to the profitability of the plant, and it is therefore essential to inspect their quality upon receipt from suppliers. Most mills rectify those rolls that show cracks for reuse. We have found that there is a common need to determine whether residual cracks are still present after grinding process, invisible to the naked eye but not to the electromagnetic fields. Additionally, assessing the quality of rolls before their use in the mill, including verifying hardness and estimating service life, is vital for enhancing productivity and plant efficiency. Traditional electromagnetic methods have limitations in these areas, prompting the development of an alternative industrial method using Magnetic Barkhausen Noise (MBN). The results presented in this article demonstrate the ability of Magnetic Barkhausen Noise (MBN) technique to detect microstructural degradation in rolling rolls. The data provided by this technique could be used to anticipate roll maintenance strategies, thus extending the service life of the rolling mill.

Keywords: rolling mill, Magnetic Barkhausen Noise, Eddy Current Testing

INTRODUCTION

The steel industry is one of the essential pillars of modern society, on which fundamental sectors such as construction, transport, energy and the automotive industry, among others, are based. To better understand the importance of this sector, we can talk about some data from the sector in the global market.

In 2023, the steel market was estimated to be worth around USD 1,470 billion. The demand for steel is driven over the years by factors such as urbanization, the development of new infrastructure and the transition to renewable energy, among others.

The cornerstone of the steel production process is the rolling mill, which is responsible for taking the steel and shaping it into a final product. To shape the steel, it is passed through different sets of rollers that gradually round the product and reduce its diameter. In order to shape the steel, the rolls are made of very hard material such as steels with a high carbon composition or even solid carbides. These rolls are subjected to high pressures and temperatures in abrasive conditions and are therefore quite susceptible to degradation. Some of the consequences of being subjected to this stress can be material fatigue, surface flaking or even surface cracks that can cause the roll to crack.

To observe the emergence of these defects, the implementation of NDT techniques is vital, as they allow the material to be assessed quickly without causing any damage to the integrity of the component being inspected. This saves costs by predicting the occurrence of defects such as those mentioned, which would make the material passing through these rolls susceptible to being damaged by the roll defects and therefore having to be scrapped.

To detect those defects, we will focus on two fundamental techniques, such as Magnetic Barkhausen Noise (MBN) and Eddy current testing (ECT). The MBN technique allows us to characterize the microstructure of the material being inspected, allowing us to know the number of defects that exist in the material and their nature. This technique is based on the evolution of the magnetic domains within the material and how their walls become pinned to the different defects present in the microstructure of the material. The materials from which the rollers are made are not very magnetic (especially solid carbides), but they are sufficiently magnetic to allow us to appreciate this effect, although at a low intensity. This technique has been applied with this type of material on other occasions with satisfactory results [1,2].

On the other hand, Eddy current testing allows us to detect cracks or surface defects in the rolls based on the disturbance experimented by the induced current due to the presence of a defect. Although the conductivity of solid carbides is not very high, they have a sufficiently high conductivity to apply this technique, as has been proven in other studies [3].

Through the application of these techniques, we will try to characterize the degradation of different samples of rolling mill rolls we are provided with.

THEORETICAL BASIS

The properties and behavior of most metals at the macroscopic level are largely determined by their microscopic structure and characteristics, such as grain size, phase distribution and the presence of impurities or dislocations.

The rolls we want to examine are manufactured by sintering tungsten carbide, which is a ceramic compound whose crystalline structure gives it a great hardness but makes it less tenacious and can be fragile. To correct these weaknesses, the tungsten carbide particles are glued together with a metallic binder (the most common ones are usually cobalt, iron, nickel...). During the sintering process these binders are partially melted and redistributed among the tungsten carbide grains. When this metallic phase solidifies again, the atoms are organized into crystalline structures, each of these crystalline regions grows in one direction, forming what we denominate as grains.

Depending on the heating and subsequent cooling, the internal structure of the binder will be one or another, changing characteristics such as grain size, the phases of which it is composed and the presence of dislocations.

The presence of these types of characteristics within the material is what allows us to obtain an MBN signal.

MBN (Magnetic Barkhausen Noise) is a technique based on how magnetization occurs within ferromagnetic materials and can be correlated with their mechanical characteristics [4]. Ferromagnetic materials can be magnetized by applying an external magnetic field that orients the dipoles inside the material. When this field is removed, the sample is partially magnetized (this is what we know as remanent magnetism), so that in order to eliminate this magnetization we must impose an external field in the opposite direction. If we measure the magnetism of the sample as a function of the applied external field, we obtain what is known as hysteresis cycles. The magnetization of the material with the applied field does not occur continuously, but occurs in the form of small jumps (Fig. 1), this is what is known as MBN.

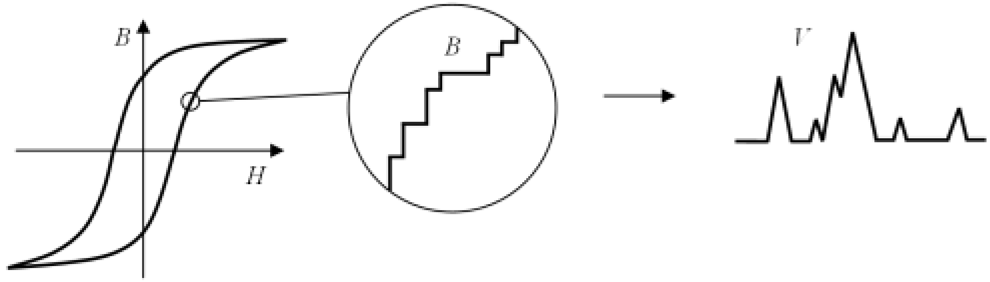


Figure 1: MBN in hysteresis cycles

In ferromagnetic materials when a sample is found to have zero magnetization, this does not imply that all its dipoles are randomly oriented as occurs in paramagnetic materials. In ferromagnetic materials the dipoles are grouped in small zones, and within each of these zones the dipoles have the same orientation. The boundary between these zones is what we know as domain walls (Fig. 2), and when magnetization of the sample occurs the domain walls move, making certain domains grow (those whose dipoles have the same orientation as that of the external field) reducing the size of the rest (Fig. 3).

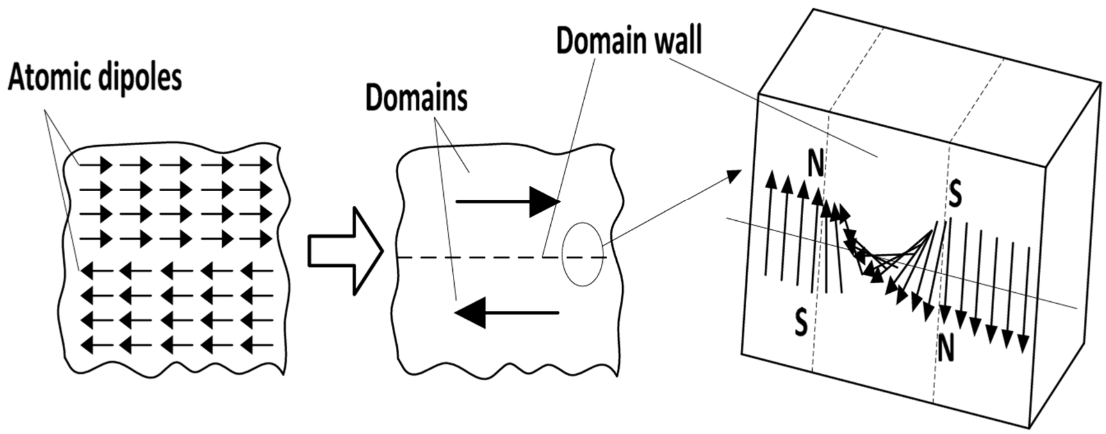


Figure 2: Domain walls representation

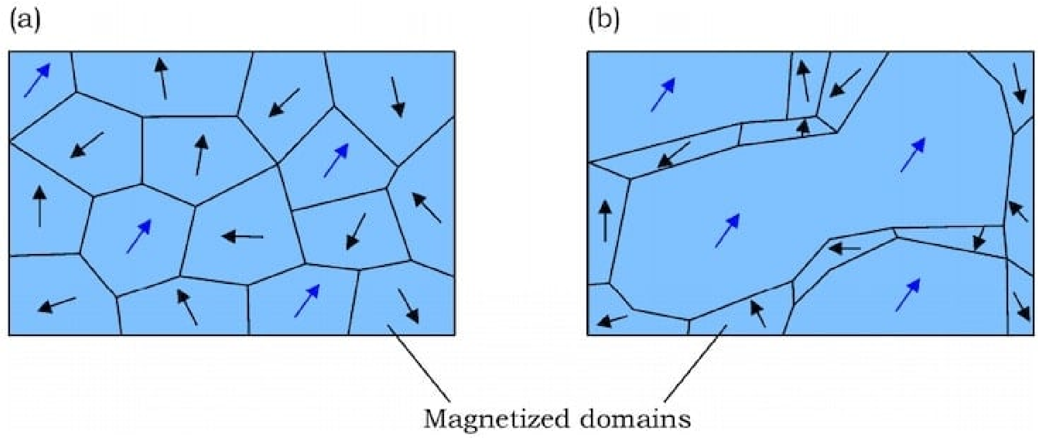


Figure 3: Domain growth in ferromagnetic material

During their motion, the domain walls can be pinned down by certain structural defects. This is because the dipoles can be understood as the lattice atoms, which acquire a net magnetic moment due to the spins of the unpaired electrons. This spin is coupled to the structure of the atom to which it belongs and to the electrostatic environment created by neighboring atoms, so that obstacles such as grain boundaries, internal dislocations or the phase arrangement of the metal cause the dipole to be anchored and unable to reorient itself. When the energy provided by the external magnetic field becomes strong enough, the unpaired electron will acquire enough energy to overcome the potential barrier associated with the defect, and will use the remaining energy to displace the domain wall as much as possible (as long as it does not encounter another obstacle in the way). These sudden displacements of the domain wall are the jumps that we observe in the hysteresis cycle and that can be captured by an electromagnetic probe.

The MBN signal can therefore provide us with information about the internal structure of the metal binder of the rolls, which is responsible for a large part of their mechanical characteristics.

On the other hand, changes to the internal structure can affect the net magnetic conductivity and permeability of the material, which allow us to try to measure the degradation of the rolls by applying eddy currents. This technique is based on the application of an alternating magnetic field to the material by means of a coil. The response in this case can be due to two causes: the appearance of eddy currents due to the conductivity of the material (which oppose the applied field) and by the modification of the inductance of the coil due to the permeability of the material.

These changes will be manifested in the voltage that we will observe in the inspection coil, so that we can separate the voltage in its real part and in its imaginary part, thus representing it in an impedance plane.

The application of these two techniques allows us to know, in some way, the level of fatigue that we have in metallic samples.

DISCUSSION

1. Samples

In order to perform this study, different samples of rolling mill rolls of different grades will be provided.

1.1 C15C

Roll with an outer diameter of 140mm and with an internal diameter of 86mm this roll has two canals for steel rolling of the same diameter, and both appear to be unused (Fig. 4).

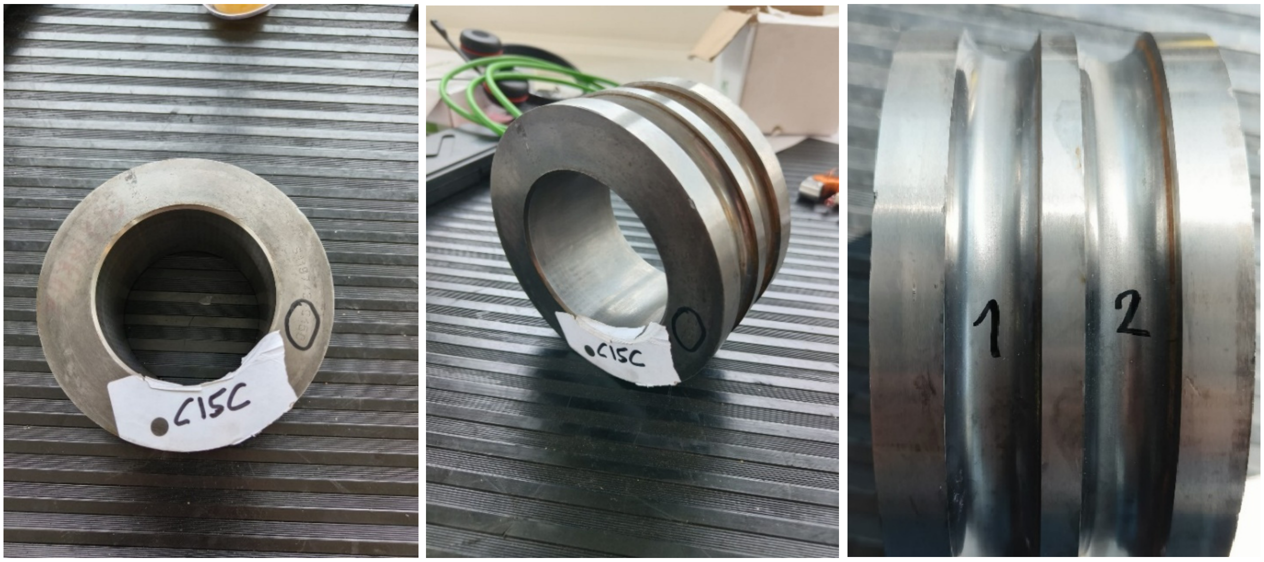


Figure 4. Roll C15C

1.2 C20C

Roll with an outer diameter of 205mm and with an internal diameter of 130mm this roll has two grooves for steel rolling, however in this case one of the grooves has a larger diameter than the other (this larger diameter has been achieved by machining one of the roll's grooves). In this case the larger diameter channel seems to have been used and the smaller diameter channel apparently remains unused. The visual consequences of this use can be seen in Fig. 5, where the difference in appearance between the two channels can be appreciated.

Figure 5. Roll C20C

1.2 YGR45

Roll with an outer diameter of 195mm and with an internal diameter of 120mm in this case we have a roll whose two rolling grooves have been used for steel production, so that both show visual signs of deterioration as shown in Fig. 6. We can also see in the images that the roll has a large crack that crosses both grooves of the roll. We cannot assert that this crack has been produced due to the existing fatigue in the material, since it is also possible that it has been produced by an impact at the entrance of the material in the rolling process.

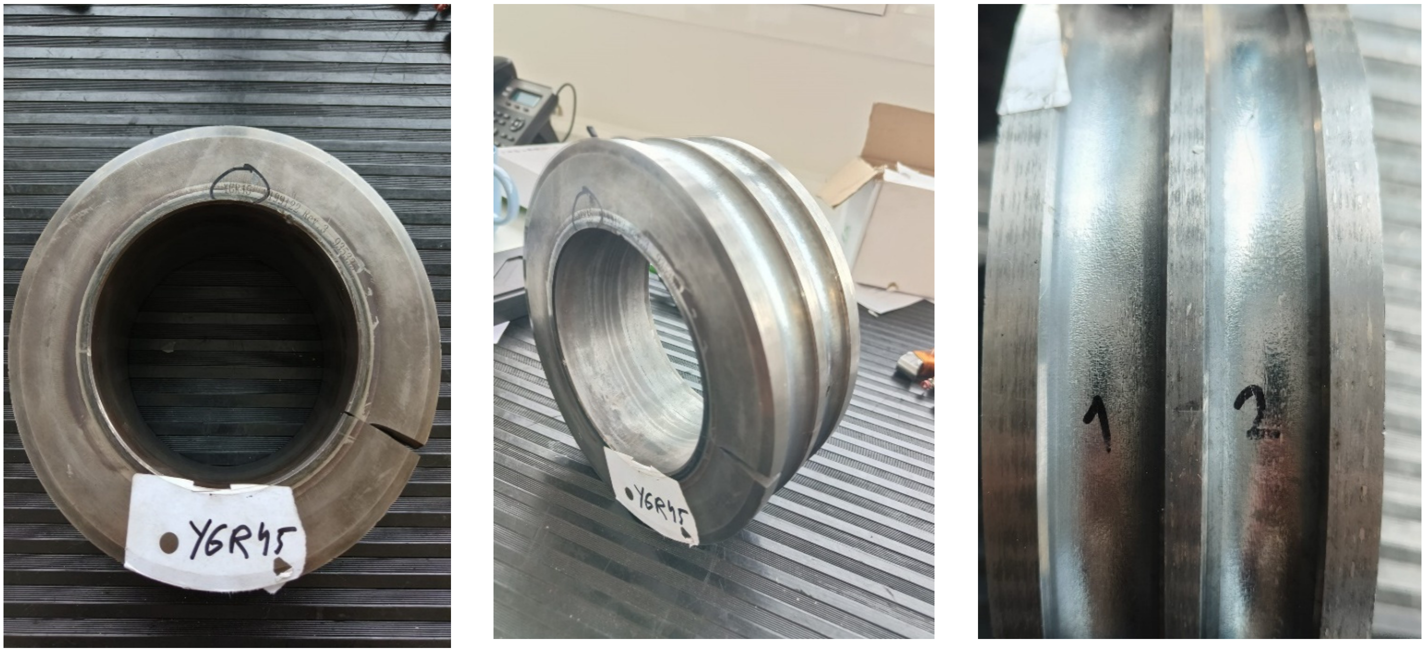


Figure 6. Roll YGR45

All rolls have different grades, so the conclusions drawn from each roll are unlikely to be extrapolated to other rolls outside our sample space.

2. Magnetic Barkhausen Noise Measures

For MBN inspection we will use a modified shape yoke for the rolling side of the samples (Fig. 7).

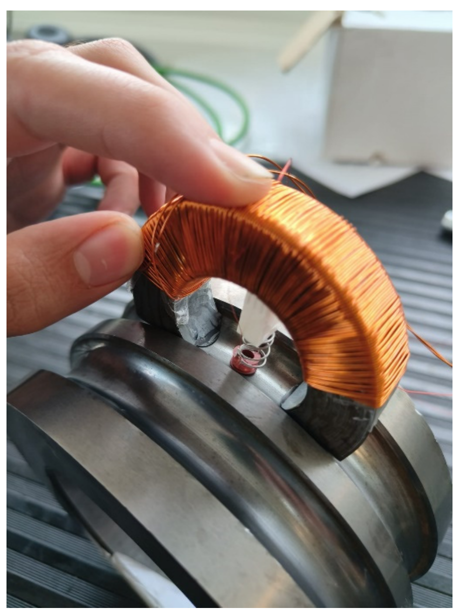


Figure 7. Modified yoke and U shape yoke

Since we have to adapt to the shape of the roll groove to examine the rolling side, the contact of the probe is not complete due to the complex geometry, making the signal weaker in general for this prototype on the rolling side. For the analysis of the samples we will always proceed in the same way, we will obtain the signals from both the inner part of the groove and the external part of the groove (Fig. 8).

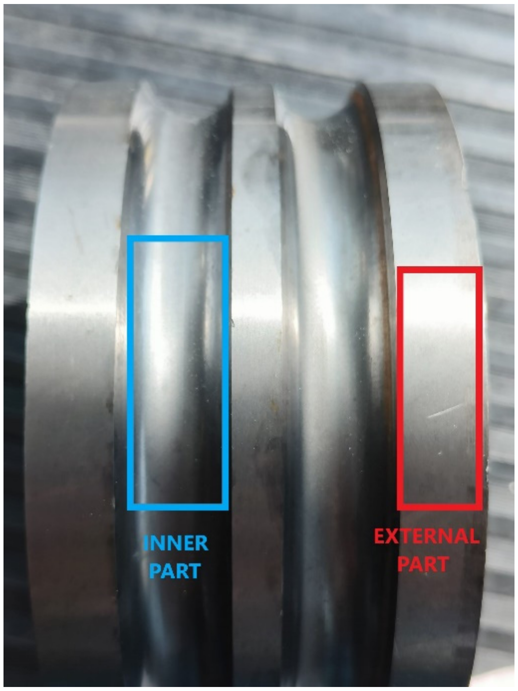


Figure 8 Representation of external part and inner part in rolls

In this way we will be able to compare an area of the roll subjected to the highest possible stress (the inner part of the rolling canal) and an area with a similar geometry, but which is not subjected to stress or at least not to such a high stress (external part). During the analysis of the canals, we will examine 4 zones separated 90º from each other, so that we will be able to see if the roll has suffered a similar stress along its entire circumference. To do this we will apply an operating frequency of 100Hz and average the signals obtained during 1 second at each point. Taking all this into account we will see the results obtained in each of the samples we have.

2.1 C15C

Initially we proceed to the analysis of the two rolling grooves (Fig. 9).

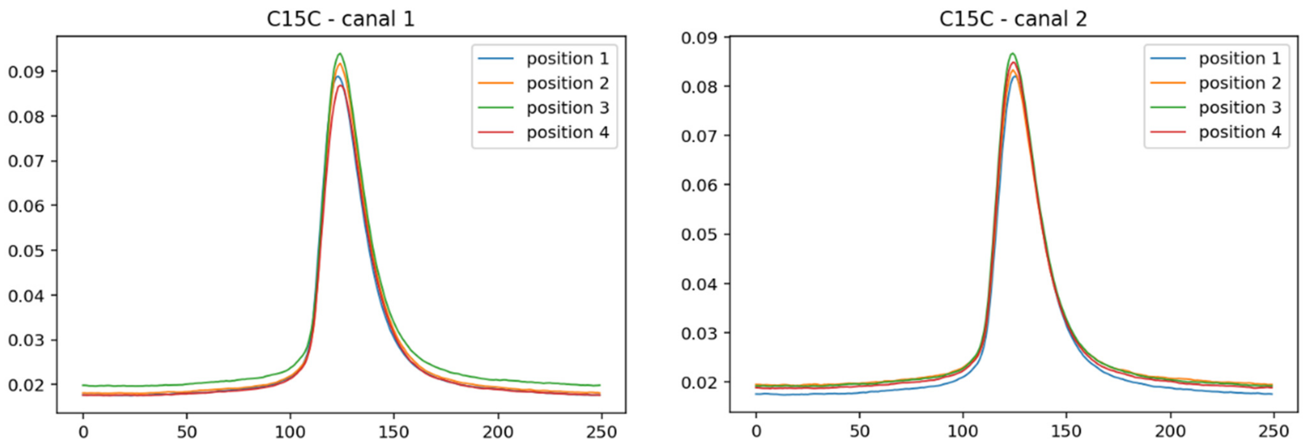


Figure 9: MBN profile in different canals for C15C sample

We can see how the signal obtained in each of the positions is very similar in both grooves and at the same time both grooves have a very similar signal level.

Now we will make an average of each of the grooves and compare the signal with the one obtained from the measurement of the external part (Fig. 10).

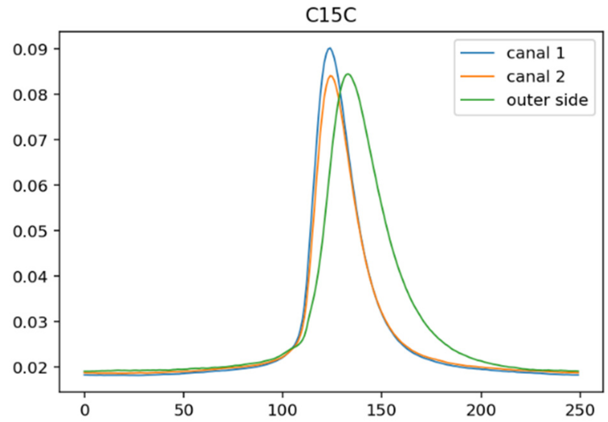


Figure 10: MBN profile comparison between outer part and external part

We can see how the signal obtained in the 3 cases is very similar. These results are consistent with the fact that this roll appears to be practically new, so that it would not have suffered deformations in its internal structure yet due to the steel rolling process.

2.2 C20C

Initially we proceed with the analysis of the two lamination canals (Fig. 11).

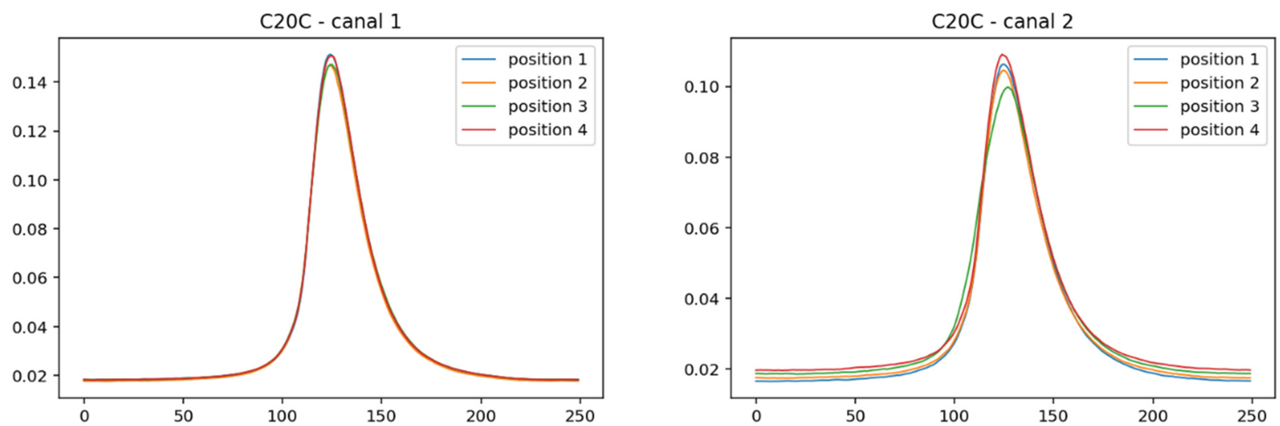


Figure 11 MBN profile in different canals for C20C sample

We can see how the signal obtained in each of the positions is very similar in both channels, but in this case the signal level of one of the channels is significantly higher.

Now we will average each of the channels and compare the signal with the one obtained from the measurement of the external part (Fig. 12).

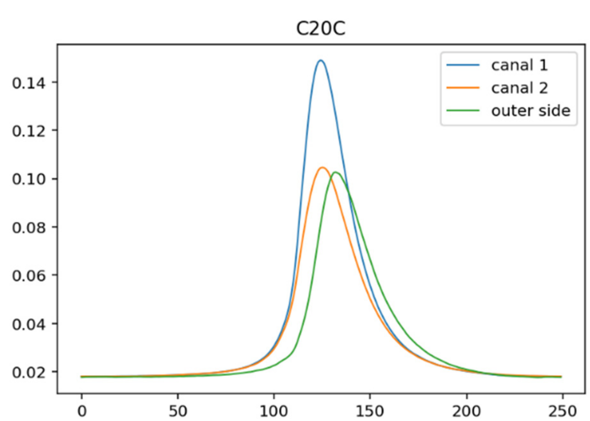


Figure 12 MBN profile comparison between outer part and external part

We can see how the average signal of groove 2 is very similar to the signal of the external part, however the signal of groove 1 is 23.8% higher than groove 2. These results are consistent with the fact that in this roll groove 2 is the one that seems to be unused, while groove 1 has abrasion marks produced by the steel rolling process. During the rolling process, the roll is subjected to great efforts, both by the compression of the steel and by the friction with it, and it is also subjected to sudden changes in temperature, as the steel is at approximately 1000ºC and the rolls are cooled during the process. This means that micro-tempering can occur on the surface of the rolls, making the material more fragile, or even the accumulation of internal tensions due to the mechanical stresses. All this wear and tear generates a greater number of defects in the internal structure of the material, generating a greater signal of MBN.

2.3 YGR45

Initially we proceed with the analysis of the two lamination canals (Fig. 13).

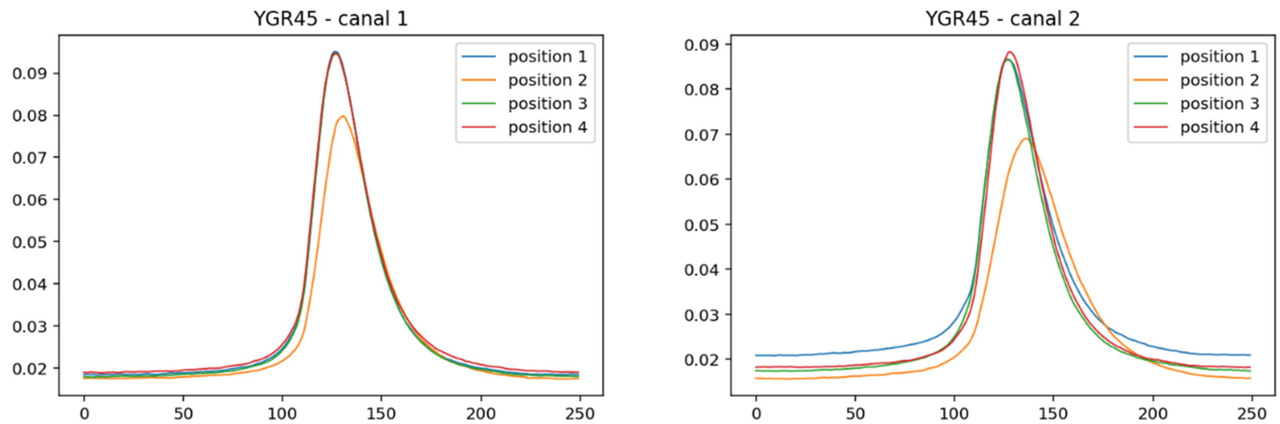


Figure 13 MBN profile in different canals for YGR45 sample

We can see how in this case we have a signal decrease in position 2, this is due to the fact that this position coincides with the crack that crosses the roller from one side to the other as described in the presentation of the samples.

Now we will make an average of each of the grooves (leaving out position 2 which would distort the result) and compare the signal with that obtained from the measurement of the external part (Fig. 14).

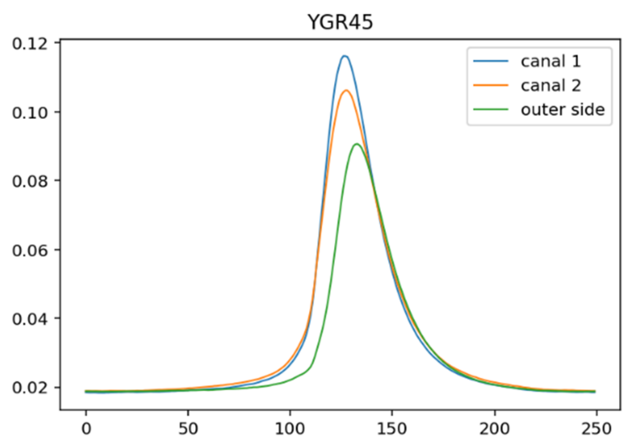


Figure 14 MBN profile comparison between outer part and external part

We can see how the signal obtained within the rolling grooves is slightly higher than the one obtained on the external part. In this case, this deviation is less significant, as it represents a 16.7% increase for the signal obtained from groove 2, while the increase is 27.8% for groove 1. These results are consistent with the wear marks observed on both grooves in this sample, where we could deduce from the signal obtained that groove 1 has suffered greater deterioration than groove 2.

We can thus ensure that using this technique we can characterize the different rolls and we can take account for their internal microstructural defects.

2. Eddy Current Testing Measures

For eddy current inspection, an absolutely eddy current probe has been developed to detect changes in the conductivity or permeability of the roll material.

In this case the results are much less conclusive, since although we can see differences in the measurements made, in most cases the permeability/conductivity change in the material follows the same path in the impedance plane as the lift-off (Fig. 15), so they could easily be confused with each other.

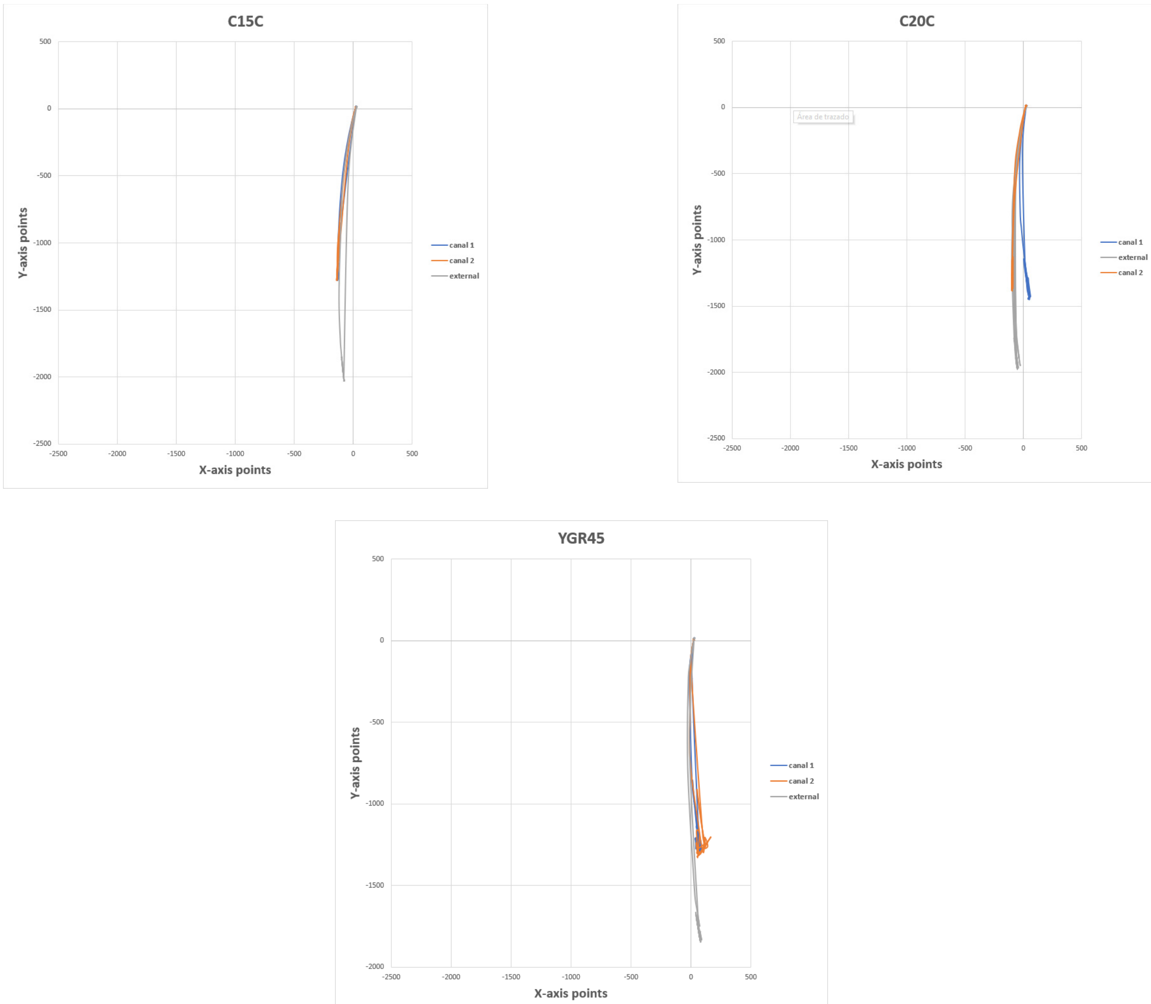


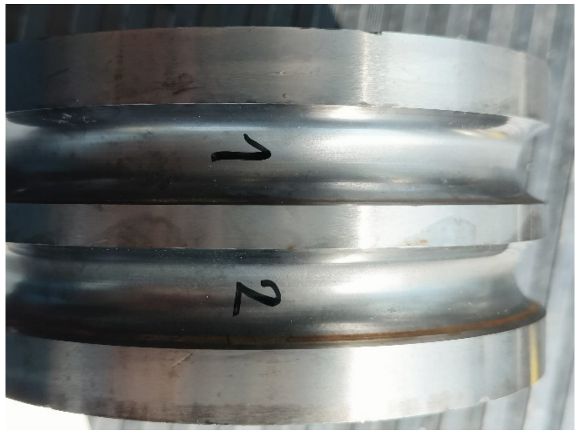
Figure 15 Eddy current impedance plane representations

In the figures we can see how the direction in which the curves move is very similar in all the samples, in addition to the fact that there are no large variations in the modulus of the curves (Fig. 16), as was the case with the MBN technique.

	Max module
C15C canal 1	1286,35
C15C canal 2	1288,35
C15C external	2031,35
C20C canal 1	1451,53
C20C canal 2	1389,80
C20C external	1981,43
YGR45 canal 1	1304,34
YGR45 canal 2	1330,00
YGR45 external	1847,53

Figure 16 Max. module of each inspection by eddy current

CONCLUSIONS



This study has demonstrated the strong performance of the Magnetic Barkhausen Noise (MBN) technique in quantifying the deterioration of the test samples. The results obtained via MBN showed a correlation between the MBN signal and the microstructural condition of the material, allowing the detection of microstructural degradation. The technique’s sensitivity to dislocation density, residual stresses, and magnetic domain behavior positions it as a valuable tool for non-destructive evaluation of material integrity.

This study also demonstrates the effectiveness of the Magnetic Barkhausen Noise (MBN) technique in quantifying deterioration in tungsten carbide samples, a capability that other NDT methods cannot achieve in an industrial setting.

In contrast, the eddy current (EC) method yielded comparatively less accurate results in the specific context of this study. While EC is effective in identifying surface and near-surface discontinuities and heterogeneities, its ability to resolve gradual structural degradation was more limited under the given experimental conditions, where we have a high concentration of a non-metallic material such as tungsten carbide. Nevertheless, it is important to highlight the complementary nature of both techniques. A combined analysis of MBN and EC data holds significant promise for enhancing the overall assessment capability and may lead to a more robust detection of deterioration mechanisms.

Within the scope of the sample set analysed, the results have been satisfactory, enabling the detection and characterization of degradation across multiple stages. Although the study was conducted within a limited material and process domain, the findings support the effectiveness of the employed NDT methodologies in evaluating progressive damage in steel rolling rolls subjected to service conditions. Developing predictive models that integrate both MBN and EC data could provide a foundation for anticipating failure/cracking and optimizing maintenance strategies and replacement criteria for rolling steel rolls.

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