

Investigation of the Trend Between the Results of the Barkhausen Magnetic Noise (MBN) Method with Classical Methods for Ion Nitrided Testing of Steel, BH11

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Abstract - The Barkhausen magnetic noise (MBN) method has emerged as a promising technique for non-destructive measurement of residual stresses, especially in ion nitrided instrumental steels. The study determines the applicability of MBN in comparison to traditional X-ray diffraction (XRD), relative wear resistance and microhardness measurements by focusing on its potential for faster and more reliable evaluations. The comparison is made on MBN speed because it provides a rapid assessment compared to other methods that often require more extensive sample preparation and longer measurement times. MBN does not alter the test material, preserving its integrity for later use. While traditional methods, such as XRD, are surface sensitive, MBN can offer information on subsurface stresses depending on the measurement configuration. The correlation performed, links the study on the one hand to the process logic and on the other hand to microhardness and tribological testing.

Keywords — Barkhausen magnetic noise (MBN), ion nitrided instrumental steel, residual stress, X-ray diffraction (XRD).

I. INTRODUCTION

Chemical-thermal treatment processes are essential for modern industrial applications improving the surface properties of materials. They improve the hardness and wear resistance of materials. Nitride layers derive their outstanding mechanical properties from internal stresses and phase composition, which are tightly controlled in

modern plasma processes. By enriching the surface layer with elements such as nitrogen, carbon, or a combination of the two elements the mechanical properties are significantly improved, which by its mechanism is due to an increase in the residual internal surface stresses. The mechanism of formation of nitride layers consist in that nitrogen atoms diffuse into the surface of iron-carbon alloys [1]. The nitrogen atoms penetrate the iron lattice forming different phases depending on the temperature and nitrogen concentration, the γ' -phase Fe_4N possesses, a wall-centered cubic lattice with a nitrogen solubility of 5.7-6.1% at 500-590°C, and the ϵ -phase $Fe_{2-3}N$ a hexagonal lattice. Above 590°C, 4.55-11.1% N. The phase composition has a direct influence on the mechanical properties: the hardness of the ϵ -phase is of the order of (1 200-1 400 HV) for wear resistance, and the γ' -phase Fe_4N (FCC) guarantees 20-30% higher fatigue strength compared to the base material), corrosion resistance [2].

The ion nitriding process allows precise adjustment of the thickness and composition of the carburized layer, which is crucial for achieving the desired performance characteristics resulting from the different phase composition obtained on the surface. X-ray crystallography is in this respect the most widely used method for the analysis of surface stresses (up to 20 μm depth) by measuring changes in interatomic distances [3,4]. The study [5] is based on the change of magnetic properties under the influence of stresses, and sometimes neutron

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diffraction is used, allowing the analysis of stresses in bulk materials [6]. As demonstrated in the cited references, different phases in the nitride layers determine different internal stresses dictated by the concentration of the diffusing element. The internal stresses occurring after chemical-thermal treatment are determined by specialized methods that take into account the influence of the phase composition on the mechanical properties of the material. These stresses are critical to the reliability and durability of the workpieces. In the present study an attempt has been made to compare the results obtained, by MBN method and XRD method. The MBN method is based on the phenomenon in which abrupt changes in magnetization occur in ferromagnetic materials due to stress changes known as Barkhausen jumps. This method is sensitive to microstructural changes and residual stress fields in materials, making it suitable for non-destructive evaluation of residual stresses [7,8]. MBN is characterized in that it provides a rapid assessment compared to XRD, which often requires more extensive sample preparation and longer measurement times. It has the advantage of not altering the material under test, preserving its integrity for later use and while traditional methods, such as XRD, are surface sensitive, MBN can offer information on subsurface stresses depending on the measurement configuration [9,10 and 11].

Compared to MBN, XRD is a well-established method for measuring residual stresses, but is associated with certain limitations, among which are longer measurement times and complex setups, which can be a disadvantage in industrial applications requiring rapid evaluations, as well as the need for precise sample preparation, leading to variability and potential errors in the results. In contrast, studies have shown that MBN provides a simpler approach with faster results. For example, studies have shown that the root mean square (RMS) stress of MBN signals is highly sensitive to changes in stress, demonstrating a significant increase under applied loads compared to the minimal changes observed with XRD under similar conditions. Despite its advantages, the MBN method faces challenges accurate quantitative results require careful calibration due to the influence of microstructure along with residual stresses [12]. Simultaneous variation of microstructure and residual stresses can complicate the interpretation of data from different transport applications [13,14,15].

II. MATERIALS AND METHODS

The aim of the study is to demonstrate that the Barkhausen magnetic noise method represents a viable alternative to traditional analysis with classical methods for testing ion nitrided steel. The steel BH11 is taken as an example. One of the tasks of the study is to demonstrate that MBN's ability to give faster results while maintaining non-destructive integrity makes it particularly attractive for industrial applications. Nonetheless, to provide reliable quantitative measurements, calibration and mixed effects challenges must be overcome.

The stages and sequence of work in the study were subject to the methodology described in [16, 17]. Since this methodology was developed for the four parameters, they guarantee, on the one hand, the adequacy of the results subsequently obtained and, on the other hand, the intelligent representation of the solution itself. Following the selection of the object of study, heat-resistant steel BH11/BS4659/, Table 1 shows the chemical composition and Table 2 indicates the range of variation of the main input parameters:

TABLE 1 CHEMICAL COMPOSITION OF STEEL, BH11/BS4659/, [%]

Steel	C	C	M	S	M	W	V	Ni	C	S
		r	o	i	n				u	
BH11	0,3	4,	1,	0,	0,	-	0,	0,	0,	0,00
	8	50	20	91	22		47	14	11	6

After conducting the experiment, the surface microhardness of the nitrided layer-HV0.1, the relative wear resistance of the nitrided layer-KV, the thickness of the bonded zone- δ_{bz} ., the total diffusion thickness of the nitride layer- δ_{tot} . were determined in [16]. All these parameters were implemented by the authors of [16] by standard methodologies.

TABLE 2 RANGE OF VARIATION OF INPUT PARAMETERS

	Process parameter of ion nitriding and pre-heat treatment	Low level		Average value		High level	
		Mode change interval value					
		C	/-1/	C	/0/	C	/+1/
		O		O		O	
		D		D		D	
		E		E		E	
1	Nitriding temperature $T_{nit} [^{\circ}C] - (X_1)$	510		530		550	
2	Ammonia pressure $P_{NH3} [Pa] - (X_2)$	150		300		450	
3	Nitriding time $\tau [h] - (X_3)$	4		7		10	
4	Temperature tempering before nitriding $T_{tem} [^{\circ}C] - (X_4)$	600		650		700	

From the experiment set up in this way, eight regimes were analysed on processed ion nitriding samples using both the classical and the recommended methodology of the Barkhausen Magnetic Noise (MBN) method. These modes are described in Table 3.

TABLE 3 TECHNOLOGICAL REGIMES TO BE INVESTIGATED AND ANALYSED

Zyu	Test mode parameters	Structure
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		T_{nit} [°C] (X_1)	$PNH3$ [Pa] (X_2)	τ [h] (X_3)	T_{tem} [°C] (X_4)	
1	1	510	150	4	600	γ'
2	9	510	150	4	700	α
3	13	510	150	10	700	γ'
4	5	510	150	10	600	γ'
5	3	510	450	4	600	$\gamma' + \epsilon$
6	4	550	450	4	600	γ'
7	16	550	450	10	700	$\gamma' + \epsilon$
8	8	550	450	10	600	γ'

The Barkhausen effect consists in the fact that when a ferromagnetic material is magnetized by an external magnetic field, it is accompanied by numerous jumps in the magnetization. When an external magnetic field is applied, the domain walls move. These movements generate electromagnetic pulses. Magnetic noise characteristics are measured with an inductive receiver with a piezo sensor. To study the Barkhausen effect, a setup was created to measure the non-destructive informational characteristics of magnetic noise emission in ferromagnetic materials. In fig. 1. the basic block diagram of the equipment for measuring EBN is shown

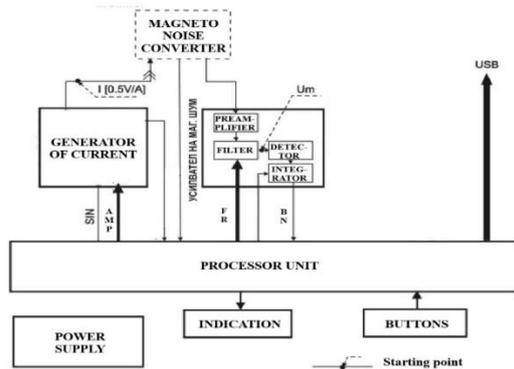


Fig. 1. Block diagram of the device for measuring EBN.

III. RESULTS AND DISCUSSION

The data from the measurements of technological modes presented in Tab. 3 modes are presented in Table 4. Their analysis, however, must be carried out in an integrated way, from all the data presented in the table. Nevertheless, it should be noted that higher values of the noise voltage amplitude are associated with less residual compressive stress. However, this statement can be analyzed, specifically for each of the modes, because from the simultaneous analysis of a class of heat-resistant steels, it turned out that combinations of different alloying elements, have a more significant effect on the internal stresses, than the combinations of the ion nitriding mode parameters [2].

The difference between the first and second mode (Table 4) lies in the recoil temperature, with the internal stresses being smaller at 7000 C, the amplitude of the stress

noise, larger, which is evidenced by the microstructure nitride ferrite. When comparing the third with the fourth mode, despite the same structure, nitride austenite and different recoil temperature, in the case larger residual stresses and smaller noise amplitude is associated with the larger diffusion zone. When comparing mode one with mode three, the lower amplitude of the mode one noise stress is due to the minor bonded zone, which is also reflected in the larger hardness.

TABLE 4 RESULTS OF THE MEASUREMENTS OF THE TECHNOLOGICAL MODES UNDER ANALYSIS

	Hv	Ub	Related zone μm	Diffusion zone μm	Structure
1	1131	10.5	1	120	γ'
2	998	17.9	0	110	α
3	1124	15.1	0	120	γ'
4	1225	12.9	1	220	γ'
5	1206	18.7	0	130	$\gamma' + \epsilon$
6	1108	13.6	7	210	γ'
7	1050	20.7	1	220	$\gamma' + \epsilon$
8	1097	12.8	9,5	230	γ'

The higher stiffness of the fifth mode (1206) is conditioned with a more stable microstructure, but the smaller thickness of the diffusion zone is the reason for the higher stress amplitude from noise. This is overcome in mode four, which is characterized by a larger diffusion zone, a smaller noise stress amplitude, and a correspondingly larger microhardness.

Everything in Table 4 can be generalized to the seventh and eighth modes, where despite the difference in the 7000C recoil temperature (in the seventh mode), the more stable structure is unable to lower the stress amplitude, which is also reflected in the lower microhardness. Mode seven compared to mode one, despite the smaller diffusion zone, the higher hardness determined in mode seven significantly affects the trend found for the stress amplitude from noise. The same, but to a lesser extent, can be verified by the eighth process mode, where the lower amplitude than the seventh mode corresponding to larger residual stresses is due to the larger widths of the coupled and total diffusion zone as well as the lower recoil temperature.

From this detailed systematic analysis of the complex interactions between different parameters affecting the properties of the nitrided layer, trends can be identified, which, however, are not able to express a precise correlation between all the quantities analysed. Nevertheless, this kind of analysis, besides describing the complexity of the problem, highlights a user-friendly method, the advantages of which focus on the benefits described above.

CONCLUSION

The analysis presents a holistic approach to understanding how different nitriding parameters affect the steel properties due to internal stresses, as accounted for by the Barkhausen magnetic noise (MBN) method, with predetermined results from classical test methods. This combines theoretical justification with practical applications to help the user. The above findings highlight the relationship between the conditions and the material processing, the determined characteristics, with contributions to knowledge in materials science and engineering. The conclusions that follow in this direction:

The high internal residual stresses obtained under certain nitriding conditions (temperature, ammonia pressure, time and temperature of treatment), in addition to the higher hardness, will be associated with a higher relative wear resistance for the BH11 steel, which is guaranteed by the presence of γ' -phase nitride associated with improved wear resistance due to reduced adhesive forces.

It is found for the investigated steel BH11, that less nitriding time and reduced ammonia pressure can increase the residual stresses, hardness and wear resistance. Conversely, longer processing time and higher chamber pressure also contribute positively on this effect.

The specific machining conditions of BH11 steel yield significant results: after quenching, subsequent tempering as remarkable microhardness, as reported, by the amplitude of the stress from noise occurs at lower tempering temperatures.

In this way, the characteristics of the stress signal provide information about the properties and condition of the material without damaging it.

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

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