Measurement of Residual Stresses in the Carburized Steels by Non-Destructive Techniques

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Abstract

Residual stress state on the surface layers has a critical effect on the service performance and fatigue life of the carburized components. Non-destructive determination of residual stress state in a rapid and reliable way has being gained importance for industrial applications. The aim of this study is to investigate the efficiency of the magnetic Barkhausen noise (MBN) method for monitoring the residual stress variations as a function of carburizing process parameters. For this purpose, MBN and XRD measurements were performed on a series of samples prepared by changing process parameters, and then, the results were compared and discussed.

Keywords: Carburizing, Residual stresses, Non-destructive measurement, magnetic Barkhausen noise

1. Introduction

Carburizing is one of commonly used surface treatment process which enhances hardness, wear resistance, and fatigue performance of the highly stressed machine parts such as shafts and gear wheels. This thermochemical treatment induces carbon diffusion into the surface of the low carbon steel. After saturation of carbon at the surface at elevated temperatures, quenching process is applied in order to create martensite phase in the superficial layers. Martensite formation improves the strength and induces compressive residual stresses [1,2]. Compressive residual stresses compensate the effects of external tensile stresses so the tendency to failure can be remarkably reduced.

Residual stress is defined as self-equilibrating stress, that is, local areas of tensile and compressive stresses sum to create zero force and moment resultants within the material. It is the result of the metallurgical and mechanical processing history of the component during its manufacture. Moreover, it also arises from the differences between neighboring regions or phases within the material. Three main causes of residual stresses exist: Non-uniform plastic deformation, material phase and/or density changes and surface modification.

The failure of an engineering structure or component is not only due to external loads, residual stress state should also be taken into account. Any manufacturing process introduces a state of residual stress which may result in either positive or negative effect. For instance, compressive residual stress at the surface improves fatigue performance while tensile residual stress at the surface will increase the tendency for stress corrosion cracking in a corrosive environment.

Different microstructures and residual stress states may be observed in carburized components even if they are having the same hardness profiles. Prediction of the microstructural transformation and the residual stress distribution is a quite challenging task.

Several methods have been developed to measure residual stresses. However, these are either destructive or of limited capability. Among various methods available to measure residual stress, only the X-Ray Diffraction (XRD) method has the appropriate spatial and volumetric resolution that adequately characterizes the residual stress distributions. However, it is relatively expensive and requires long measurement periods.

Industry has been requesting alternative ways to measure residual stresses accurately, quickly and easily without damaging the material. A less conventional approach, the magnetic Barkhausen noise (MBN) method, is of particular interest because of its potential as a non-destructive tool to measure residual stress in the industrial environment.

The MBN method depends on the abrupt motion of domain walls in magnetostrictive materials that is caused by changing in magnetization.

MBN is produced by discontinuous changes in the magnetic flux density related to the jump of domain walls between pinning sites [3]. A sensor coil can monitor these small changes in the plane of the component surface.

It is known that residual stress affects the total domain wall area while microstructure affects the pinning sites for domain walls [4]. Tensile residual stress enhances the area of 180^o domain walls which causes an increase in the MBN emission [5].

It has been reported that the maximum value of the compressive residual stress increases and its position shifts toward the sub-surface zone with increasing case hardening depth [6].

XRD measurements in the carburized 21NiCrMo2 steel showed the presence of the compressive residual stresses on the surface up to 550 MPa [7].

There are limited numbers of publications about the characterization of carburized steels by MBN technique. The influence of elastic tensile and compressive stresses of various magnitudes on the MBN signals was verified by XRD technique, and the peak amplitude of MBN emissions was found to correlate with both residual and applied stress, showing a clear rising trend for the transition from compressive to tensile stress [8]. Both high and low-frequency MBN measurements in the carburized steels were correlated to the residual stress depth profiles measured using XRD method: the high-frequency MBN emission indicated the changes in the surface residual stress, but not deeper than 10 μm [9]. Case-hardened 17CrNiMo7-6 steels were investigated to establish a multi-parameter MBN method for determining residual stress, and the results indicated that the response of the material was mainly consistent with the MBN emission, but some unequal correlations were found [10]. In another study, the RMS value of the MBN voltage and coercive force showed the best correlation with residual stress variations in the quenched steels [11].

The aim of this study is the nondestructive monitoring the variation of surface residual stresses in the steel samples produced by applying different carburizing parameters. The results of the MBN measurements on the carburized 19CrNiH5 samples were compared with those of the XRD measurements.

2. Experimental Procedure

The samples (100mmx45mmx10mm) were prepared from the 19CrNi5H steel rods (Table 1) by machining and grinding. Four sample sets were prepared by applying different carburizing-tempering procedures in Türk Traktör Company.

Table 1. Chemical composition of 19CrNi5H steel (wt%)

C	*Si*	*Mn*	*P*	*S*
0.18	0.26	0.95	0.014	0.026
Cr	*Ni*	*Mo*	*Al*	*V*
1.01	0.94	0.05	0.031	0.009

After holding the samples at 180°C, the carburizing process was applied by using the mixture of $C_3H_{8(g)}$ and the shielding gas (33% H_2, 28% CO, 0,8% CH_4). The samples were held under the atmosphere containing 1.1% C, and then, carburizing process was continued with the atmosphere containing 0.8% C, not to exceed the surface carbon concentration of 0.9% C. After cooling down to the shell oxidation temperature of 880°C, the samples were quenched in oil. One of the specimens was kept without carburizing, as the reference sample. The next operation was tempering which was applied to observe the variation of residual stresses. Tempering treatments were applied at 180°C, 240°C and 600°C for 3 hours, while one set was left in the as-quenched condition. At the end, the samples were sand blasted.

In XRD measurements by Stresstech Xstress 3000 G2/G2R, Cr-Kα radiation was employed by focusing on the ferrite {211} planes at 2Θ≈156°. The average penetration depth was 4.7 μm [12]. Equally spaced five points were chosen for the measurements. Totally 10 tilt angles from -40° to +40° were evaluated. Using $\sin^2\Psi$ technique, residual stress values were calculated.

The MBN measurement parameters were optimized by altering the voltage from 2 to 16 volts and the frequencies from 0 to 1000 Hz. Reliability, sensitivity, validity of MBN signal with respect the residual stress levels obtained by XRD measurements were considered for choosing the optimum MBN measurement parameters [10].

Microstructure examination was performed on the samples that were ground, polished and etched with 2% Nital solution. The RD-ND (rolling direction–normal direction) planes of the samples were examined via an optical microscope under bright field illumination. The Vickers hardness measurements were performed by Shimadzu HMV-2T using 200 g load, and the readings were taken from the surface zone of each specimen.

3. Results and Discussion

3.1. Residual Stresses

XRD measurements revealed that compressive residual stresses exist at the surface, and their magnitude decreases with increasing tempering temperature (Figure 1).

Carburized specimens are almost always tempered to obtain tempered martensite with improved ductility and toughness, to minimize the amount of the retained austenite and distortion.

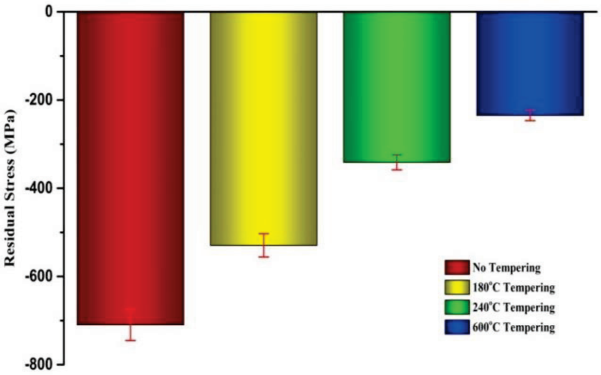


Figure 1. Effect of tempering on the surface residual stress of the carburized samples (XRD measurements)

During cooling, thermal and phase transformation induced internal stresses may cause local, non-uniform plastic deformation. Upon cooling, first the sub-surface region consisting of austenite with lower carbon content, i.e., with higher M_s temperature, starts to transform into martensite. Formation of martensite causes an increase in volume while untransformed regions restrain this expansion. When the temperature compensation between the core and the surface is completed the compressive residual stresses exist at the surface, and they are balanced by the tensile residual stresses in the core.

MBN measurements indicated that RMS values of the samples increase with increasing tempering temperature since the magnitude of the compressive residual stress decreases (Figure 2). In the as-quenched specimen, the high dislocation density in the martensite needles acts as a barrier to the movement of the domain walls. A stronger magnetic field is required for reversal of magnetization due to reduced domain wall mobility and difficulties in domain wall nucleation. Upon tempering, the crystal structure of the martensite losses its tetragonality and dislocation density decreases; thus, domain wall motion may take place at lower magnetic field strength. All these factors count for easy domain wall movement, hence, the amplitude of the MBN increases.

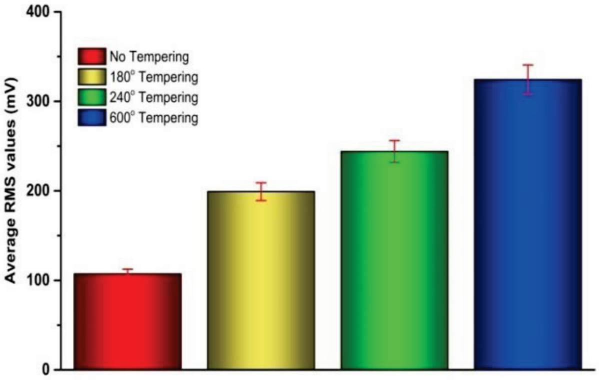


Figure 2. MBN root mean square values of the carburized and tempered samples

When root mean square values of MBN measurement was compared with the residual stress state, it can be deduced that MBN measurement was reliable for residual stress determination (Fig. 3). This correlation shows that residual stress values can be determined by Magnetic Barkhausen Noise method. Compared to XRD stress measurement, MBN measurement technique is faster for determining the stress values almost as accurate as XRD technique.

It should be noted that when the carburizing conditions and/or steel type changes another correlation has to be found. Moreover, the MBN-RMS values depend on both hardness and residual stress levels. Since, increasing tempering temperature effects the RMS values and the residual stress levels in the same direction, the correlation is excellent.

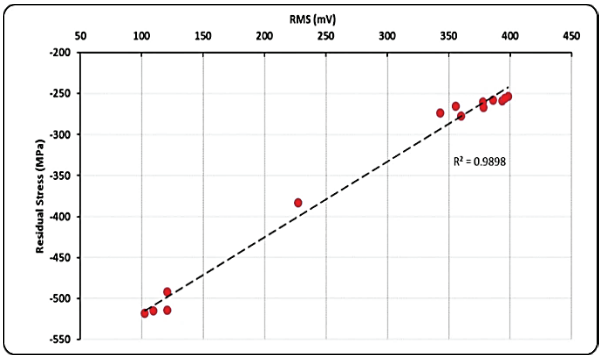
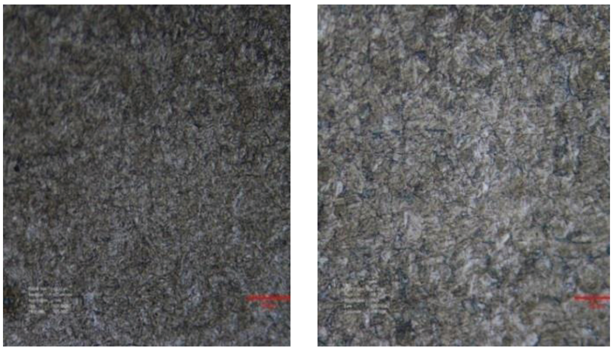


Figure 3. Correlation between residual stress and MBN-RMS

3.2. Hardness and Microstructural Analysis

Hardness measurements showed that hardness values increase remarkably from the core to the carburized surface regions. On the surface layer of the as-quenched sample, the hardness value is about 70 HRC. When tempering temperature increases to 600°C, surface layer softens down to 45 HRC.

Microstructure of the case region consists of needle-like martensite, while the core region has martensite and Widmanstätten ferrite that started to grow at the prior austenite grain boundaries. Ferrite and/or pearlite phases were not observed in the core since there is only slight difference between the cooling rates of the case and the core due to low wall thickness of the samples.



a) Carburized sample (Case)

b) Carburized sample (Core)

Figure 4. Representative micrographs of the samples

4. Conclusion

Various sample sets were prepared from 19CrNi5H steel by carburizing at 900°C for 8 hours, followed by tempering at different temperatures (180°C, 240°C, 600°C). The effectiveness of the Magnetic Barkhausen Noise (MBN) method for non-destructive monitoring of residual stress variations in the carburized samples was investigated by comparing the MBN results with those of XRD method. XRD measurements revealed that compressive residual stresses exist on the surface of the carburized sample, and their magnitude decreases with increasing tempering temperature. The results of the MBN measurements give the similar tendency. Domain wall pinning effect of high dislocation density and needle-like martensite lower the MBN activity. After tempering, the magnitude of residual stress decreases; nucleation and movement of the domains in the microstructure become easier. The RMS value of MBN emission increases with increasing tempering temperature.

Measurement by the MBN technique is much faster than the XRD technique while both techniques give similar tendency for residual stress variations. MBN technique is a strong candidate for nondestructive qualitative monitoring of residual stress variations. With an appropriate pre-calibration procedure considering also the effect of microstructure, MBN technique may give reliable quantitative results for the residual stresses.

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