AN APPLICATION OF BARKHAUSEN MAGNETIC NOISE IN THE CHARACTERIZATION OF FRICTION STIR WELDS

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Abstract. Friction stir welding (FSW) is an alternative process of joining materials, characterized by high deformation forces and lower peaks of temperature when compared to fusion welding. The FSW produces a variety of microstructures due to a different amount of deformation and cooling rates during welding, producing a complex profile of residual stress. In this study, the main goal was to use the Magnetic Barkhausen Noise (MBN) technique, a non-destructive and qualitative method, to evaluate residual stress, hardness, and microstructure along the FSWelded joint region. The material used was a 9.5 mm thick X80 steel plate, welded using a 300 rev min^{-1} spindle speed and 100 mm min-1 welding speed with a polycrystalline cubic boron nitride with tungsten-rhenium (PCBN-WRe) tool. The results show a good correlation with profiles of residual stress and hardness reported in the literature for this type of joints, as well as the differentiation of the microstructures through the different evaluated regions.

Keywords: Friction stir welding; non-destructive testing; residual stresses; magnetic Barkhausen noise.

1. INTRODUCTION

The residual stress (RS) is typical in manufacturing processes (Hauk, 1997), which can affect the mechanical properties and may modify the geometry of produced parts (Hensel et al., 2017). RS plays a fundamental role in the mechanical behavior of welded parts subjected to cyclic loads and corrosive environments. Therefore, the existence of RS can be beneficial or deleterious for the safety of welded structures. Fusion-welded joints show a peak of tensile stress in the center of the joint, and decreasing stress towards the base metal, sometimes shown with an "M" shape profile (Alipooramirabad et al., 2017).

The Magnetic Barkhausen Noise (MBN) technique is a non-destructive method, which can be applied after performing the welding, serving only for ferromagnetic samples, such as the steels used in the manufacture of pipes for the transport of oil and gas. This technique has been under development for two decades and can be applied in several engineering areas (Augustyniak et al., 2015), e.g., measurement of grain size (Pal'a and Bydžovský, 2013), carbon content (Saquet et al., 1999), residual stresses (Kolařík et al., 2016), hardness (Franco et al., 2013) and plastic deformation (Perez-Benitez et al., 2008). This technique is based on the principle of detecting the "noise" generated by the movement of magnetic domains in response of the magnetization of ferromagnetic materials by a variable electric field using a coil (Jiles, 2000).

In the present study, MBN measurements were performed on the surface of a FSW joint on an X80 steel, in order to perform rapid assessments of RS, hardness, and identification of the microstructures. Previous studies were used to correlate the types of the microstructure (Avila et al., 2016a, 2016b), hardness (Avila et al., 2016a, 2016b) and RS (Sowards et al., 2015) present in each region of the welded joint.

2. EXPERIMENT

2.1. Samples

The material used was a 9.5 mm thick X80 steel plate with a chemical composition of 0.04 C, 0.32 Si, 1.56 Mn, 0.06 Cr (wt.%). The one-pass FSW joint was performed with a spindle speed of 300 rev min^{-1} and welding speed of 100 mm·min^{-1}, with a PCBN-WRe tool. Welding parameters were defined in previous studies (Avila et al., 2016b, 2016a).

Figure 1 shows part of the weld joint, with 190 mm wide and 300 mm long. There inside is an analysis area of 100 x 100 mm², where MBN measurement took place. Figure 1 also shows the MBN probe used to carry out the measurements.

2.2. MBN Measurements

For the measurement of MBN, an equipment developed at the Mechanical Engineering Department at UNICAMP was used and the measurement scheme system is shown in Fig. 1b. A sinusoidal current with 20 Hz and 0.8 A was applied in the probe to the produce the magnetic excitation coil. The MBN signal was measured with a high sensitivity coil (3000 turns of 44 AWG), amplified (30 dB), filtered (1-150 kHz) and sampled at 300 kHz. Each measured signal is composed of MBN signals (4 bursts) generated in two magnetization cycles. Three parameters were calculated and analyzed from the measured signals; rms value (MBNrms), number of events, and peak signal envelope position (MBN peak-position). A smoothing of the MBN signal shape was performed by using the moving average method to obtain the envelope. A step of 2.5 mm on the horizontal and vertical direction was set, thus totaling 1600 measurement points in the 100 x 100 mm² area. The applied field was parallel to the weld direction, and each measurement condition was repeated 10 times.
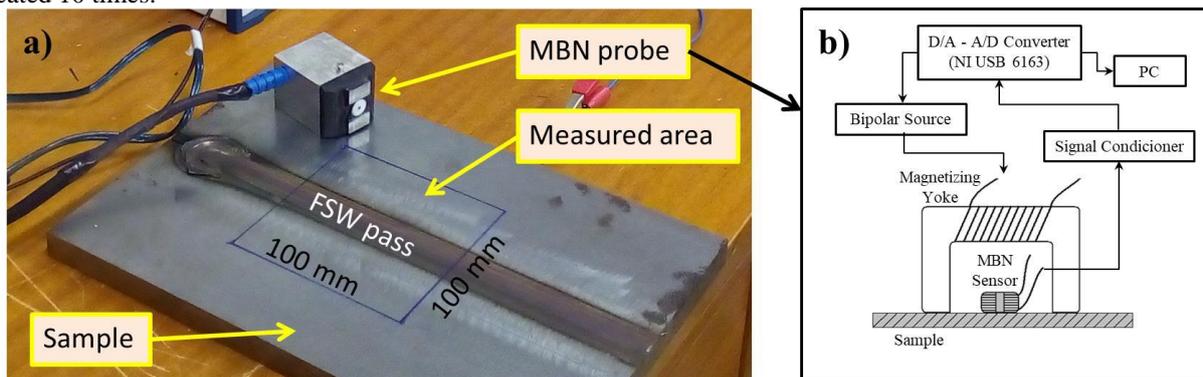

Figure 1. a) API 5L X80 steel plate FSWelded, sample region measured with MBN technique, 100 x 100 mm², and MBN probe; b) scheme of the MBN measurement system.

3. RESULTS AND DISCUSSION

The calculated parameters of the MBN signals are of qualitative analysis. A calibration procedure with experimental results of RS, hardness and microstructural results will be needed to obtain MBN quantitative values. In this work, the behavior of three calculated parameters of the MBN signal is presented and compared with the results of RS, hardness, and microstructure found in the literature.

Figure 2 shows the behavior of the MBNrms parameter obtained through the measured area, as indicated in Fig. 1a. The MBNrms value is the most sensitive parameter to the residual stresses variations generated in the material. The MBNrms parameter is directly proportional to the stress, increasing with tensile stresses and decreasing with compressive stresses. Tensile stresses align the magnetic domains in the stress direction. Thus, when the magnetic field is applied in that direction, a high amount of 180° domain walls is previously aligned in the magnetic field direction, and therefore the generated MBN signal increases. The compression stress aligns the domains perpendicular to the applied stress, generating a decreasing effect on the MBN signal. The distribution of amplitudes observed in Fig. 2 indicates the variation of MBNrms signal according to the microstructure. The analyzed area covers the base material, the region of the weld bead (stir zone - SZ), which has a lower RS and a change in the specific area of high hardness by the formation of a bainitic lath-type microstructure, the hard zone (HZ). The HZ bainite presents a regular and straight lath morphology, while the rest of SZ presents an irregular lath morphology (Avila et al., 2016a). The region of transition, the heat affected zone (HAZ), has a higher RS compared to the other regions. Similar results, with an "M" shaped profile, when performing RS measurements on FSWelded joints using neutron diffraction technique were reported by (Sowards et al., 2015). Tensile stresses were observed in most part of the welded joint, with smaller values

in the SZ and a voltage peak along the transition region between SZ and HAZ. Due to the shoulder size of the FSW tool of 20 mm, the stir zone is equivalent to this same value, likewise, its thermal affectation created a large HAZ.
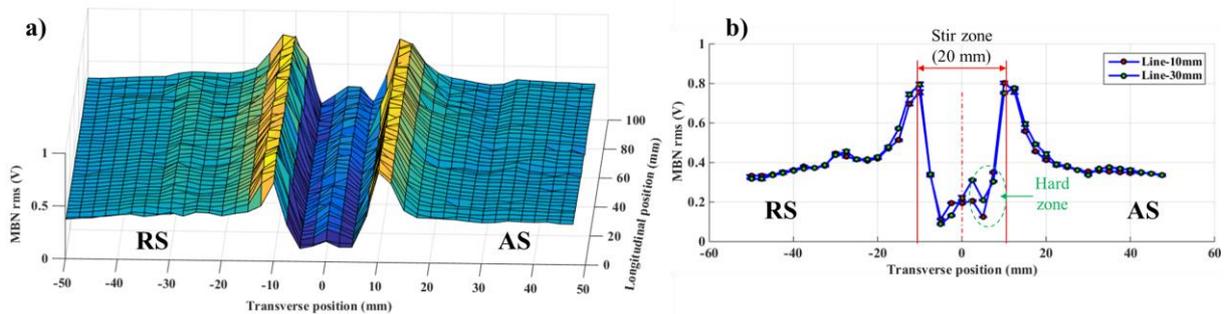

Figure 2. Magnetic measurement by MBN showing the MBNrms parameter behavior on the FSWelded sample´s surface, a) 3D profile and b) 2D view of the longitudinal direction. RS: retreating side; AS: advancing side.

Materials with high hardness, which have a high density of microstructural defects, have a high Hc (coercive field) value and the movement of the magnetic domain walls is performed with difficulty which generates a low amplitude in the MBN signals (low MBNrms). To perform the inversion of the magnetic flux within the material in this condition it is necessary to apply external magnetic fields of relatively high amplitude, thus generating higher Hc values. In addition, and because the MBN burst emission is close to the Hc position, the MBN peak position parameter will also have relatively high values. In this way, the peak position of the MBN burst profile and the parameter Hc obtained in the magnetic hysteresis curve, vary directly proportional to the hardness of the material ((Franco et al., 2013; Moorthy et al., 2003)).

Figure 3 shows the behavior of the MBN peak-position parameter. The amplitude distribution indicates that the hardness of the SZ region is higher than the base material and that HAZ presents the lowest hardness among the microstructure. This behavior is characteristic of FSW joints in steels, as reported in previous studies (Avila et al., 2016a, 2016b; Liu et al., 2018; Sowards et al., 2015).
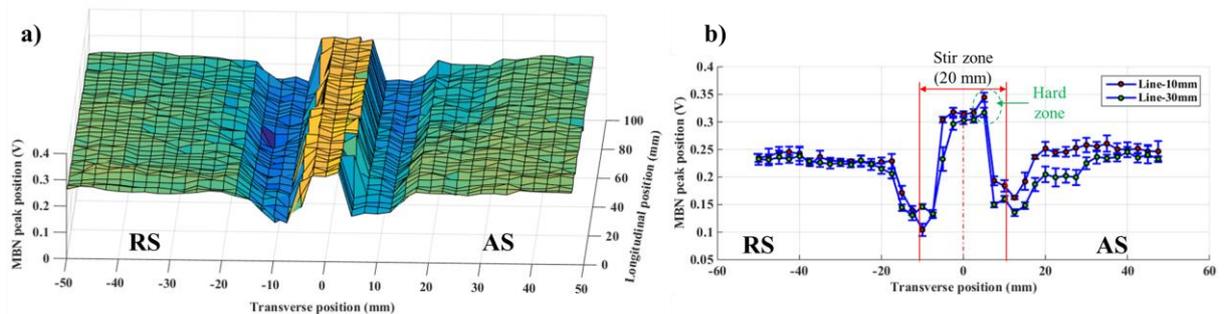

Figure 3. Magnetic measurement by MBN showing the peak-position parameter behavior on the FSWelded sample´s surface, a) 3D profile and b) 2D view of the longitudinal direction. RS: retreating side; AS: advancing side

The number of MBN events allowed to observe and correlate the variation of the microstructure type and the grain size observed. Figure 4a depicts a peak of intensity at the center line of the FSW joint, with a gradual decrease towards HAZ, with a subsequent increase towards the base metal. A variation of the number of events along the plate length is obtained due to different regions and microstructures of the steel. The base metal is characterized by a microstructure of fine grains (about 5 μm) of elongated ferrite and bainite (Avila et al., 2016a). At SZ, bainite packets' size is around 20 μm (Avila et al., 2016a), irregular and acicular laths were observed within these packets. The HAZ presents a microstructure similar to that of the base metal, but with lower hardness.
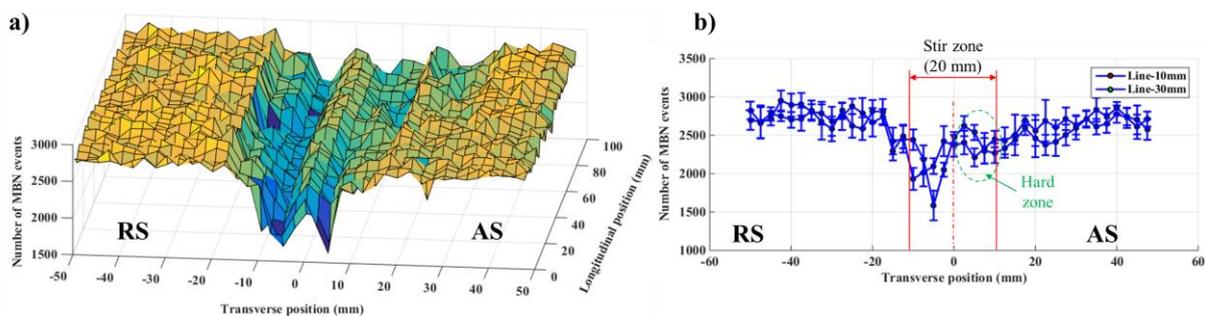
Figure 4. Magnetic measurement by MBN showing the number of events parameter behavior on FSWelded sample´s surface, a) 3D profile and b) 2D view of the longitudinal direction. RS: retreating side; AS: advancing side

4. CONCLUSIONS

- Measurements made by MBN allowed performing qualitative correlations of three characteristics of the steel plate: 1-residual stresses, correlated to MBNrms parameter; 2-hardness, correlated to MBN peak-position parameter; and 3-grain size, correlated to the number of MBN events.
- There is no need for surface preparation for MBN measurements for a regular and smooth surface, such as those produced by FSW.
- The MBN technique is a useful method for a rapid and qualitative method to assess components with microstructural, hardness and RS variation, such FSWelded joints in API steels, with good correlation to the experimental results reported in other studies.

5. ACKNOWLEDGMENTS

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