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Barkhausen noise analysis of friction stir processed steel plate

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This work investigates the variation in material properties of steel upon friction stir processing through its magnetic response. The steel plate of grade IS 2062 having a thickness of 3 mm have been friction stir processed (FSPed) using a tool of tungsten carbide with a 15 mm shoulder diameter along with 3 mm pin diameter with traverse of 150 mm/minute and a 800 RPM revolving speed. Magnetic response of these processed plate and base metal has been recorded using Barkhausen noise (BN) analyzer in terms of BN signal parameters *i.e.* the rms value and pulse count or number of pulses. Barkhausen noise analysis results have been validated with micro-hardness testing and metallographic study of as received metal and the processed samples. Higher microhardness has been found in processed sample in comparison to the as received metal due to grain refinement owing to the combined effect of plastic flow of material during stirring action of the rotating tool and the frictional heat. Barkhausen noise analysis has been performed in a wide range of magnetic field intensity (MFI) and excitation frequencies to study their effect on variation in rms value and the number of pulses.

Keywords: Friction stir processing, Steel, Barkhausen noise, Magnetizing frequency, Magnetic field intensity, Grain refinement

1 Introduction

The Welding Institute (TWI) in 1991, designed and developed friction stir welding machine (FSW)[1]. FSW has emerged as a very promising process for low temperature melting material like copper[2], aluminium[3], magnesium[4] and their alloys. But, FSW of steel is still a challenging task[5]. Friction stir processing (FSP) comes under solid state process which is similar in working principle as FSW[6]. The FSP method consists of a tool having shoulder & a specially manufactured pin which penetrates into the work material to be processed and moves the rotating tool to move in specified direction. The pin of the tool and shoulder has very important role in FSP. Shoulder and pin generates the friction heat to plasticize the material then pin of the tool stir the plasticized material. The length of thetool-pin[7] has to keep a little shorter than the thickness of the plate to avoid the damaged of the pin and provide the appropriate contact between tool shoulder and work-piece surface after insertion of the pin into the plate. Frictional heat generated due to plasticization of the work-piece material by the rotating plunged pin, this frictional heat transferred into work material[8].The mechanical action of the rotating pin and the frictional heat result in grain refinement[9] which leads to improved hardness[10].

In the presence of varying magnetic field, magnetic domain of ferromagnetic material moves for aligning themselves along the external magnetic field. These domain movement gets hindered due to the presence of imperfections like grain boundaries, dislocations or inclusions. If enough magnetic field is available then the domains overcome these imperfections and generates a voltage pulse, known as the Barkhausen noise (BN) signal. Barkhausen noise signal gets affected by grain size, hardness, microstructure and residual stress hence it can be applicable for material characterization. BN signal is used for non-destructive characterization of ferromagnetic material as this technique offers many advantages such as rapid process, portable, low cost, short testing time for material characterization, whereas optical metallographic analysis, micro-hardness testing, X-ray diffraction and other laboratory based techniques are time consuming.

Barkhausen noise is sensitive to hardness, phase and microstructural variation and residual and applied stress as these material properties affects the domain configuration. Tavares *et al.*[11] correlate the embrittlement of super martensitic stainless steel through the influence in BN signals. Neslušan *et al.*[12] evaluated the surface damage of railway wheel on the basis of plastic deformation with the help of Barkhausen noise emission. Vashista *et al.*[13-16]

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*Corresponding author (E-mail: mvashista.mec@iitbhu.ac.in) effectively used the BN technique on ground steel surface to assess the of residual stress. They used the high speed super-abrasive grinding process with moderate depth of cut[17] and super-abrasive grinding domain[18]. As the processed material exhibit the poor magnetic response[19], hence BN signals needs to processed using MATLAB programming for better understanding. Singh *et al.*[20] also characterized the carbon steel plates with the help of Barkhausen noise analysis. Zhu *et al.*[21] attempted the microstructure characterization of boron steel using Barkhausen noise detection. Manh *et al.*[22-23] proposed a modal to correlate the magneto crystalline energy (MCE) to Barkhausen noise signal by considering the crystallographic texture as a parameter. Vourna *et al.*[24] evaluate the residual stress of gas tungsten arc welded steel plates from Barkhausen noise analysis and justified their results with the X-ray diffraction technique.

In the nutshell of comprehensive literature review reflects that previous researchers attempted to process the steel plates through friction stir process, even few of them used other non-destructive method to characterize the processed steel plates, but none of them used the BN methods to characterized the processed steel plate. Hence, the current experimental work has been performed to characterize IS2062 steel upon friction stir processing using Barkhausen noise technique to fill that literature gap. Further, magnetic response of the as received as well as processed metal was analyzed in a larger domain of exciting frequencies and magnetic field intensity.

2 Experiment Details

Friction stir processing was performed on steel plates of 3 mm thicker using a 3 tonne friction stir welding machine (Fig. 1). Table 1 represents chemical percentage of the as received mild steel. To sustain the generated heat during FSP, commercial available tungsten carbide was opted as a tool material. Processing was preformed up to the 180 mm of length with 15 mm in width as the tool has a 15 mm shoulder diameter and a 3 mm pin diameter (Fig. 2).

Processing was performed under the shoulder area at150 mm/minute traverse speed, 800 RPM revolving speed of tool and at tool tilt angle of 1.5°. Figure 3 (a, b) depicts surface modification of the samples upon friction stir processing. Samples from base metal and processed metal were cut for microhardness measurement & metallographic analysis and were prepared as per standard procedures. Microhardness measurement was performed at 300 gm load and 10 s dwell time.

As received metal and friction stir processed sample were characterized by a Magstar MBN analyzer, designed and fabricated by NML, Jamshedpur and Techno four Pune. External varying magnetic field was applied through pole of the magnetizing probe to receive magnetic response from ferromagnetic material inform of BN signal (refer Fig. 4). External magnetic field may be applied in sinusoidal or triangular waveform. In the present study a sinusoidal wave form was opted to applying different external magnetic field between 200 Oe to 1000 Oe between the magnetizing frequency range

Fig. 1 — Friction stir welding machine (3 tonne capacity).

Table 1 — Elemental composition of base metal.

C%	Mn%	Si%	S%	P%	Mo%	Cr%	Al%	Ni%	Cu%	Co%	V%	Nb%	Pb%	Fe%
0.1650	0.3700	0.0470	0.0110	0.0070	0.0260	0.1080	0.0420	0.0260	0.0170	0.0360	0.0090	0.0040	0.0020	99.1580

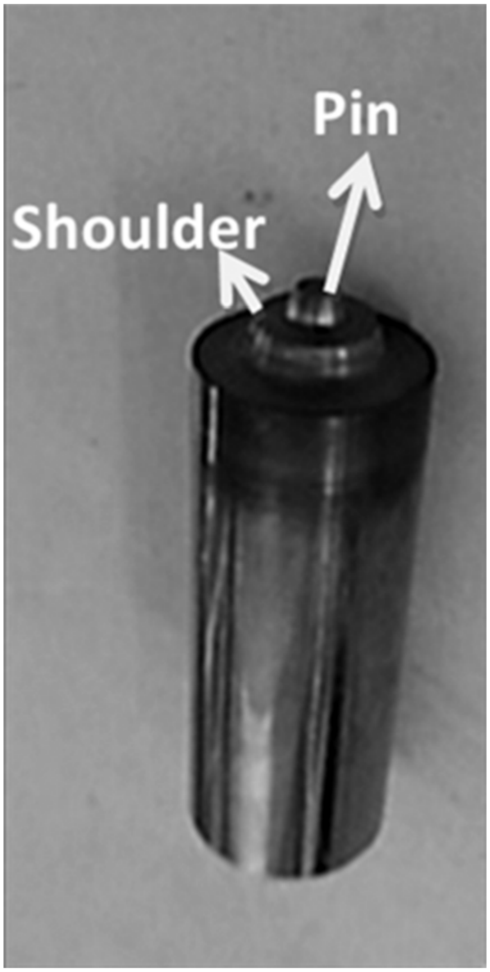

Fig. 2—Tungsten carbide tool used for FSP.

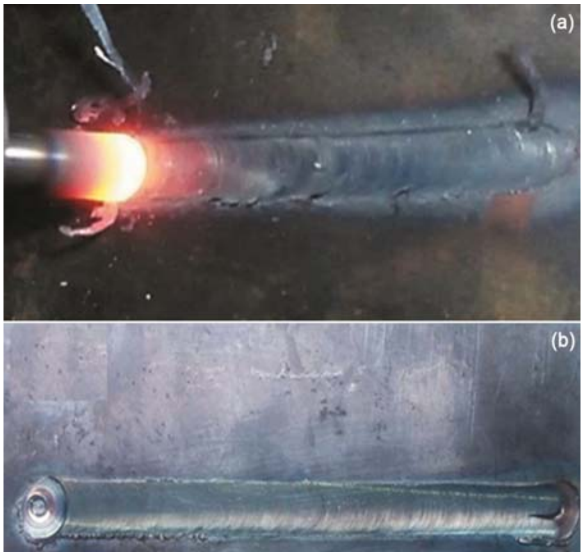

Fig. 3 — Friction stir processing of (a) Steel sample and (b) FSPed sample.

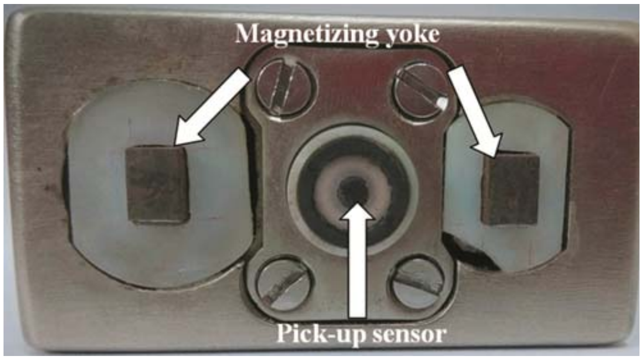

Fig. 4 — Magnetizing yoke of BN analyzer.

(10 Hz to 50 Hz). Figure 5 shows the BN burst and the applied magnetic field as the screen shot. In presence of magnetization, avalanches of domain wall at very high frequency is captured in the form of BN signal.

Barkhausen noise signals get hindered due to the waviness and roughness of work surface as pickup coil needs almost flat surface for capturing BN signals. Hence, friction stir processed surface needs to be smooth before performing the BN characterization. Central portion of the processed plate were smoothen for performing BN measurements. Every jump of domain wall generates voltage pulse in form of spikes and complete BN burst consists of all those pulses occurred during magnetization process owing to domain wall motion for aligning them along the direction of magnetic field.

3 Results

Optical microscope was used for metallographic analysis to observe micro-structural changes upon friction stir processing. Figures 6 & 7 depicts the micro-structural changes upon friction stir processing. The change in micro-hardness of the base metal upon friction stir processing is represented in Fig. 8.

Many electric pulses in the form of spikes generates the Barkhausen noise signature (burst) as shown in Fig. 5. The jump of domain wall while crossing hurdles creates a voltage pulse. Figure 9 represents the effect of frequency on number of pulses. Figure 9 depicts that the pulse count gets reduced with the increase in the magnetizing frequency for both samples and pulse count was more in the base metal than in the friction stir processed sample.

Applied external magnetic field supplies the energy to magnetic domain walls for motion to achieve the saturation condition for stability. The generation of

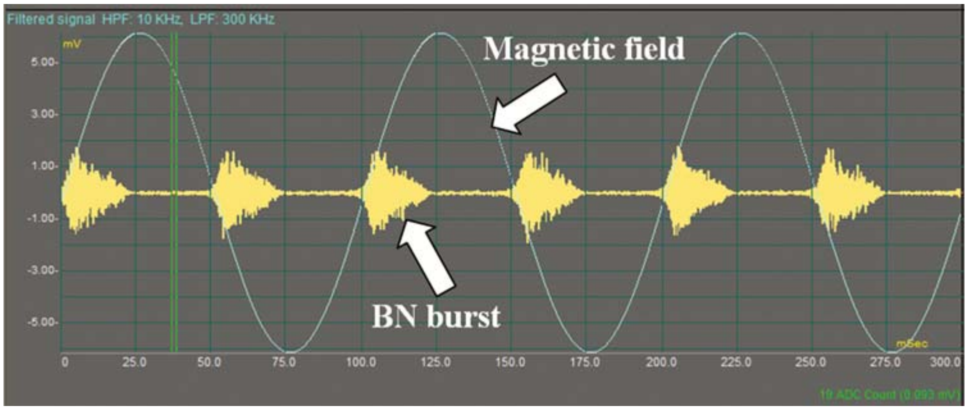

Fig. 5 — Raw Barkhausen noise signal with applied field.

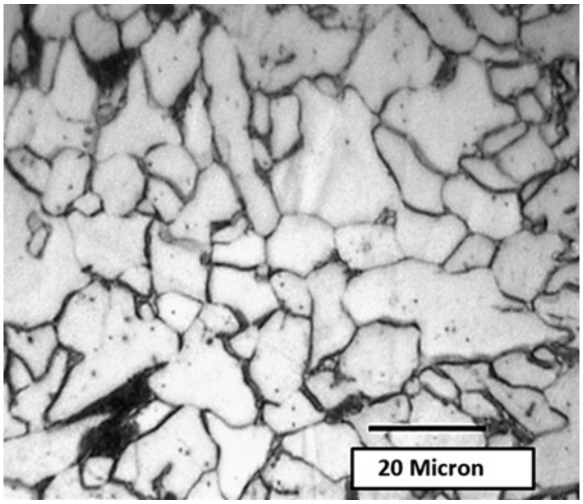

Fig. 6 — Microstructure of the as received sample.

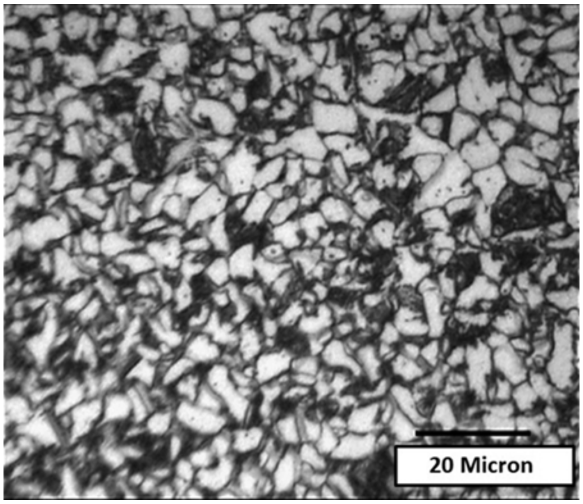

Fig. 7 — Microstructure of the friction stir processed region.

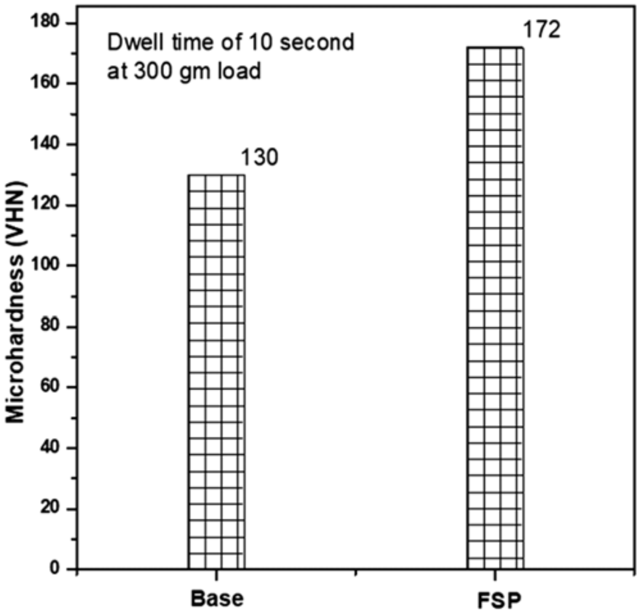

Fig. 8 — Microhardness of as received material and the FSP samples.

voltage pulses depends on the MFI. Figure 10 represents variation in pulse count with MFI. The response of base material was more towards magnetic field intensity in comparison to friction stir processed sample as well in both the samples increase in magnetic field intensity increases pulse count.

Barkhausen noise burst/signature is typically enveloped by a curve for analysis purpose. This curve is known as Barkhausen noise signal profile and characterized by amplitude or peak, peak position, FWHM and rms value. The rms value is important and popular characteristics for analysis of Barkhausen noise signal. Figure 11 depicts increase in rms value of BN signal profile with MFI. As received metal responded in a better way (due to allowing the more penetration of magnetic field into the material) as compared to FSP sample since rms value obtained from the base metal was more in the whole range of excitation frequency.

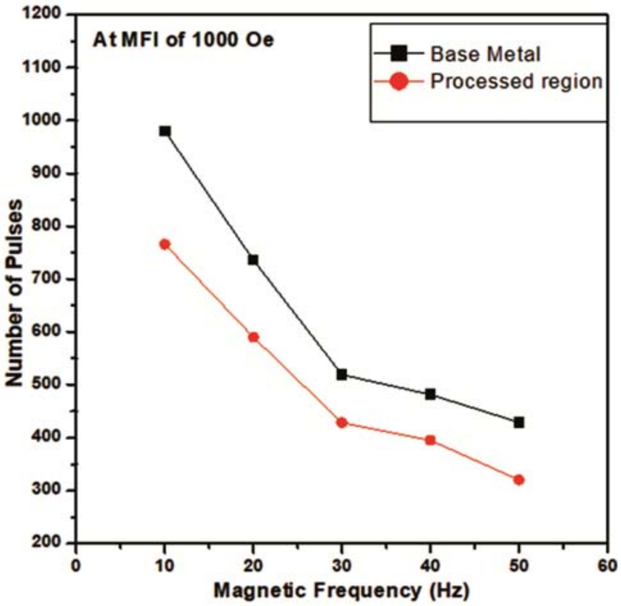

Fig. 9—Variation in the pulse count for both samples.

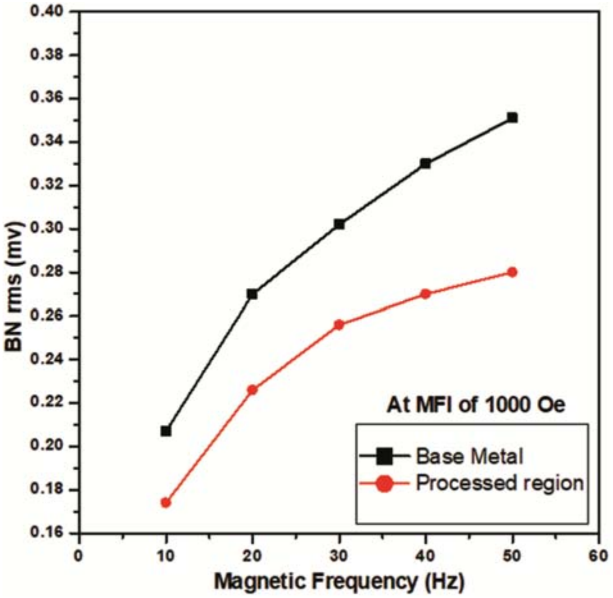

Fig. 11 — Variation in the rms value with the excitation frequency in the base metal and the FSP samples.

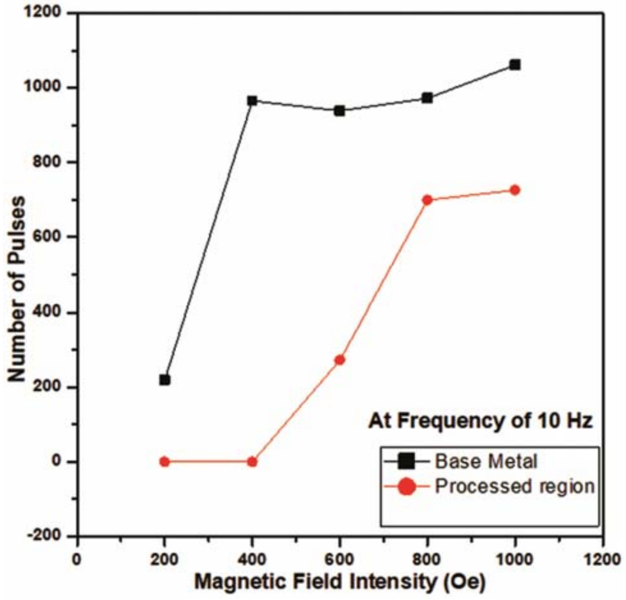

Fig. 10 — Effect of MFI on pulse count.

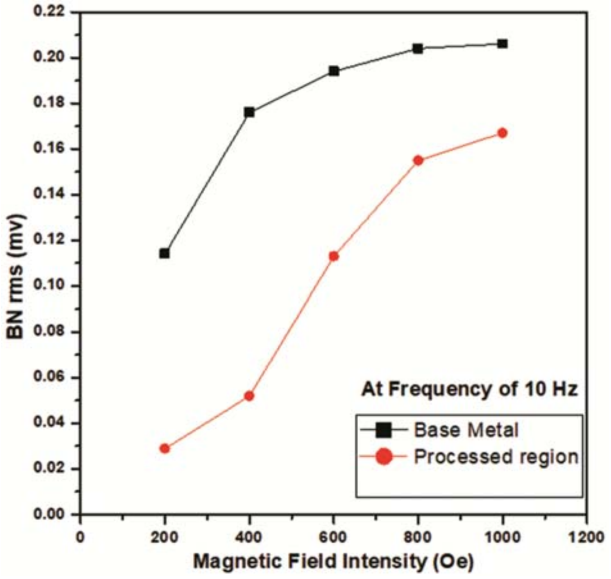

Fig. 12 — Effect of MFI on BN signal (rms value).

In the present study, MFI was varied from 200 Oe to 1000 Oe. Figure 12 depicts the change in rms value of BN signal with MFI.

4 Discussion

Metallographic study & micro-hardness measurement of base material and friction stir processed sample depicts friction stir processing induced changes in microstructure and micro-hardness. It is clearly shown that friction stir processing leads to the grain refinement in the processed region. Frictional heat along with applied load plasticizes the material, further tool pin stirs the plasticize material and causes grain refinements. Raja *et al.*[25,26] also reported the grain refinement upon friction stir processing. The microstructure of the FSP sample clearly indicates approximately 7 times smaller grain in the processed zone &leads to more hardness than base metal hardness as shown in Fig. 8.

Grain boundaries act as hurdle for the motion of magnetic domains upon application of magnetic field. Grain refinement in the friction stir processed region generated more grain boundaries that reduced the domain wall activities and leads to poor response of FSPed sample as compare to base metal.

Grain boundaries behave as hurdle for movements of magnetic domains, as FSPed sample consists of finer grain i.e. more number of grain boundaries, hence shows the poor magnetic response in terms of lower rms value of BN signal. Higher micro-hardness value of processed region also indicates grain refinement upon friction stir processing.

Barkhausen noise analysis gets influenced by excitation frequency (magnetizing frequency) and field intensity. Penetration of magnetic field into work sample depends upon excitation frequency and it decreases with increase in excitation frequency. Higher excitation frequency provides lesser time of the magnetic field to penetrate into the material and reduced the coverage area of penetrating magnetic field. Therefore, less number of magnetic domains wall get involved in the movement. As the number of voltage pulse indicates the activities of magnetic domains inside the material, thus less number of voltage pulses generates due to lesser number of active (participating) magnetic domains. Further, in the processed zone, more pinning site is formed that provides the more resistance for the movement of domain wall. More number of grain boundaries are responsible for this resistance in motion of domain wall. Thus, the pulse count obtained from FSPed samples is lower in comparison to base metal (Fig. 9).

The applied magnetic field supplies the magnetization energy to magnetic domain for their motion to the stability condition by aligning them in direction of magnetic field. Higher MFI provides the higher energy input to the magnetic that causes domain wall movement with higher acceleration. As mentioned previously, grain boundaries act as obstacles and resists the movement of magnetic domains and whenever magnetic domain moves over hurdle it generates electric pulse in form of voltage signal. Higher MFI enables more energized magnetic domains to move over the large number of grain boundaries, that generates more number of pulses. This may be attributed to increase in number of voltage pulses with MFI (Fig. 10). In this experimental work, variation in magnetic field intensity was in wide range i.e. 200 Oe - 1000 Oe to observe the effect of low MFI and high MFI on the activity of magnetic domains.

In the work sample, the number of voltage pulses rises (200 to around 1000) with the increase in MFI (200 Oe to 400 Oe). It is very interesting to observe the zero pulse reading from the processed zone when applied MFI raised from 200 Oe to 400 Oe. Generally, a minimum field strength is required to cause movement of the domains and enables them to cross the hurdles. The grain refinement in the FSP region imposed more resistance to the movement of magnetic domain wall due to increase in number of grain boundaries. In FSP sample, boundaries of finer grains impose more resistance to the domain motion and applied magnetic field does not provide the sufficient energy in between 200 Oe to 400 Oe to enable them for movement and crossing hurdles. Whereas, when MFI increases from 400 Oe, it starts to generate the pulses from the processed regions. This increased magnetic field provides more energy for the movement of domain walls to jump over the hurdles. Increase in magnetic field leads to generation of more number of pulses as increased field energized the more domains to participate in the motion.

Barkhausen noise burst is a combination of voltage pulses generated in form of spikes during the change in global magnetization process of material under the influence of magnetic field. Generally BN burst is enveloped by BN signal profile. Barkhausen noise signal profile is mainly characterized by root mean square value (rms value) of burst signals. A higher peak amplitude of the envelop represent larger rms value. Increase in excitation frequency increases the number of BN signals if the MFI is sufficient for motion of magnetic domains. Increase in excitation frequency reduces the exposed area of the signals to penetrate into the materials. A sufficient amount of MFI is required to be distributed among the more number of magnetic domains at low magnetic frequency. This reduces the participation of the domain wall for the motion. At low frequency, domain wall have not the sufficient energy to excite them all to cross the hurdles. Hence supply of less amount of energy generates less number of BN signals. In contrast to this, at higher excitation frequency the applied amount of magnetic field strength need to distributed among lesser number of magnetic domains, which provides the more active and sufficient energized favorably oriented domains for motion and generate the higher BN signal. In this experimental work, rms value of BN signal increase by increase in the excitation frequency at 1000 Oe of

MFI as observed in Figure 11.This increase in rms values was observed in both processed as well unprocessed sample between the varying magnetizing frequencies from 10 Hz to 50 Hz. Finer grains in the processed region increased the grain boundaries with respect to unit volume that leads to generation of more pinning site for restricting motion of magnetic domains, similarly increased dislocation in processed zone also increased the pinning site that leads to more voltage pulse. Processed regions have the more compressive residual stress. Therefore resultant of this phenomenon lower the rms value of BN signal of friction stir processed region.

At constant frequency, increase in MFI supply more amount of energy to magnetic domains. This enables highly energized magnetic domains to move over the more number of grain boundaries, in this way each and every jumps of domain would contribute in enlargement of BN signal. Hence larger rms value is observed with increased MFI as represented in Fig. 12. Increase in grain boundaries upon friction stir processing resulted lower root mean square value within whole range of magnetic field intensity in comparison to the as received material.

5 Conclusions

This work shows the successful attempt of friction stir welding for processing of steel as well demonstrate applicability of BN technique for analyzing FSPed steel samples at different analysis parameters. Following are the conclusions derived from the present study.

(i) Generated frictional heat along with the mechanical loading stir the material. This causes finergrain in the processed region that leads the higher value of micro-hardness in the FSP sample.

(ii) Mechanical properties of the processed region get changed due to generation of finer grains. Magnetic response of the material reduces with increase of hardness of the material.

(iii) Proper strength of magnetic field is required to initiate the motion of magnetic domain. Increased level ofMFI delivers more energy to magnetic domains while the higher excitation frequency lowers the penetration depth of material.

(iv) Generation of voltage pulses gets reduced with increase in excitation frequency whereas increased MFI allow to generation of more voltage pulse. RMS value of signal increases with increase in magnetic fields and excitation frequencies.

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