AEROSPACE RECOMMENDED PRACTICE

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Superseding ARP4462B

Barkhausen Noise Inspection for Detecting Grinding Burns in High Strength Steel Parts

RATIONALE

ARP4462C is the result of a Five-Year Review and update of the document. The revision addresses temperature considerations (see 1.6.i), updates terminology to clarify intent (see 4.2.g) and revises Table B1.

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1. SCOPE

1.1 Purpose

This recommended practice establishes the requirements and procedures for Barkhausen Noise (BN) inspection of ferromagnetic steel components. See Appendix B for a list of common materials for BN inspection. Applications of the method are listed in 1.2 through 1.5.

1.2 Application to Grinding Burns

This test method may be used for the nondestructive detection of grinding-induced thermal damage of base ferromagnetic material in finish ground parts. This test method is primarily utilized on high-strength, low-alloy steel parts which have been ground in accordance with MIL-STD-866, or some commercial standard, before and/or after coating or plating. This test method may be used to detect grinding burn, which can be confirmed in accordance with MIL-STD-867 in bare components, or upon removal of coatings, platings, etc., from the base material.

1.3 Application to Stresses

This test method may be used for the nondestructive detection of mechanically induced stresses in bare or coated/plated parts. Examples include overload yielding residual stress and localized induced stress resulting from manufacturing, maintenance, or in-service events.

1.4 Application to Microstructure/Heat Treatment Defects

This test method may be used for the nondestructive detection of defects induced during heat treatment including, but not limited to, lack of heat treatment, soft spots, decarburization, improper case depth, etc., as well as defects induced during other surface treatments such as shot peening.

1.5 Application to Miscellaneous Thermally Induced Defects

This test method may be used for the nondestructive detection of defects induced by any process which results in absorption of excess heat. This includes friction burns, arc burns, etc. Typical applications include thermal damage which results in microstructure transformation and/or stress relief.

1.6 Measurement Preconditions

The BN inspection method is an electromagnetic test and is sensitive to anything which affects the magnetic properties of the surface to be tested. Peripheral processes which affect the measurement must be considered and controlled. Examples include:

a. Coating/plating thickness will affect the measurement in through-coating/plating inspections. Coating/plating thickness should be determined to be constant or a minor factor.

b. Ferromagnetic coatings and patches (for example, Ni patches) will affect the measurement and can provide false rejects.

c. Grit/media blasting or shot peening processes can remove a surface layer of material which may contain otherwise detectable damage. This can decrease the ability of BN (or Nital etch, X-ray diffraction) to detect damage on the surface. Blasting also induces compressive residual stresses which affect the BN measurement and can result in reduced sensitivity. It is not recommended to grit/media blast, shot peen, or use any other stress-inducing cleanup method before testing with BN, if possible.

d. Measurements can be made in situ with loaded components. *Baseline* values will be different for components when they are under load and, as a result, rejection limits may differ. Thermally induced defects detected in loaded components should be verified as detectable in the unstressed/unloaded state.

e. Parts to be tested should be free of defects due to earlier manufacturing processes. For example, defects present before grinding may be visible after grinding and can thus affect the measurement. Such defects include soft spots and edges due to defective heat treatment, decarburization, stress variations due to cooling rate changes, etc.

f. Sensor measurements can be made through a nonconductive protective layer/film. Protective films create an attenuating layer (i.e., lift-off) which will decrease the BN signal intensity as the layer thickness increases. Layer thickness is typically limited to 0.50 mm or less. Some applications allow for thicker layers (up to +1 mm), and some are limited to a thinner layer (0.05 mm). This depends on the alloy measured, the sensor geometry and electrical design, and the magnetizing parameters. Care must be taken to ensure that protective film thickness is maintained during measurements, as a varying thickness will result in an artificial influence on the measurement result.

g. Measurements made without sensor contact are possible. They are, however, subject to the same limitations as protective films as specified in 1.6.f.

h. BN measurements have depth sensitivity, which varies according to fundamental laws of electromagnetic damping. Material properties such as magnetic permeability and conductivity, as well as magnetizing frequency, voltage, and analysis frequency band, can affect depth sensitivity. Typical BN measurements made with magnetizing frequencies between 10 and 500 Hz, along with analysis bands between 10 and 500 kHz, have a depth penetration between 0.010 to 0.100 mm.

i. Part temperature extremes should be taken into consideration. Verifying the reference samples in the same environment as the parts to be tested will ensure that the system sensitivity is maintained.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

HS-784 Residual Stress Measurement by X-Ray Diffraction

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM E915 Standard Test Method for Verifying the Alignment of X-Ray Diffraction Instrumentation for Residual Stress Measurement

2.1.3 U.S. Government Publications

Copies of these documents are available online at https://quicksearch.dla.mil.

MIL-STD-867 Temper Etch Inspection

2.2 Definitions

2.2.1 BACKGROUND

The measured BN signal acquired with the sensor contacting the sample surface while no magnetic field is applied (i.e., magnetizing voltage = 0 V).

2.2.2 BARKHAUSEN NOISE LIMIT (BN_{lim})

The ratio between the *correlation threshold* and *baseline*, with both values being first corrected for the *background*.

2.2.3 BASELINE

The expected nominal BN measurement value of the surface to be tested when it is free of defects.

2.2.4 CORRELATION THRESHOLD

The specific BN value, determined via mathematical correlation to secondary measurement results, at which the qualification method used deems a sample to be defective/rejected.

2.2.5 EFFECTIVE MEASUREMENT AREA

The size of the sample (surface area) contributing to a measurement result at a given time. The size is equal to the surface area of the sensing element (pickup) of the sensor used.

2.2.6 ELECTROMAGNETIC INTERFERENCE (EMI)

A disturbance generated by an external source that affects an electrical circuit (BN measurement) by electromagnetic induction, electrostatic coupling, or conduction.

2.2.7 OPEN AIR

The BN value measured while the sensor is sufficiently far from the sample surface magnetizing and measuring the response of the air.

2.2.8 REJECTION LIMIT

The raw BN measurement result at which samples are determined to be rejected. This value is calculated as a function of *baseline* and includes *background* correction.

3. EQUIPMENT REQUIREMENTS

3.1 Barkhausen Noise Equipment Requirements

A minimum of one Barkhausen Noise analyzer and one Barkhausen Noise sensor are required to complete a BN measurement. In the case of evaluation of applied stresses or residual stresses induced via loading, two sensors may be required in order to properly perform a bi-axial measurement. Two sensors must be used when consistent, repeatable surface contact in both measurement directions cannot be achieved with a single sensor. Typically, a second sensor is required for samples having a significant change in geometry between two orthogonal axes. For example, as illustrated in Figure 1, bi-axial measurements on the outer diameter surface of a cylindrical component require one flat sensor for measurements in the axial direction and one concave sensor for measurements in the circumferential direction.

3.1.1 Barkhausen Noise Analyzer Requirements

Acceptable BN analyzers must meet the following minimum performance requirements to be considered compatible with the procedures set forth in this recommended practice.

a. Compatible instruments must be capable of applying an alternating magnetic field at 125 Hz.

b. Compatible instruments must be capable of measuring BN within a pass-band of 70 to 200 kHz.

c. Compatible instruments must be capable of calculating the BN root mean square (RMS) and displaying it for the user in real-time on the instrument (see Figure C1 in Appendix C, for example). Alternatively, the RMS may be recorded with a PC and data collection software.

d. For automated measurements, the BN analyzer must be capable of communicating with a PC and data collection software.

3.1.1.1 Barkhausen Noise Analyzer Calibration/Certification

BN analyzers must be certified to comply with BN analyzer original equipment manufacturer (OEM) specifications on an interval recommended by the OEM. Calibrated parameters must include:

a. Frequency response of analyzed BN signal for each filter band available.

b. Amplifier gain and linearity for analyzed BN signal.

c. Frequency response of magnetizing signal output.

    1. For constant voltage devices, the voltage output is tested.

    2. For constant current devices, the current output under load is tested.

d. Amplifier gain and linearity for magnetizing signal output.

    1. For constant voltage devices, the voltage output is tested.

    2. For constant current devices, the current output under load is tested.

3.1.2 Barkhausen Noise Sensor Requirements

Appropriate sensors must be used which consider the material being inspected, surface geometry, coatings or platings, and they must be compatible with the BN analyzer.

a. Sensors must be appropriately shaped such that all magnetic poles make contact with the area to be measured in a repeatable manner, or both the magnetizing flux through the area to be measured and any air gap between the measurement pickup pole piece and the area to be measured are controlled and repeatable.

b. Multiple sensors are required for bi-axial measurements of directional defects (e.g., applied or residual stress) in the case that a single sensor does not meet the requirements in 3.1.2.a, for both directions.

c. Special high-power sensors may be required for through-coating/plating measurements. Please consult with the sensor/analyzer OEM or any applicable commercial testing specifications.

d. Sensors must be specified by the OEM to be compatible with the BN analyzer utilized.

3.1.2.1 Barkhausen Noise Sensor Response Repeatability

Sensors must be verified to measure in a repeatable manner utilizing reference samples as described in 4.1 and 4.2 of this specification. Sensors must also measure in a steady and repeatable manner in the open air (see 7.4.3). Reference sample and *open air* measurement history should be recorded and monitored for variations. The recommended interval for response verification is daily in most cases. An ideal verification interval will depend on a number of factors, including sensor wear, environment cleanliness, and part and sensor-handling equipment. As a result, this interval should be determined on a case-by-case basis. Allowable measurement variance must be determined during an initial repeatability study, as explained in Section 4 of this specification. Causes of sensor measurement variations include:

a. Damage - Sensor damage due to impact or other occurrences can result in measurement variations. Consult with the sensor OEM to determine if repair is necessary.

b. Wear - Usually sensors measure by contact, and they are thus subject to wear. Sensor wear can affect the measurement level, as well as the measurement sensitivity. In the event where sensor wear affects the measurement level, yet sensitivity remains acceptable, it may be possible to compensate with sensor gain control. Consult with the sensor OEM or any applicable commercial testing specifications to verify.

c. Electromagnetic Interference (EMI) - Measurement results can be affected by sources of EMI including, but not limited to, cellular phones, RFID systems, etc.

3.2 Scanning Equipment Requirements

Scanning measurements require a compatible BN analyzer and sensor, appropriate sample and sensor holding, sample and/or sensor movement apparatus, and, optionally, a PC equipped with data collection software that is compatible with the BN analyzer. Manual scanning may be performed in lieu of a semi- or fully-automated movement apparatus in cases where measurements can be made with adequate consistency and repeatability.

3.2.1 Sample and/or Sensor Holding

Any sample or sensor holding fixtures must provide a constant and repeatable sensor contact through the measurement. Part holding should not induce applied stresses in areas to be measured.

3.2.2 Sample and/or Sensor Movement Apparatus

Any sample or sensor movement apparatus must result in a constant and repeatable sensor contact through the measurement. The maximum allowed linear movement velocity of the sensor relative to the sample surface is 120 in/min. Special conditions, including nontraditional magnetizing frequencies, rough surfaces, or very large or small sensors, may require a higher or lower limit.

Movement speeds greater than the specified limit are allowed if it is demonstrated to have a negligible effect on the ability of the BN measurement to detect the relevant defect. Speeds utilized and deviation justifications must be documented.

For complete surface coverage, sensor overlap must be at least 25% of the effective measurement area.

3.3 Measurement Recording Equipment Requirements

For completion of manual measurements, if data collection software is not used, the operator is required to view the BN value as displayed by the analyzer (see Figure C1 in Appendix C for an example of a common analyzer display) and document the results accordingly.

For completion of automated measurements, a computer equipped with data collection software is required. The computer and software must be compatible with the BN analyzer.

a. The data collection rate of the BN value must not exceed the measurement magnetizing frequency.

b. The data collection software must record BN signal RMS values as defined in 3.1.1.c.

4. REFERENCE SAMPLE REQUIREMENTS

At a minimum, relative reference samples (see 4.1) must be used to verify the functionality of the equipment. Reference sample measurements should be recorded and tracked to verify long term performance of equipment. When possible, it is recommended that absolute reference samples (see 4.2) be created. Absolute reference samples can be used in place of relative reference samples. A multi-operator repeatability study should be performed when the equipment and procedures are initially qualified to establish acceptable levels of measurement variance. These results should also be used to define acceptable tolerances for reference sample BN response.

4.1 Relative Reference Samples

Relative reference samples are only used for verifying sensor and analyzer level and sensitivity at regular intervals. These samples are not to be used in the selection of rejection criteria, nor should they be used in comparison to accept or reject parts. Relative reference samples must:

a. Exist, at a minimum, as a pair of high/low samples or a single sample with both high and low areas of measure (a larger spectrum of conditions and corresponding samples, though, is recommended).

b. Measure above the background such that (low measure)/(background) ≥1.5 on the low measurement area or sample (similar to the restriction on setting a baseline; see 7.4.1.a.4).

c. Exhibit a ratio of the high measurement to the low measurement greater than 1.5:1.

d. Have similar measurement area geometry.

e. As much as possible, have measurement areas that are well-defined and easy to detect and report.

4.2 Absolute Reference Samples

Absolute reference samples are used for verifying sensor and analyzer level and sensitivity, as well as setting rejection criteria for appropriate parts. Absolute reference samples satisfy the requirements of relative reference samples (see 4.1) and meet additional requirements. These samples are typically provided by the part manufacturer. Any deviation from the sample requirements listed below shall be considered, and the influence (if any) shall be evaluated and accounted for or determined to be insignificant in regard to the specific application. Absolute reference samples shall:

a. Be the same alloy as parts to be tested.

b. Have been subject to the same manufacturing process as the parts to be tested, including all surface treatments (including shot peening, heat treatment, coatings, etc.).

c. Have both defective and non-defective conditions present in separate areas (or as separate samples), with the defect size and severity matching the desired detection threshold requirement on the parts to be tested.

d. Be of a comparable geometry to the parts to be tested (cylindrical for cylinders, flat for flat, ID for ID, etc.).

e. Have coatings representative in composition and conductivity, and comparable in thickness to the coatings on the parts to be tested.

f. Have plating representative in composition and conductivity, and comparable in thickness to the plating on the parts to be tested.

g. Be manufactured in pairs with identical processing and conditions when used as defect correlation samples (see 6.2). One sample in the pair may be destructively tested and therefore may not be suitable for future reference and the other sample in the pair will serve as an absolute reference sample.

5. TRAINING REQUIREMENTS

5.1 Personnel Training

All personnel (operators and evaluators) must complete training on Barkhausen Noise and Magnetic Theory.

5.1.1 Automated Scanner Operator

Must complete additional training regarding the use of the specific BN analyzer and sensor(s) per manufacturer's recommendations. Operators must have additional training covering the setup and use of all automated scanning equipment and software. The operator must understand all safety precautions to prevent operator harm, as well as damage to the part or BN sensor. Further, the operator must demonstrate the capability and understanding of how to:

a. Set automated scanning and data acquisition parameters in accordance with 3.2 and 3.3, if applicable.

b. Prepare samples for measurement in accordance with 7.1.

c. Properly load and orient samples into the scanning apparatus.

d. Identify indications of sensor measurement variation outlined in 8.2, if applicable.

e. Perform inspections in accordance with Section 7.

5.1.2 Manual Scanner Operator

In addition to 5.1 and 5.1.1.b, d, and e, manual operators must demonstrate proficiency and repeatability in scanning samples and recording data in accordance with the requirements outlined in 3.2 through 3.3.

5.1.3 Evaluators

In addition to 5.1.1 and/or 5.1.2, evaluators must:

a. Verify sensor feedback for measurement quality, if applicable (see 8.2).

b. Understand applicable rejection criteria to be used (see Section 6).

c. Interpret BN measurement plots and graphs.

6. REJECTION CRITERIA DEVELOPMENT

Rejection criteria should be developed from a spectrum of samples with varying levels of the relevant defect. These include absolute reference samples. Defects are qualified according to industry or commercial standards and/or practices, such as MIL-STD-867, for grinding burn. The method of qualification will depend on the nature of the defect, as well as other circumstances.

6.1 Alternative Rejection Criteria for Ground Coated Surfaces

In the case that absolute reference samples or defect correlation samples (see 6.2) cannot be created, for the detection of grinding re-temper burn of 4330, 4340, and 300M steels through ground HVOF, or chrome-plated surfaces, the following rejection criteria may be applied.

a. Measurement equipment must be set to use an analysis frequency band of 70 to 200 KHz.

b. Measurement equipment must be set to use a magnetizing frequency of 125 Hz, except in cases where magnetization setup is completed according to 7.2.1.2.

c. Localized measurements exceeding ((2 x *Baseline*) - *Background*), $BN_{lim} = 2$ is observed in each of two perpendicular directions of measurement indicating re-temper burn for chrome plating and HVOF coating thicknesses less than 0.010 inch.

d. Localized measurements exceeding ((1.5 x *Baseline*) - (0.5 x *Background*)), $BN_{lim} = 1.5$ is observed in each of two perpendicular directions of measurement indicating re-temper burn for chrome-plating thicknesses greater than 0.010 inch.

e. See 7.4.1 for establishing a *baseline* value and 7.4.2 for determining a *background* value.

6.2 Defect Correlation Samples

A spectrum of samples is required for defect correlation.

a. A minimum of two samples or areas on a single sample is required:

   1. One "acceptable" sample, no defects present.

   2. One "defective" sample, clearly defective as determined by the qualification method.

b. Three samples or areas on a single sample are recommended:

   1. One "acceptable" sample, no defects present.

   2. One "borderline" sample, very near the rejection criteria set forth by the qualification method.

   3. One "defective" sample, clearly defective as determined by the qualification method.

c. Meet the requirements listed for absolute reference samples (see 4.2).

d. Identical parts should be manufactured for use as absolute reference samples (see 4.2).

6.3 Defect Qualification Methods

a. Grinding Burn

   1. The preferred method for measuring grinding re-temper burn, and correlating it to BN, is residual stress depth distribution measurements via X-ray diffraction and electrochemical layer removal (see Appendix A).

   2. An alternative method for grinding re-temper burn verification and correlation is Nital etch, according to MIL-STD-867.

b. Residual Stress Defects

   The preferred method for measuring residual stress and correlating it to BN is residual stress depth distribution measurements via X-ray diffraction and electrochemical layer removal (see Appendix A). Other quantitative stress measurement methods may also be used for defect qualification:

   1. Non-destructive surface residual stress measurements via X-ray diffraction are applicable in cases where subsurface stresses are inconsequential or of no interest. Depth sensitivity of BN measurements needs to be accounted for when deciding to measure surface only versus through depth stresses (see 1.6.h).

   2. Hole drilling methods using strain gauges, optical interferometry, or other methods of surface strain measurement are acceptable in most cases. Spatial resolution of the methods must be considered as most BN sensors have an effective measurement area smaller than typical hole-drilling measurement areas.

   3. Other stress measurement methods such as slitting, contour, and more can be used when appropriate.

c. Microstructure, Heat Treatment, and Other Thermally Induced Defects

1. Metallurgical inspection including micro-hardness, microscopy, etc., are the preferred qualification methods for microstructure and heat treatment defects.

2. In some cases, Nital etch and visual/optical inspection can be utilized to qualify heat treatment or thermally induced defects such as soft spots, decarburization, surface heat treatment pattern, or friction and arc burns.

6.4 Sensor Orientation and Sensitivity to Stresses

Sensor orientation is critical during measurements. Most sensors consist of two outer magnetizing pole pieces with a sensing pole piece located between them. BN is a directional measurement and, in some cases, bi-axial measurements are required to detect specific defects.

Detection of stresses, for example, is a directional application. The BN method is sensitive only to stresses parallel to the axis of magnetization. An example of sensor geometry and directional sensitivity can be seen in Figure 1.

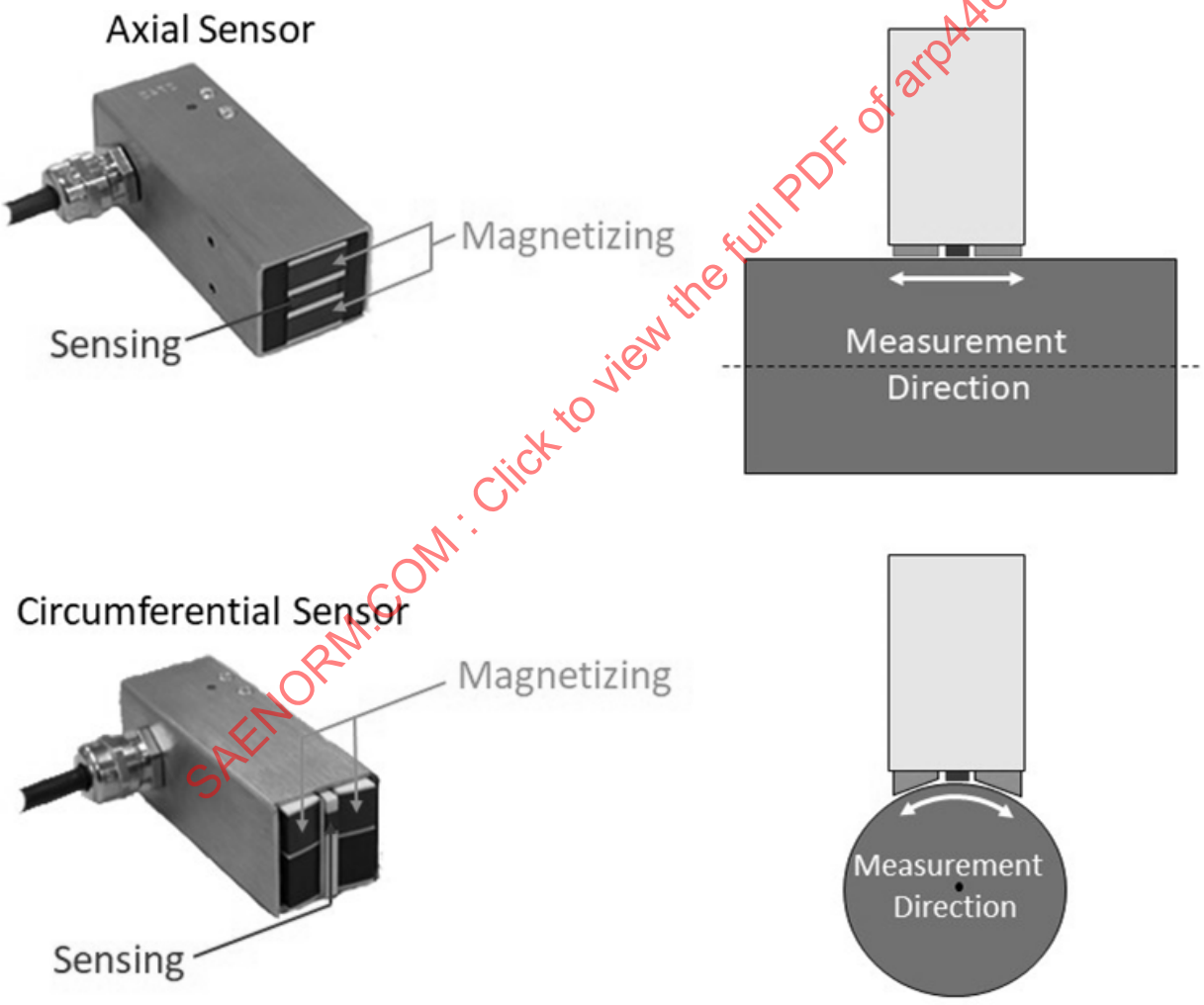

Figure 1 - Examples of sensor geometry and measurement directionality

6.5 Setting Rejection Criteria

Rejection criteria can be set after completing the correlation study between BN and the relevant defect qualification method. The preferred method of correlation is via quantitative methods, XRD for example, as presented in 6.5.1. Qualitative methods can be utilized as an alternative method of correlation. An example correlation between BN and Nital etch is given in 6.5.2. For simplicity, in both examples the *rejection limit* has been rounded to the nearest two decimal places.

a. Rejection limit is to be determined as a ratio of the *baseline*.

b. At which point the qualification method deems a measurement to be defective/rejected, the BN measurement value *correlation threshold* should be recorded. See Figure 2 for an example.

c. The *Barkhausen Noise Limit* (BN_{lim}) should be calculated as ratio of the *correlation threshold* and *baseline* both corrected for the *background*. See 7.4.1 and 7.4.2 for establishing the *baseline* and *background* values, respectively.

$$BN_{lim} = \frac{(\text{Correlation Threshold} - Background_{corr})}{(Baseline_{corr} - Background_{corr})} \quad \text{(Eq. 1)}$$

Where $Background_{corr}$ is the *background* determined from the correlation sample(s), and $Baseline_{corr}$ is the *baseline* determined from the correlation sample(s).

d. The *rejection limit* is established by correcting the *Barkhausen Noise Limit* for the *background*:

$$Rejection\ Limit = \left(BN_{lim} x\ (\ Baseline_{meas} - \ Background_{meas})\right) + \ Background_{meas} \quad \text{(Eq. 2)}$$

Where $Baseline_{meas}$ is the *baseline* determined from the specific sample(s) being measured, and $Background_{meas}$ is the *background* determined from the specific sample(s) being measured.

e. In cases where the correlation *baseline* and *background* values are identical to the corresponding measurement *baseline* and *background* values:

$$Rejection\ Limit = Correlation\ Threshold \quad \text{(Eq. 3)}$$

6.5.1 Setting Rejection Criteria Quantitative Example

Below is an example correlation between BN values and surface residual stress measured via XRD and the steps used to determine the *rejection limit*. Five defect correlation samples were supplied, two “acceptable” samples (No Burn 1 and 2), two “borderline” samples (Burn 1 and 2), and one “defective” sample (Burn 3). A spectrum of sample conditions is recommended to obtain a meaningful mathematical correlation. Here, a strong linear correlation (R^2= 0.97) is present.

a. Optimal measurement parameters determined using the appropriate areas on samples "No Burn 1" and "Burn 3" following the procedure explained in 7.2.1.2.2.

b. The $Baseline_{corr}$ value is determined using sample “No Burn 1” following the procedure explained in 7.4.1.a.1. Here, the $Baseline_{corr}$ equals a BN value of 97.5.

c. The $Background_{corr}$ value is determined following procedure 7.4.2. For this example, $Background_{corr}$ equals a BN value of 1.2.

d. The manufacturer required limit on subsurface residual stress is less (more compressive) than -150 MPa. Using the correlation shown in Figure 2, the *Correlation Threshold* then equals a BN value of 135.

e. Therefore, using Equation 1, the *Barkhausen Noise Limit* is:

$$BN_{lim} = \frac{(\text{Correlation Threshold} - Background_{corr})}{(Baseline_{corr} - Background_{corr})}$$

$$BN_{lim} = \frac{135 - 1.2}{97.5 - 1.2} = 1.3894$$

f. A new sample is then measured to have a $Background_{meas}$ equal to a 5.8 and $Baseline_{meas}$ equal to 103.7. For this sample, the *rejection limit* from Equation 2 is then:

$$Rejection\ Limit = \left(BN_{lim}\ \text{x}\ (\ Baseline_{meas} - Background_{meas})\right) + Background_{meas}$$

$$Rejection\ Limit = (1.3894\ \text{x}(103.7 - 5.8)) + 5.8 = 141.82$$

g. Thus, if the sample, at any point, measures 141.82 or greater, it is rejected; otherwise, it is accepted.

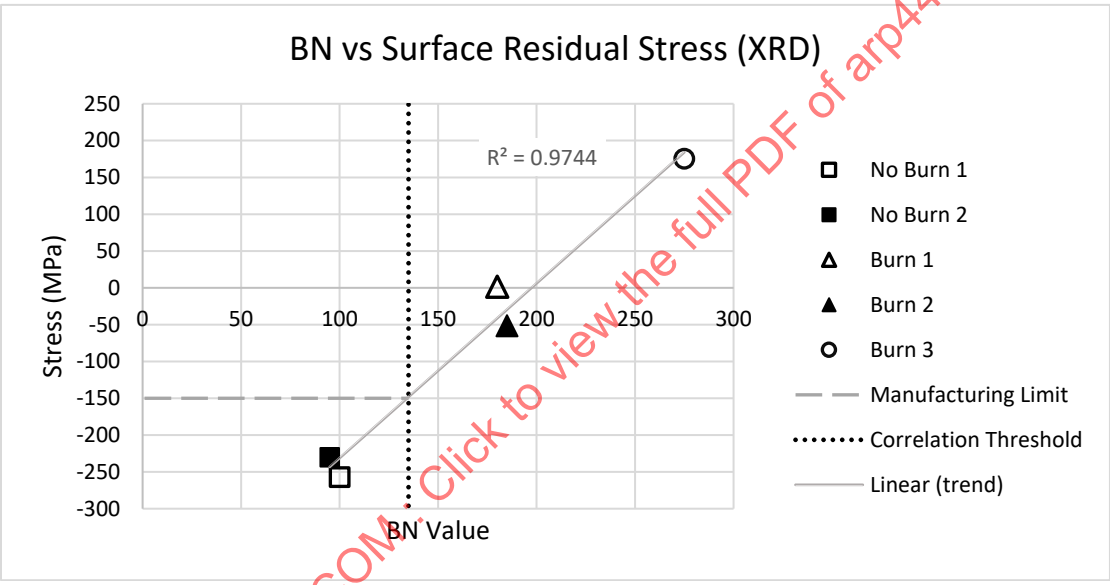

Figure 2 - Example correlation between BN value and residual stress measured via XRD

6.5.2 Setting Rejection Criteria Qualitative Example

Below is an example correlation between measured BN values and the results of Nital (acid) etch inspection. Fifteen samples of unknown condition were provided. All BN measurements were carried out prior to Nital etch inspection.

a. Optimal parameters were determined following the procedure in 7.2.1.1.

b. From a sample showing consistent BN values, the $Baseline_{corr}$ was found to be a BN value of 20.5 and $Background_{corr}$ was equal to a BN value of 0.8.

c. All samples were measured using BN and then inspected using Nital etch. The histogram in Figure 3 shows the correlation between both methods. In this case, the *correlation threshold* was chosen to be a BN value of 40.

d. From Equation 1:

$$BN_{lim} = \frac{(\text{Correlation Threshold} - Background_{corr})}{(Baseline_{corr} - Background_{corr})}$$

$$BN_{lim} = \frac{(40 - 0.8)}{(20.5 - 0.8)} = 1.9898$$

e. Therefore, the *rejection limit* for a subsequent sample with $Baseline_{meas}$ equal to 22 and $Background_{meas}$ equal to 3.5, from Equation 2 is:

$$Rejection\ Limit = \left(BN_{lim}\ \text{x}(\ Baseline_{meas} - Background_{meas})\right) + Background_{meas}$$

$$Rejection\ Limit = \left(1.9898\ \text{x}\ (\ 22 - 3.5)\right) + 3.5 = 40.31$$

f. Thus, all points on the sample must measure below 40.31; otherwise, it is rejected.

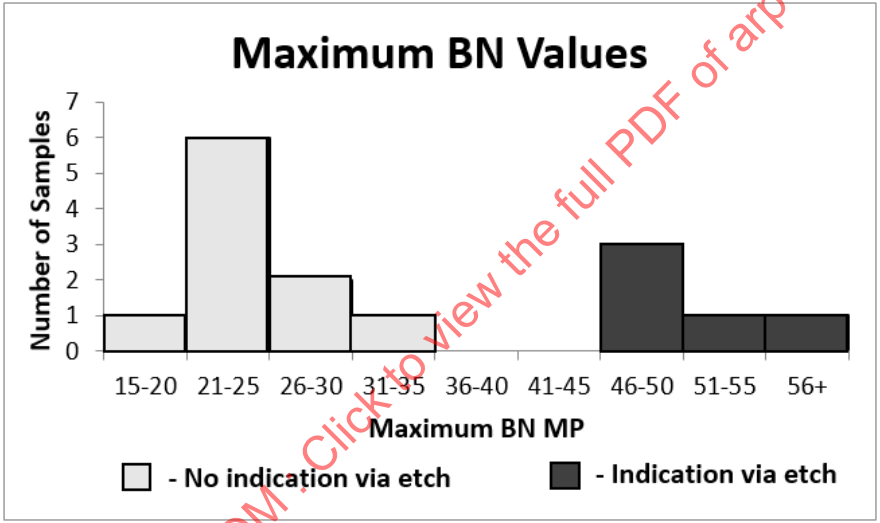

Figure 3 - Example histogram of max BN values

NOTE: Light gray bars represent samples that etch clean, and dark gray bars represent those that showed visual indications of grinding damage via Nital (acid) etch inspection.

7. INSPECTION REQUIREMENTS AND PROCEDURE

7.1 Preparing the Sample

7.1.1 Cleaning the Sample

The sample surface to be measured must be cleaned using acceptable materials to remove any foreign substances from the surface which may affect measurements or damage the sample, including dust, chips, grease, etc. A thin layer of lubricant may be applied on the surface to reduce sensor wear.

7.1.2 Residual Magnetism

Samples must be measured for residual magnetism using an appropriate gauge prior to BN inspection. Readings must be no greater than ±3 gauss. If greater magnitudes are measured, the sample must be demagnetized, and gauss measurements repeated.

Residual magnetism greater than the specified limit is allowed if it is demonstrated to have a negligible effect on the ability of the BN measurement to detect the relevant defect. Measurements and deviation justifications must be documented.

7.2 Optimizing Inspection Settings

Each BN analyzer has unique settings and parameters that can be adjusted to optimize inspections (i.e., magnetization voltage and frequency, gain, filter range, etc.). The major factors that will affect the required settings to achieve effective measurements include coating/plating thickness, material type, heat treatment, and shot peen intensity. Settings will also be affected if protective film is used for sensor protection. Each combination could result in different settings. These settings must be optimized for every sensor to be used. Settings must be established by one of two methods, either by developing absolute reference samples for each representative combination of factors (see 4.2), or by following 7.2.1.

7.2.1 Optimizing Magnetizing Voltage and Frequency

7.2.1.1 Knee Method

In the case that Absolute Reference Samples are not created, the “knee” method outlined below should be followed to determine optimal measurement parameters.

a. If available, the frequency and filter settings must be set to 125 Hz and 70 to 200 kHz, respectively.

b. Scan the entire part surface and identify an area which represents the *baseline* measurement value, as described in 7.4.1, using a magnetizing voltage of 50% of the instrument maximum

c. Statically place the sensor at a representative *baseline* location and set the magnetizing voltage to the lowest available voltage setting that is greater than zero. Record the magnetizing voltage selected and the measured BN value.

d. Incrementally adjust the magnetizing voltage by no more than 10% of the maximum available voltage. Record the magnetizing voltage and measured BN value at each increment until the maximum voltage has been reached.

e. Plot the data with the magnetizing voltage along the x-axis and measured BN value along the y-axis, as shown in Figure 4. Typically, a voltage will be reached such that the BN values will flatten. This represents magnetic saturation. Further increase in magnetizing voltage will result in a loss of sensitivity.

f. The optimal magnetizing voltage should be selected as the highest voltage along the curve which occurs before the “knee” in the curve. For example, see Figure 4.

g. In the case that saturation does not occur (no upper horizontal asymptote), the highest magnetizing voltage available should be selected.

h. Verify that *baseline*/*background* ≥1.5 utilizing the new magnetizing settings. If this condition is not met increase the magnetizing voltage determined in 7.2.1.1.f using the smallest possible increments until the condition is met.

i. Document all settings and record them along with measurement data for every measurement.

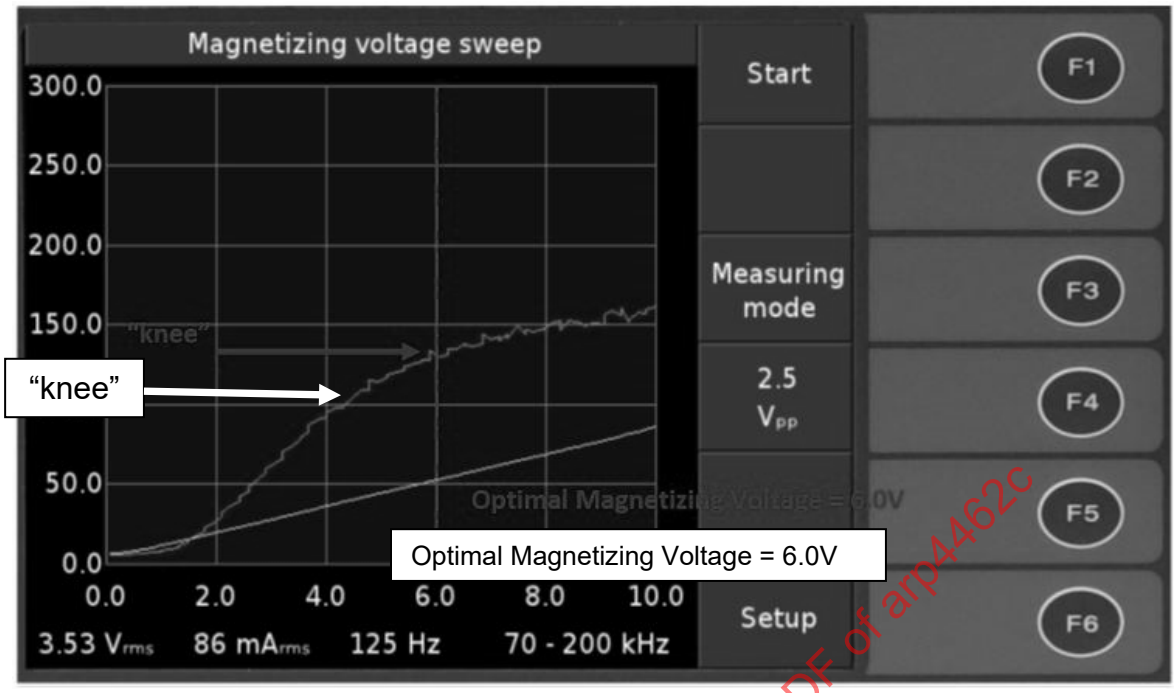

Figure 4 - Example of the knee method, using a fixed frequency magnetizing voltage sweep, to determine the optimal measurement magnetizing voltage

7.2.1.2 Ratio Method

For all other cases, absolute reference sample(s), outlined in Section 4, should be used to determine optimal settings using the "ratio" method explained below.

7.2.1.2.1 Fixed Frequency BN Analyzers

a. Identify the surface locations of high (defective) and low (*baseline*) measurement. These areas should be labeled for future reference.

b. Statically place the sensor on the high (defective) absolute reference sample (area). Beginning with the lowest available magnetizing voltage, record the measured BN value. Continue this process, incrementally adjusting the magnetizing voltage by no more than 10% of the maximum available magnetizing voltage. Record the voltage and BN value measured at each increment.

c. With the sensor placed on the low (*baseline*) Absolute Reference Sample (area), repeat the process in step b. Using the same increments of magnetizing voltage as before, record the measured BN values for each increment.

d. Using the data recorded in b and c, calculate the ratio of measured high (defective) absolute reference BN value to low (*baseline*) absolute reference BN value for each magnetizing voltage measured.

e. The optimal magnetization voltage is that which results in the maximum ratio calculated in step d.

f. Verify that *baseline*/*background* ≥1.5 utilizing the new magnetizing settings. If this condition is not met, increase the magnetizing voltage using the smallest possible increments until the condition is met.

g. Document all settings and record them along with measurement data for every measurement.

7.2.1.2.2 Variable Frequency BN Analyzers

a. Identify the surface locations of high (defective) and low (*baseline*) measurement. These areas should be labeled for future reference.

b. Select a desired measurement filter range. The default recommended value is 70 to 200 kHz on BN analyzers which support this feature.

c. Set the magnetizing frequency to 10 Hz.

d. Follow 7.2.1.2.1 b.

e. After all values (magnetizing voltage and BN value) have been recorded, incrementally increase the magnetizing frequency by no more than 10 Hz and repeat step d. Record all values. Continue this process until reaching a magnetizing frequency no greater than 500 Hz.

f. With the sensor placed on the low (*baseline*) absolute reference sample (area), repeat steps b through e.

g. Using the previously recorded data, calculate the ratio of the measurements taken at the high (defective) location versus measurements at the low (*baseline*) location.

h. The ratios can be represented as a heat map as shown in Figure 5.

i. Optimal settings are chosen from the parameters which lie in the “hot zone” containing the highest ratios.

j. For equipment with more than one filter range, 7.2.1.2.2.c through e may be repeated using each filter range for further optimization.

k. Verify that *baseline*/*background* ≥1.5. If this condition is not met increase the magnetizing voltage using the smallest possible increments until the condition is met.

l. Document all settings and record them along with measurement data for every measurement.

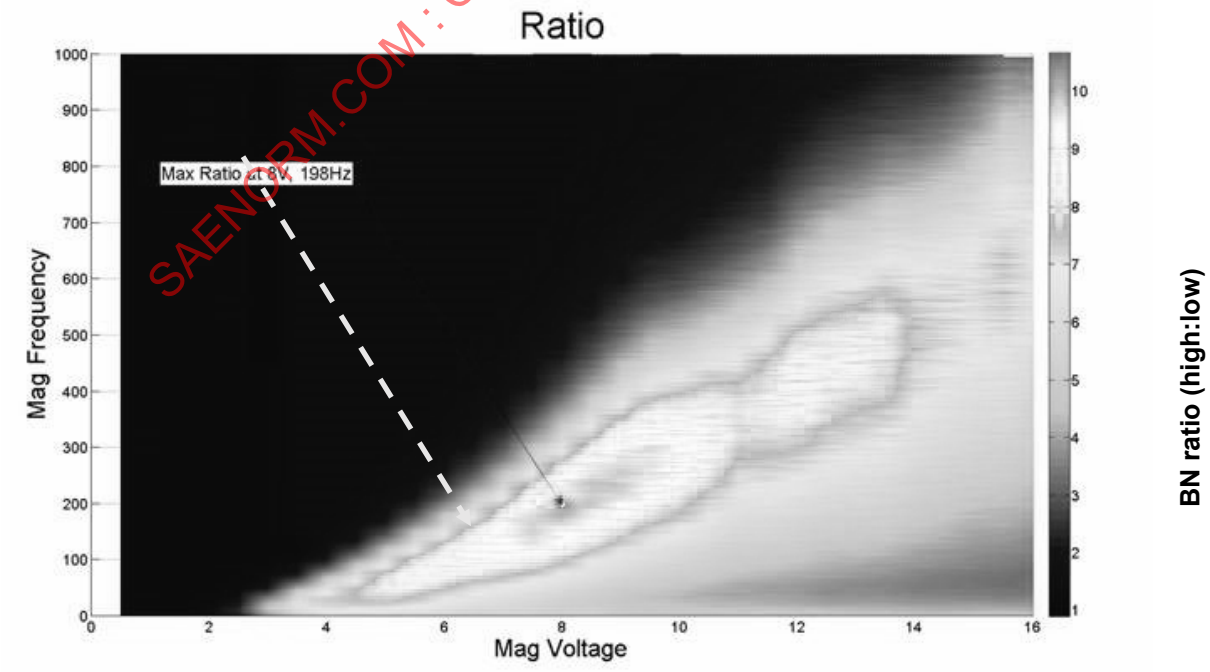

Figure 5 - BN value ratio chart for determining optimal measurement magnetizing voltage and frequency

7.3 Equipment Setup

a. The entire surface of the sensor face must be cleaned of any foreign debris and inspected for wear or damage.

b. If protective film is to be used on the sensor, ensure that the film is not torn or dirty.

c. Connect and power on the BN analyzer. Note that the BN analyzer should be grounded to the part/measurement sample unless a nonconductive protective film covers the sensor face.

d. Connect and power on data acquisition software/CPU, if applicable.

e. Connect and power on automated scanning apparatus, if available.

f. Set and verify the BN analyzer magnetization frequency and voltage, filter range, etc., per specific analyzer, sensor used, and sample. These settings may be controlled via hardware and/or software. The process for determining optimal settings is explained in 7.2.

g. Record the *open air*. Verify the value against established values, if possible. If values do not agree, then verify that all previous steps have been completed and BN analyzer is functioning properly. If no solution is found after troubleshooting, contact the original equipment manufacturer.

h. Record the *background*. Verify the value against established values, if possible. If values do not agree, then verify that all previous steps have been completed and BN analyzer is functioning properly. If no solution is found after troubleshooting, contact the original equipment manufacturer.

i. Ensure proper sample and sensor orientation.

j. Verify sensor feedback for measurement quality, if applicable (see 8.2).

7.4 Completing Measurements

7.4.1 Establishing a Baseline

A *baseline* value is defined as the expected nominal measurement value of the surface to be tested when it is free of defects. The *baseline* value, like all BN measurements, is dependent on geometry, sensor type, analyzer settings, etc. Care should be taken to ensure that *baseline* values utilized are appropriate for the current measurement scenario. $Baseline_{corr}$ is the *baseline* measurement determined from the absolute reference sample(s). This value is determined initially during development of rejection criteria. It must be recorded for future use. $Baseline_{meas}$ is the *baseline* value determined for each part prior to or during inspection. $Baseline_{meas}$ can be established and used for multiple parts/measurements if the measurement conditions and sample properties are kept constant.

A *baseline* can be established in several ways:

a. By measuring a sample which is known to be free of defects:

   1. The sample is measured using the appropriate apparatus and parameters and the mean measurement value for the surface is defined as the *baseline*.

   2. In the case of dynamic or scanning measurements the mean is calculated from all measurement values from the complete surface.

   3. In the case of static or handheld measurements, the mean is calculated from a random survey of at least 15 measurement locations on the surface.

   4. Verify that *baseline*/*background* ≥1.5. If this condition is not met, increase the magnetizing voltage determined in 7.2, using the smallest possible increments until the condition is met.

b. By measuring a sample which is of unknown condition:

1. The sample is measured using the appropriate apparatus and parameters and the *baseline* is calculated as *baseline* = mean - σ, where σ is the standard deviation and mean is the mean of all measurement values for the surface.

2. In the case of dynamic or scanning measurements, the mean and standard deviation are calculated from all measurement values from the complete surface.

3. In the case of static or handheld measurements, the mean and standard deviation are calculated from a random survey of at least 15 measurement locations on the surface.

4. Verify that *baseline*/*background* ≥1.5. If this condition is not met, increase the magnetizing voltage determined in 7.2, using the smallest possible increments until the condition is met.

7.4.2 Determining Background

The measurement *background* is determined by placing the sensor on the sample just as if making a BN measurement. However, in order to detect electrical noise or other potential interference, while measuring *background* the sensor should not apply magnetizing to the sample. This is achieved by adjusting the magnetizing voltage to 0 V. $Background_{corr}$ is the *background* measurement determined from the absolute reference sample(s). This value is determined initially during development of rejection criteria. It must be recorded for future use. $Background_{meas}$ is the *background* value determined for each part prior to or during inspection.

7.4.3 Measuring the Open Air

Open air measurements are used to verify that the sensor is functioning properly and also free of any ferromagnetic debris (metal shavings) before making measurements on a sample. The sensor shall be set to the previously determined measurement parameters and held appropriately far from the sample surface. Typical *open air* values will not be equal to zero, as the air will magnetize to some degree. The *open air* values should be recorded for each individual sensor, and all measurement parameters to be used at the time of installation and monitored frequently.

7.4.4 Measurements by Hand

a. Verify that rejection criteria have been established in accordance with Section 6.

b. Complete setup procedure specified in 7.3.

c. Verify equipment functionality and sensitivity by measuring reference samples defined in Section 4. Compare to historically expected measurement values.

d. Load sample and/or sensor into any fixtures to be used.

e. Scan entire surface to be measured in accordance with 3.2 through 3.3.

f. All data points must measure within the rejection criteria (below *rejection limit*, for example), or the sample fails inspection.

g. Remove the sample and process accordingly.

7.5 Automated Measurements

a. Verify that rejection criteria have been established in accordance with Section 6.

b. Complete setup procedure specified in 7.3.

c. Verify equipment functionality and sensitivity by measuring reference samples defined in Section 4. Compare to historically expected measurement values.

d. Load sample into automated scanner.

e. Verify sensor contact and orientation.

f. Verify scanning routine and BN parameters to be used in accordance with 3.2 through 3.3.

g. Verify safe movement of sensor/part and any other safety procedures required.

h. Begin measurement routine.

i. All data points must measure within the rejection criteria (below Rejection Limit, for example) or the sample fails inspection.

j. Remove the sample and process accordingly.

8. NOTES

8.1 Measurements Near Surface Edges

Sensor geometry must be considered when making measurements near the edge of a surface. Typical BN sensors include a measurement pickup, which is located between two magnetizing poles. The result is that, in some cases, the effective measurement area cannot be moved entirely to the edge of a surface while also keeping both magnetizing poles in contact with the surface. Except in cases where it can be documented to have negligible effect, all three sensor poles (2 magnetizing and 1 pickup) must be in contact with the surface to be measured, either directly or via a protective film or controlled gap. See Figure 6 for example measurement scenarios.

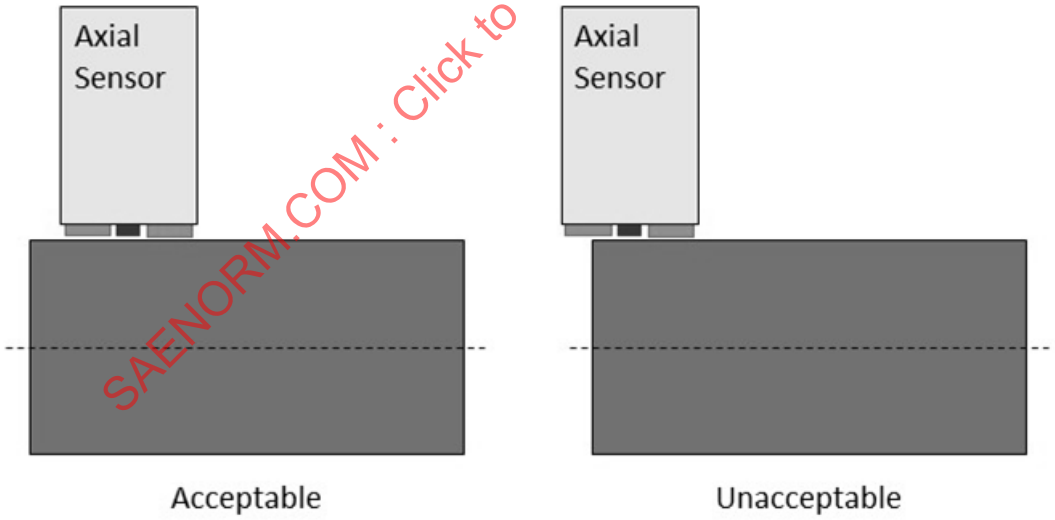

Figure 6 - Example of acceptable and unacceptable measurement arrangements with a specific sensor geometry

NOTE: All sensor poles (two magnetizing and one pickup/sensing) must cover the measurement surface. Lack of contact/coverage by one pole can influence the measurement.

8.2 Sensor Feedback

Some advanced BN analyzers provide a sensor feedback measurement. This is a measure of the current flowing through the magnetizing coils of the sensor. This sensor feedback is reported as parameter I_{rms} with units mA_{rms}. Sensor current feedback is affected by a number of variables.

8.2.1 Interpreting Sensor Feedback

Sensor current feedback is known to increase in the following cases (assuming that magnetizing voltage and frequency are held constant):

a. Magnetizing poles of sensor are making a smaller contact area with the sample measured.

b. Part coating or sensor coating thickness (if applicable) is increased.

c. Sensor-to-part air gap (if applicable) is increased.

Sensor current feedback is known to decrease in the following cases (assuming that magnetizing voltage and frequency are held constant):

a. Magnetizing poles of sensor are making a greater contact area with the sample measured.

b. Part coating or sensor coating thickness (if applicable) is decreased.

c. Sensor-to-part air gap (if applicable) is decreased. Note that sensor current feedback can also be affected by gross changes in sample microstructure, alloy content, etc.

8.2.2 Recording Sensor Feedback

Sensor current feedback on compatible instruments can be recorded simultaneously with BN measurement data. It can be stored for post-measurement analysis as well.

8.3 BN Measurement Values

Barkhausen Noise is a magnetic phenomena which manifests itself as a white-noise-like signal which is modulated by the magnetizing frequency. A number of parameters can be extracted from the "bursts" of noise in this signal. These include:

a. BN RMS - This is simply the rms value of the BN signal. It is useful because it is sensitive to both the number of Barkhausen events and the energy of those events. This is the most commonly used parameter in BN measurement systems.

b. BN Peak Position - This is the position of the peak of the bursts in the BN signal using either time or, most commonly, magnetizing current as the x-axis.

c. BN Peak Height - This is the maximum height of peak of the bursts in the BN signal.

8.4 BN Analyzer Filter Ranges

The BN signal, being white-noise-like, contains information over a very large frequency range which begins in the low Hz and extends up into single digit MHz. In order to avoid magnetizing harmonics, EMI, etc., commercial instruments include band-pass filtering to limit the analysis frequencies of the BN signal. The most common analysis band in use is 70 to 200 kHz.

Analysis bands can be changed to avoid sources of external noise or simply to improve sensitivity.