An Introduction to Barkhausen Noise and its Applications

A Paper By

Mark Willcox & Todd Mysak

Telephone
+44 (0)1981 541122

Fax
+44 (0)1981 541133

Email
Sales@InsightNDT.com

Web Site
www.InsightNDT.com

Insight NDT Equipment Ltd
The Old Cider Mill
Kings Thorn
Herefordshire
HR2 8AW

Directors
Mark Willcox BSc (Hons)
Jiang Li BSc (Hons)

VAT Registration No.
771 3060 50

Registration No.
4198815 England

Registered Office
21 St Owen Street, Hereford,
Herefordshire HR1 2JB

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1 INTRODUCTION

The purpose of this paper is to provide general information on the methods and applications in the use of Barkhausen Noise technology. This paper will address the current applications that can be found within the operations of Cummins Engine manufacturing and the technology that is associated with each application.

This manual is no way meant to be a comprehensive document covering the detailed aspects of using Barkhausen Noise for development purposes, as that would be a scope that is far too large to be useful for training. This manual is, however, designed to provide a fundamental understanding of the technology and could be used as training material. It is the authors' intent that the material included in this document will spawn advanced solutions to difficult problems in the arena of engine manufacture.

1.1 BARKHAUSEN NOISE BACKGROUND

1.1.1 Terms used in Barkhausen Noise Inspection

Barkhausen Noise uses magnetic fields that vary with time to determine certain characteristics about metallic inspection samples. The magnetic technology can be very complex and in certain circumstances, it can be very difficult to conceptually visualise the fundamentals of this technology, therefore, this manual will attempt to explain the fundamentals in the simplest of terms without getting bogged down in the tedium of magnetic theory and analysis.

A number of terms will be used quite frequently in this document, so they are defined here. This is not meant to be an involved discussion of these topics, because each one is an extensive topic in itself.

1.1.2 Excitation Field

The excitation field term refers to the magneteic field that is used to excite, or influence, the ferromagnetic specimen. This excitation causes an emission of Barkhausen Noise as the field is changing from one polarity maximum to the other. This field has to change with time to cause the Barkhausen emission to occur.

This field is a time varying field and the frequency is on the order of 120 Hz for most commercially produced systems. (See Frequency).

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1.1.3 Magnetisation

The term magnetisation refers commonly to the excitation field that is being used to generate the Barkhausen Noise signature in the inspection specimen. The strength of this field is proportional to the current that is passed through the field winding in the sensing device or sensor. In the commercial Barkhausen Noise products, this is a common system parameter setting or control, which is used to control the field winding current. Often this term will be used to refer to the magnetising current, which is the current that is used to generate the time varying external magnetic field around the inspection specimen.

1.1.4 Gain

Gain is a generic term that commonly refers to a level of amplification in an electronic system. This gain is used to make the system more or less sensitive to changes within a part and also controls the running average of the date signal. In Barkhausen inspection, a series of tests are performed to derive what is the best gain setting for a given inspection.

1.1.5 Sensor

A sensor is a device that contains the magnetic windings and their cores of the Barkhausen instrument. Sensors can come in a variety of sizes and are usually tailored to fit the geometry of the part that is to be inspected.

Some sensors come in a compact housing in which is contained several actual sensors. This is to allow rapid inspection of more than one surface at once. These types of sensors are highly dedicated to a specific geometry and can be costly to manufacture.

1.1.6 Irreversibility

With magnetic types of inspection and phenomenon there is an aspect that one frequently encounters. The aspect of irreversibility is displayed in a ferromagnetic material’s inability to return to the original magnetic state. In other words, once a ferromagnetic material has been placed in a magnetic field and taken from the field, there will remain in the material some amount of residual magnetism. This characteristic occurs on the order of the individual magnetic domains within a material, thus causing a very unrepeatable transition when the magnetic field is changing within a material.

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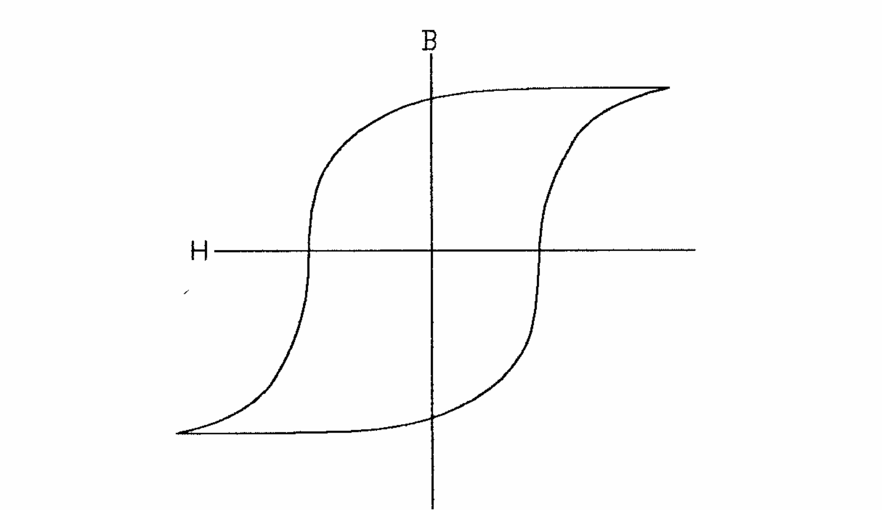
1.1.7 Magnetic Field

A magnetic field is a field of magnetism that exists between two magnetic poles and has the ability to exert a force on a ferromagnetic particle that is within the volume of the field. Generally, there are no known magnetic monopoles, so the source of a magnetic field will be a pair of initiation sites.

Magnetic fields can be static or dynamic which means they are either changing with time or they aren't. The field itself is created by moving electrical charges, or current flow, and if the flow is constant, a static magnetic field is created. This sometimes is referred to as a magnetostatic field.

1.1.8 B-H Curve

A B-H curve is generally used to describe the relationship between the magnetic flux density and the magnetic field intensity, respectively. These two parameters are beyond the scope of this text, however, they are presented here to briefly explain the diagrams that one might see when reading about magnetic phenomenon and or applications. These parameters are related by a constant which represents how well a magnetic field can penetrate the material.



Hysteresis Curve on a B-H plane

In the above figure, a hysteresis curve is plotted to illustrate the relationship of these two parameters that describe the magnetic state in a material. It should be noted that the corresponding parameter of any state is dependent on what state the material has been in previously. This is a fundamental concept for the Barkhausen Noise inspection. It is this irreversibility aspect of a ferromagnetic material that is observed on a macro level to determine the Barkhausen Noise emission from a material. The degree of irreversibility is usually demonstrated on some type of B vs H curve or plot.

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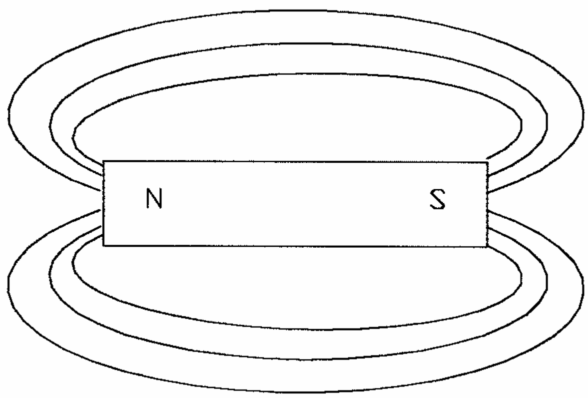
1.1.9 Magnetic Domains

Magnetic domains are commonly discussed in the articles pertaining to Barkhausen Noise technology. A domain is a region in a ferromagnetic material that is defined by a magnetic polarity boundary. As an external field is applied to the material, the boundary of the magnetic domain will transform towards an equilibrium position. The transition of this domain shift is semi-predictable and is commonly a single part of a series of changes at once. The effect within a material can be described as an avalanche, which is usually the term used in the technical literature.

1.1.10 Magnetic Flux

Often a magnetic flux is referred to in terms of magnetic flux. Magnetic flux or magnetic flux lines are non-tangible lines that trace out the path of the magnetic field through space. Their orientation in spece represents the direction of the magnetic field.

Magnetic flux lines can be seen by placing a magnet underneath a sheet of paper with ferrous filings on top. The field generated by the magnet will cause the filings to be magnetised and they will naturally align themselves with the field according to each particle's polarity. The demonstration will generally align the filings into lines which will represent the magnetic flux lines generated by the magnet. This field line characteristic is demonstrated in the following figure.



Magnetic Flux Lines Generated by a natural Magnet

1.1.11 Frequency

The frequency of a signal can casually be defined as the number of signal cycles that occur in a measured amount of time. This is given in terms of cycles per second, although the *cycle's* term is obsolete and infrequently used. The contemporary term for frequency is hertz which means cycles per second.

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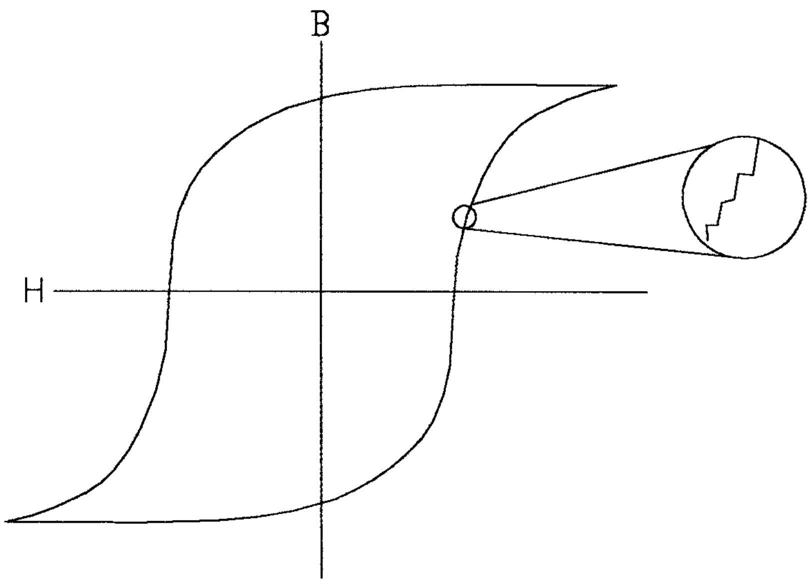
With Barkhausen Noise, the term frequency is used to describe several aspects of the inspection. The first is the description of the excitation field. Often the inspection will require an external excitation field that varies in strength according to time. This variance is periodic and continues, therefore, it has an associated frequency. The Barkhausen Noise emission changes when the frequency is changed, so this can be an inspection parameter. Normally, however, this parameter is set from the factory in commercial equipment and cannot be modified.

The other discussion about frequency in Barkhausen technology is the frequency of the data that is processed from the Barkhausen emission. This parameter is generally varied to inspect a certain depth into the part. For high frequencies, most of the emission comes from the surface of the part while lower frequencies emanate from the interior of the part.

1.1.12 Barkhausen Noise is Not Noise at All

Barkhausen Noise was discovered in 1919 by H. Barkhausen when he wound a ferromagnetic specimen with a wire and hooked it to an external speaker. He found that by changing the magnetic field around the specimen, he could induce a rushing sound in the speaker. This rushing sound was the result of many small abrupt changes in magnetic flux that was occurring within the confines of the coil. These step variations in magnetic flux occur randomly and are what is commonly known as Barkhausn Noise. This phenomenon is illustrated in the figure below.



Step Changes on a B-H Hysteresis Curve

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These step variations in magnetic flux are what is of primary interest in using Barkhausen Noise for non-destructive evaluation of materials. The amount and degree of these changes is dependent upon the metallurgical characteristics of the material that is being inspected. Often scientists develop models to simulate and predict these small magnetic changes, but it is a difficult task at best. Nevertheless, by quantifying the amount of change that takes place during a magnetic cycle will often indicate the presence of adverse metallurgical conditions.

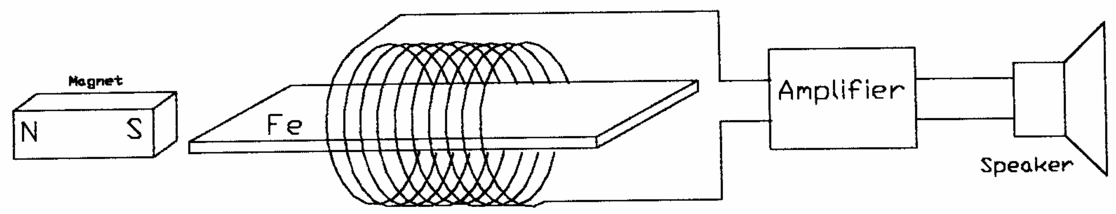
1.1.13 Is it Really Noise???

In certain discussions there is sometimes a confusion that Barkhausen Noise is actually a sound or an acoustic emission, however; in this case it is not. The sound comes from sensing the changes in magnetic field with a coil and directing the resultant current flow through a speaker. This frequency of the changes just happens to be in the audible hearing range, so with a speaker one can *hear* the changing magnetic signals. This is a very simple experiment that can be demonstrated with a magnet, a coil and a speaker with an amplifier.

1.1.14 Barkhausen Noise Inspection Equipment

Barkhausen Noise is a magnetic phenomenon that is typically sensed using a device that is capable of detecting changing magnetic flux lines. In the following figure the basic components of a Barkhausen Noise system are illustrated. As the flux changes within the confines of the inductive coil, a current is produced in the connecting wire. The current is sensed to produce a typical Barkhausen signature.

The magnet in this system should be considered dynamic and as the pole orientation changes, a magnetic stress is placed on the domains of the magnetic Fe material. At a certain point in the changing of the external magnetic field, many of the internal magnetic domains will begin to change rapidly causing small impulse changes of magnetic flux within the coil.



Simplified Barkhausen Noise Detection System

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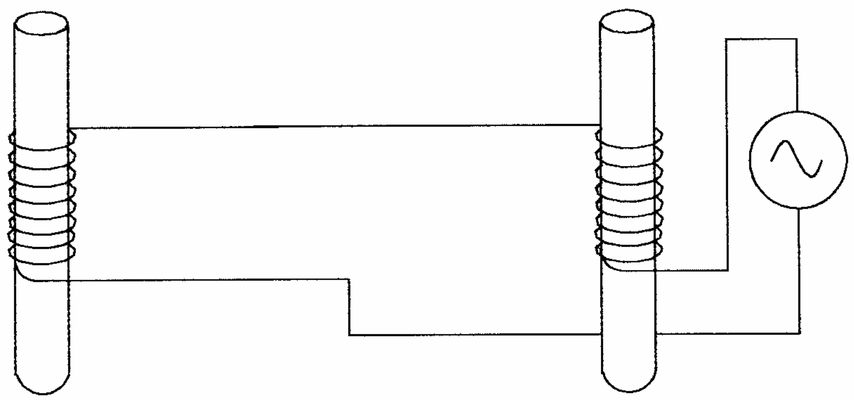
For commercial systems, the changing current is sensed in the coil wire and collected via a computerised data acquisition system. The amplitudes of these magnetic flux changes give indications to the state that the material is in. This Barkhausen signature has been showed scientifically to be sensitive to material stresses, hardness, and composition. The difficulty in using Barkhausen Noise for inspection is determining which of these parameters the instrument is sensing.

Also in computerised commercial systems, the excitation magnetic field is electronically generated and controlled. This is usually done by passing an alternating current through a pair of magnetic field windings that have solid cores. These cores many times are shaped and placed appropriately to fit the requirements of the geometry of the application. With this type of system, filtering must be employed in the collected signal to eliminate the excitation field that interferes with the inspection coil or the *listening* coil. The illustration below demonstrates the concept of the field coils and poles.



Barkhausen Noise Excitation Circuit

With the arrangement shown above the sensor coils is traditionally located between the two magnetic poles (not shown). This allows sensing to take place in an area where the amplitude of the magnetic field is large. The magnetic field also exists around the poles, outside the area between them, however, the amplitude of the field is less and the inspection is not nearly as effective.

The signals generated by these electronic arrangements are a very sporadic, randomly occurring signal. From one cycle of the magnetic field to the next, the Barkhausen Noise signature does not repeat on the macro level. The amplitude of emission remains fairly constant, but the occurrence of domains flipping happens in a very random manner. This signal is usually monitored as voltage in the pickup coil and is normally translated and stored by a digital signal processing system.

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1.1.15 Making Barkhausen Noise a Useful Inspection Tool

Barkhausen Noise is a very promising technology indeed, however, due to the irreversible nature of magnetic inspection, one will quickly find that the Barkhausen signature is very non-repeatable. It is commonly observed that the random variation for a discrete measurement value is typically 2-3% of the range of interest. In the following table, the results of a simple repeatability study is presented. For several inspection positons, the average three sigma value is given. This *Average of 3 Sigmas* represents the average variance over 200 individual inspeciton locations. Each inspection location was measured 12 times to allow for each standard deviation calculation.

1.1.16 Example Repeatability

Average Of Sigmas	Average Of Averages	Average Of 3 Sigmas	Parameters
2.15	64.80	6.44	Bearing Left
1.38	62.36	4.14	Bearing Right
3.41	60.69	10.24	Pin Left
1.00	66.60	5.98	Pin Right

Although these numbers appear to be fairly good, typically they may be worse depending on the environment. Often it is common to see some type of signal processing utilised to address this issue.

In order to make Barkhausen Noise a useful inspection tool, the commercial solutions available at this time have chosen to calculate a *Magnetic Barkhausen Noise Parameter* from the random bursts of energy that the system detects every time the inspection material is passed through the magnetic hysteresis loop. This parameter makes use of digital processing capabilities available on today's market.

1.1.17 Barkhausen Noise Parameter

The Barkhausen Noise Parameter is not limited to any particular aspect of the Barkhausen signal. This is simply a generic parameter that is calculated from a complete cycle of the Barkhausen emission. In the following two figures an example is given to illustrate the shape of the signal that results from monitoring the voltage of the listening coil during one cycle of the excitation field. The actual signal is shown in the second figure below to illustrate the random appearance of the magnetic pulse.

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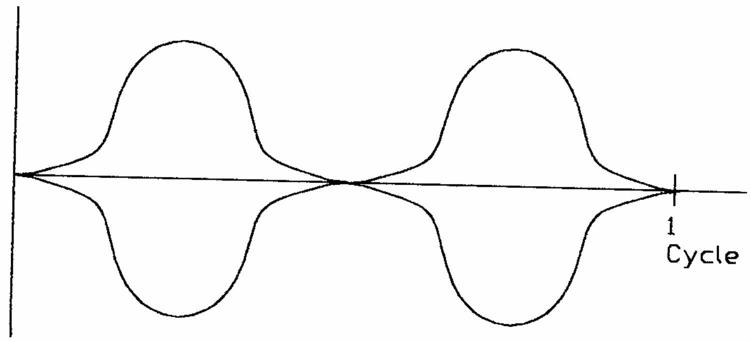
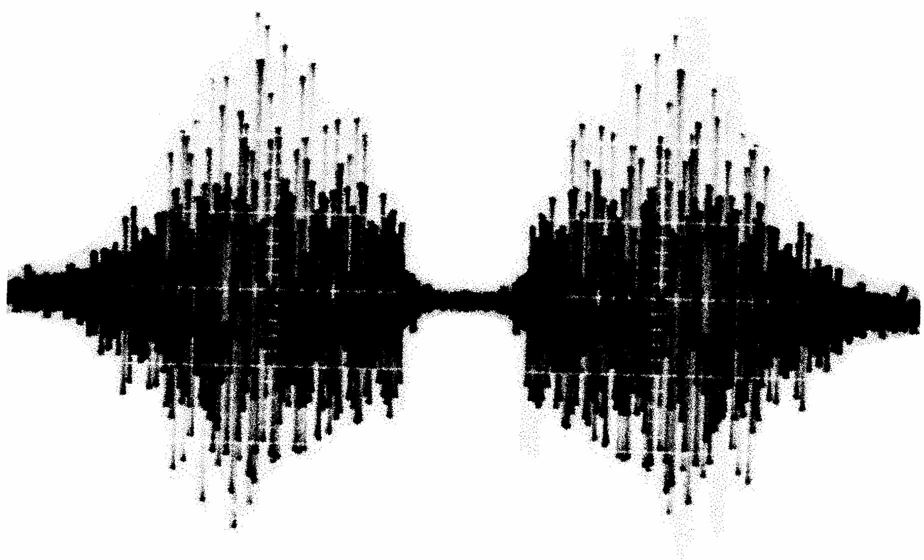
Since the voltages produced in the pickup coil are both positive and negative, the average is always nominally zero, which is semi-useless. Maximums and minimums are also of little value because the shape of this signal can change significantly without changing such things as peak amplitude. The commercial solution in finding a parameter was to select the RMS (root mean square) value of one cycle. Since the RMS value of a complete cycle is fairly stable from one inspection cycle to the next, this parameter is a good choice to select as the Magnetic Barkhausen Noise Parameter.

With the commercial equipment, the RMS value of the signal is calculated over one complete cycle and displayed as a numeric output. This output is recorded by traditional data acquisition systems and is tracked over the surface of the inspection specimen. At this point, signal deviations can be identified and quantified to determine the integrity of the part that is being inspected.



Envelope containing Barkhausen Noise Signal (1 cycle)



Photographic Scan of Barkhausen Emission Pulse

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Although it has only been stated implicity thus far, another key to making Barkhausen Noise a successful inspection tool is to capture the Barkhausen emission with a proper data acquisition system. This is extremely essential because so much of the Inspection capability is dependent upon sensor position and alignment. Hand held units seem to bounce around from value to value and appear to be very unstable in the measurement.

These systems are appropriate for sorting applications and gross measurements, however, the finer details of the inspection seem to get lost due to the operator interaction with the equipment.

2 APPLICATIONS

Barkhausen Noise is by no means a technology that is well understood or developed. In its current state, this technology has gained approval by many manufacturers as an acceptable way of detecting the presence of unwanted internal material stresses and anomalies such as grinder burn, however, if care is not taken to understand the inspection and determine careful reject criteria, there is a large possibility that the resulting inspection will not be any improvement over existing inspection methods.

This section is presented to address the area of grinder burn detection in the manufacturing environment. Barkhausen Noise has currently been used as a successful tool in detecting such defects in the manufacturing process, however, not without a number of serious setbacks. Those issues that were raised from these setbacks will be covered here to illuminate possible areas for failure and hopefully aid in successfully implementing this technology.

2.1.1 The Need for a New Method of Grinder Burn Detection

Traditionally, grinder burn has been detected through the use of an acid etching process. This process has been deemed by those who use it as caustic and environmentally unsafe, nevertheless, there has not been a good replacement. Working with acid etch provides many health concerns for those who use it and it is in the best interest of all parties involved to find a suitable replacement.

Also, there is the issue of consumables. With traditional etching methods, there are many types of materials that are consumed in the inspection process. These materials are generally high cost and require special treatment at the time of disposal. With Barkhausen inspection, these issues are virtually eliminated. The only issue may be sensor wear, which is to be expected with any type of contacting inspection technology.

The biggest issue with traditional etch methods is the issue of subjectivity. Etch indications are actually discoloration of the material surface. They occur in varying shades of grey and it is difficult as best to discern what is representative grinder burn.

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With the Barkhausen Noise inspection, this subjectivity is eliminated and the inspection process becomes purely quantitative.

2.1.2 Establishing Traceability Parameters

With Barkhausen Noise inspection, it is essential to establish the correct set of inspection parameter records. This is due to the inspection results extreme sensitivity to machine settings and variances in the manufacturing process.

Currently, a set of inspection parameters are recorded to track the manufacturing process such that if an error occurs, it can be easily determined what components in the process caused the error. The following list is the parameters that are currently recorded in the application of using Barkhausen Noise for the detection of grinder burn.

2.1.3 Traceability List

- Part Number
- Serial Number
- Inspector
- Grinder
- Probe
- Journal
- Grind Wheel Type and Grade
- Part Supplier
- Feed Rate
- Dress Frequency
- Coolant Type and Ratio

There are a number of these list items that are in italics. It was decided that these parameters were non-essential, and for production only use it would not be required that this data be collected.

2.1.4 Establishing Rejection Criteria

The most difficult part of validating an inspection with Barkhausen Noise is establishing the rejection criteria, or what noise signature determines and “good” part. In the preliminary stages, it was thought that a typical approach could be used to build a standard, borderline defect, record its reading, and then use that level as a rejection level. In theory, this is a great idea, however, it is next to impossible in practice. With Barkhausen Noise, there are far too many metallurgical parameters to control accurately to manufacture and acceptable master sample.

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The next best approach was to validate the inspection with an alternate and acceptable means of inspection. Since acid etch had long been the standard approach to grinder burn detection, it was decided that the Barkhausen inspection would have to identify and separate every indication that was seen by etch. Normally, there would be some concern that the methods may not correlate, however, in this case the sensitivity of the Barkhausen inspection is orders of magnitude better than the etch method of inspection.

2.1.5 Master Part

Although the master part does not represent a borderline reject component, it is still a useful tool to have in the inspection and quality processes. There are many types of error contributors in most measurement process that cause the baseline of the instrument to vary over time. These variances must be monitored to some degree to determine if the instrument is still operating an acceptable manner.

For the detection of grinder burn, a part was prepared by welding an area of the ground surface and then regrinding the surface back to its correct form. The weld puts many adverse metallurgical conditions in the surface of the part and when measured, produced a signature with characteristics that are easily tracked. This part is then measured on a consistent basis to determine if the instrument reading has been excessively affected by drift, electromagnetic interference, wear etc. If the master reading varies outside a certain range, the results can be numerically quantified and an appropriate maintenance action can be taken when a problem arises.

The next task is to actually determine the rejection parameters and the limit that signifies a bad part. This was a tedious task that was completed by painstakingly reviewing a large sample of inspection data. The data was scrutinised by a team of experts and the parts were verified by rejecting them with an alternate inspection method.

The rejection parameters were determined by processing the recorded data signals and numerically quantifying the aspects of the signal that would normally indicate the presence of grinder burn. These aspects could be described as peaks, valleys and localised variance.

In a cylindrical type scan, there is a tendency for the Barkhausen signature to have a slight wobble throughout the data set due to the geometry of the inspection, therefore, for specific applications it may be necessary to utilise some type of digital filtering. In the inspection that is addressed here, filtering was used to eliminate this “wobble” and also to eliminate the non-repeatable, small scale noise that occurs on every Barkhausen signature. This is a very common tool that is used in many measurement applications.

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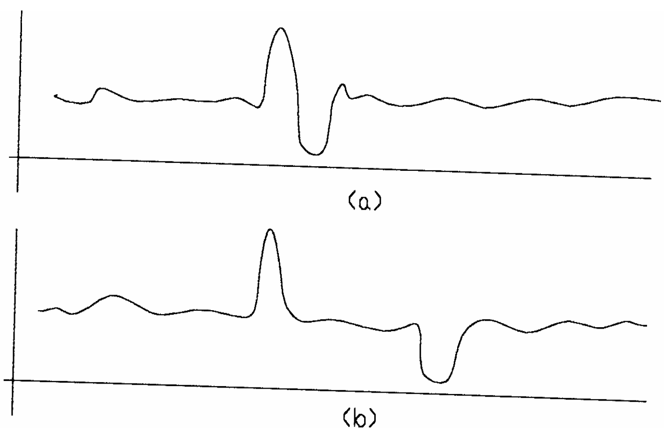
Another important aspect of the Barkhausen trace is signal mean. For traces that indicate continuous, severe burn, there is a possibility that the signal would be well behaved, but very high. For races that indicate sensor lift off, the opposite effect might be recorded. For these instances, a mean check must be implemented to verify that the instrument is operating within an acceptable range and good data is being collected, or that an unusual failure mode has not occurred.

After the analysis had taken place it was determined that the reject criteria should address the aspects in the following list. It was shown experimentally that these parameters were capble of identifying existing grinder burn on ground surfaces.

- The Largest Peak
- The Largest Valley
- The Largest Range
- The Largest Gated Range
- The Signal Average

After the initial work was performed, the development team identified the need for a special type of inspection process for the data. In the following figure, the range for trace (a) and for trace (b) are quite
Similar, however, the position of these anomolies varies significantly. The team felt that this represented different characteristics in the inspection part and needed to be treated different in the process of the data. Thus, a gated search was devised to determine the difference between readings that varied locally and readings that varied at relatively large distances apart. The width of this gate is controlled by the user and is used to identify largely varying features that are in close proximity to one another.

In figure (b) below, if a small narrow window is placed on the curve and moved from left to right, chances are, that at any given time, only a peak or a valley could be seen through the window. However, in figure (a) the same window might display both peak and valley for a singular position. This is the essence of the gated inspection process



Various Reject Barkhausen Noise Signatures

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The other parameters included in the reject criteria list are simply calculations based upon the mean of the signal. For example, the maximum peak is the maximum positive departure of the signal from the mean of the signal. The same applies for all of the other parameters.

2.1.6 Conducting the Inspection

To conduct an inspection using Barkhausen Noise equipment, there are a series of steps that must be followed to insure valid data collection. A complete version of the Cummins crankshaft inspection process is given in Appendix A, however, for general purposes the following considerations must be taken into account when setting up an inspection procedure.

2.1.7 Preparation Concerns

1. Part should be clean of dirt and debris
2. Part should be lightly oiled in the area of sensor contact
3. Part should be free of residual magnetism (see CES standard)
4. Part should be free from high electromagnetic fields

2.1.8 Traceability Concerns

1. Date and time
2. Part serial number
3. Inspector
4. Grinder
5. Probe
6. Journal

2.1.9 Data Collection Requirements

1. Adequate data sampling to cover entire surface of inspection specimen
2. Position and amplitude of Barkhausen signature should be recorded
3. Sensor should be adjusted for proper running levels
4. Electronic equipment should be adjusted for proper gain settings
5. Electronic equipment should be set for proper magnetisation of sensor

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2.1.10 General Comments on Inspection with Barkhausen Noise

Sensors are typically designed to accommodate a variance in part geometry, however, they are not so versatile that they can work adequately for parts outside of manufacturing tolerance. When collecting data it is good practice to include in the process a method for detecting sensor lift-off. This lift-off is a common source for low signal levels and should be caught by the software processes, however, it is still necessary that the operator be aware of such possibilities.

Dirt and debris can dramatically effect the data acquisition during an inspection, however, oil seems to have very little or no effect. It has been determined that a light oil is useful for inspection in that it provides a protective barrier between the Barkhausen sensor and the inspection surface. This is not to say that there is a risk of damage, however, for it is common to see wear on the sensors. Simply, it is felt that it is good practice to make an effect to increase sensor life to a maximum.

Depending on the supplier of the Barkhausen equipment, the sensors may or may not be shielded from electromagnetic interference. It is very important that an attempt is made to understand what effects the environment may be having on the Barkhausen inspection. If the environment is affecting the inspection adversely, extra shielding or relocation of the equipment may have to take place.

Sensor wear can be an issue with the inspection, especially when trying to determine if the sensitivity settings are correct. With use, a sensor’s contact surface will wear in a manner such that it becomes machined to fit the part ge0metry. This causes better coupling with the material, thus, it typically increases the average of the collected data. This is not a bad thing; however, care must be taken so that parts are not rejected without cause.

One of the biggest mistakes made with this technology is that people often try to correlate the results of the Barkhausen inspection with another technology that does not necessarily measure the same characteristic. Even when achieving excellent correlation results, one must understand that this technology sees many metallurgical characteristics simultaneously.

3 CONCLUSIONS

Through a great deal of effort, it was determined that Barkhausen Noise is an effective wat to detect hidden metallurgical properties of a manufactured part, such as grinder burn. With the proper approach, the technology can be used successfully and with a large degree of certainty, however, there is a risk if care is not taken. It has been demonstrated that this technology is cost effective and capable of identifying all defects that the previous technology could locate.

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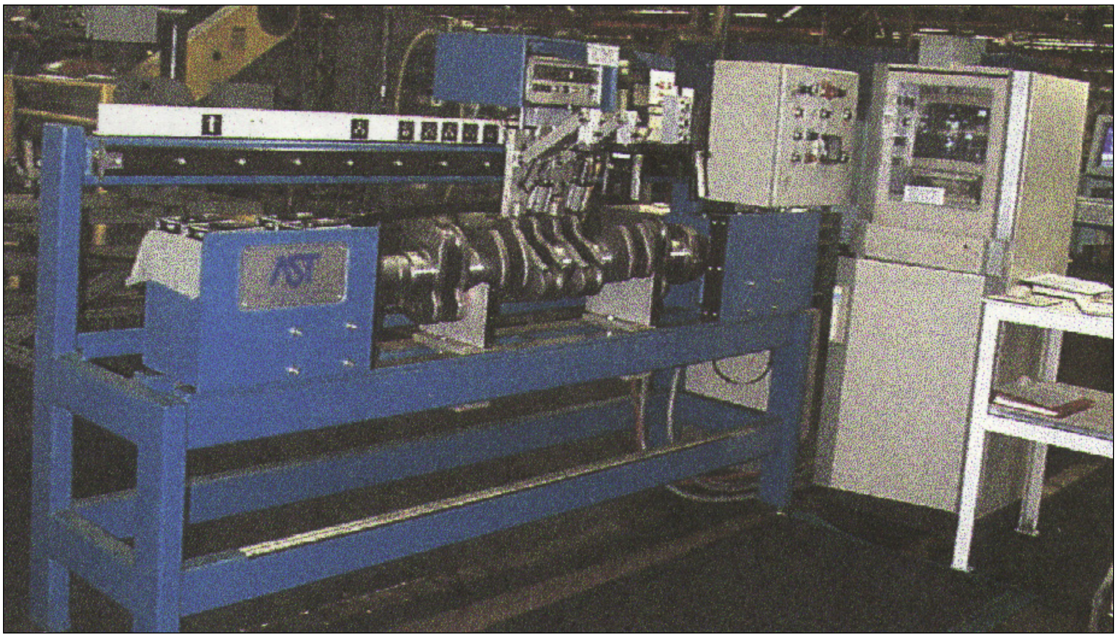
4 APPENDIX A

INSPECTION PROCEDURE FOR GRINDER BURN DETECTIONIN GROUND CRANKSHAFT SURFACES – EQUIPMENT BY AST

The following series of steps are an application for the operation of a Barkhausen Noise Inspection apparatus that is located within Cummins Engine Company, Inc. The steps are outlined such that an operator that is knowledgeable of the equipment would be able to complete an inspection properly. Following is a photo of the apparatus installed at Atlas Crankshaft in Fotoria, Oh.



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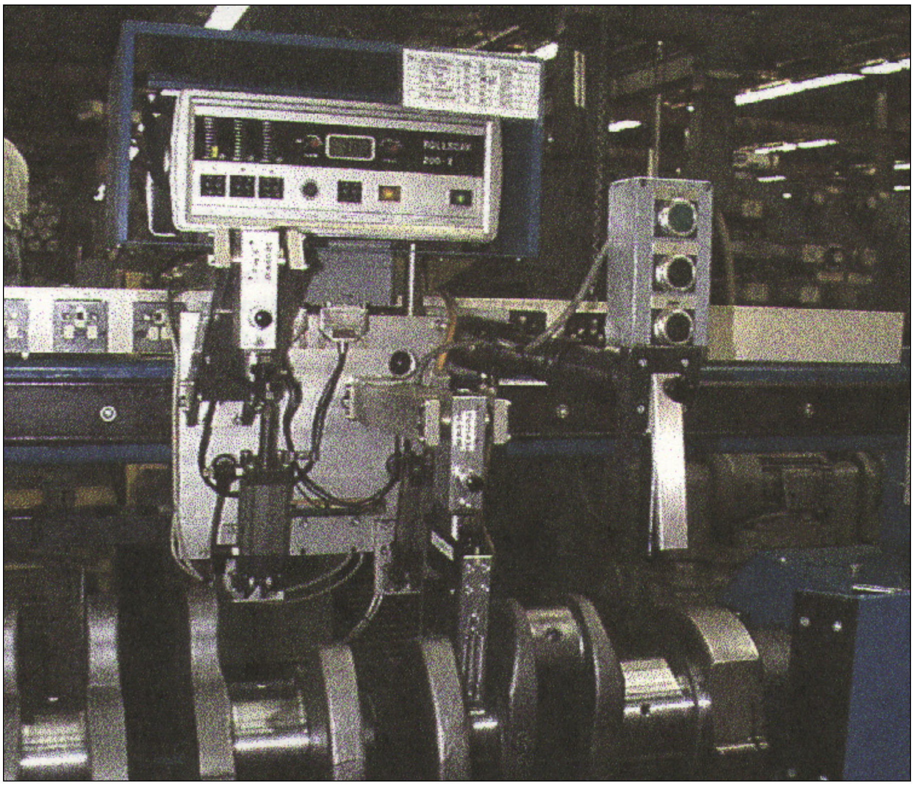

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