The Barkhausen Noise Inspection Method for Detecting Grinding Damage in Gears

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Introduction

When hardened steel components are ground, there is always the possibility of damage to the steel in the form of residual stress or microstructural changes. Methods for detecting this sort of damage have always had one or more drawbacks, such as cost, time, complexity, subjectivity, or the use of hazardous chemicals.

A relatively new method, known as Barkhausen noise analysis, meets the demand for measuring defects in ground steels in a very reliable, standardized and cost-effective manner (Refs. 1 and 5). Use of this technique is simple and can reduce product failures to 0%. Semiautomated gear inspection systems have been employed by gear manufacturers to take advantage of the capabilities of Barkhausen instrumentation.

Combined with dimensional inspection, hardness tests and periodic metallographic analysis, the Barkhausen noise analysis method can help close the loop on insuring product quality. Barkhausen noise analysis can be a strong link in the chain that ultimately leads to a long and reliable gear life.

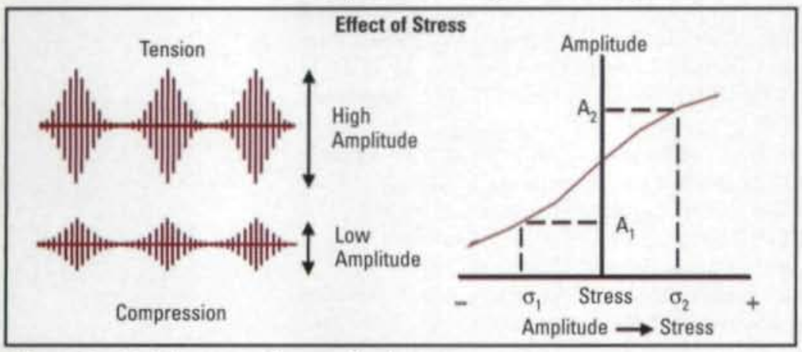


Figure 1—Barkhausen noise amplitude vs. stress.

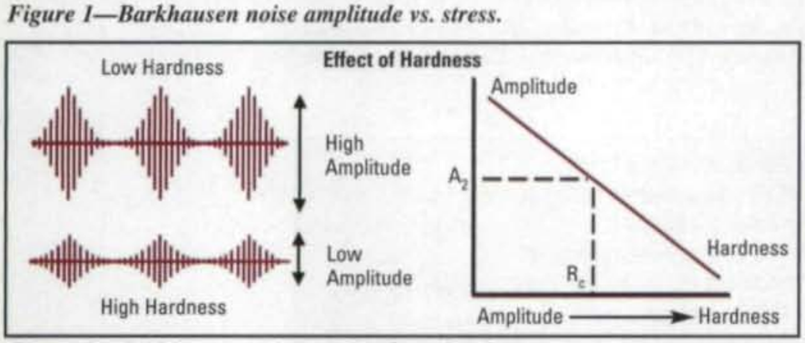


Figure 2—Barkhausen noise amplitude vs. hardness.

Measurement Techniques and Instrumentation

Barkhausen noise analysis is a technique based around a relatively simple concept involving ferromagnetic materials and a magnetizing field. When a magnetizing field is placed near a ferromagnetic material, the material undergoes a net magnetization change. This change is a result of the microscopic motion of magnetic domain walls within the material.

When a domain wall moves, it emits an electrical pulse that can be detected by a coil of conducting wire placed near the material. These discrete pulses are measured in a bulk manner, resulting in a compilation of thousands of electrical pulses referred to as Barkhausen noise (Refs. 3, 6, 7 and 9). The amplitude of this signal is sometimes referred to as the magnetoelastic parameter (MP). The amplitude is affected by anything that impedes the motion of domain walls. Some factors to consider are inclusions, precipitates, dislocations, grain boundaries, and residual stresses.

In the sense of macrometallurgy, we may sum up these factors in two categories, hardness and residual stress. In general, Barkhausen noise is increased with decreasing hardness and increasing tensile stress, and conversely, Barkhausen noise is decreased with increasing hardness and increasing compressive stress. This principle is illustrated in Figures 1 and 2.

The instrumentation required to detect Barkhausen signals is illustrated in Figure 3. A magnetizing field is created and applied to a ferromagnetic material through the use of an electromagnet. The material reacts to the magnetic field as described above and emits Barkhausen bursts, which are captured by a sensor consisting of a coil of conducting wire. The signal is then amplified and filtered. The amplitude is calculated using an RMS equation, and the data is digitized for display and output to a computer.

The Nature of Material Defects Caused by Grinding

Grinding damage is the result of energy being converted to heat. This heat is concentrated in the surface layers and may cause undesirable effects if not properly managed. Some of the factors affecting the rise in temperature in the surface layer include the coolant type, coolant concentration, coolant age, coolant flow, grinding wheel type, grinding wheel speed, grinding wheel wear, feed rate and prior processing of material, e.g. different heat-treat batches.

Wojtas, et al. (Ref. 9) explain that damage may start with the partial relaxation of desirable compressive stresses at temperatures less than 500°C. As temperatures increase to nearly 600°C, B-class thermal damage, also known as retempering burn, occurs. The effect will be an overtempering, causing a decrease in surface hardness and the onset or materialization of tensile stresses. Further temperature increase to greater than 720°C will cause D-class thermal damage, also known as rehardening burn. This defect will include regions of very hard and brittle material, as well as surrounding areas of B-class burn, "soft" material.

The residual stresses will also be complex due to ranging levels of damage across the surface. Some areas will be compressive, while others will be highly tensile (Refs. 2 and 9).

The existing techniques for detecting the damage described above include visual inspection via nital etching (Ref. 4), microhardness testing, residual stress profiling with x-ray diffraction and Barkhausen noise analysis. Each of the defects described above can be detected via Barkhausen noise analysis and can be done in a totally nondestructive manner. The x-ray diffraction technique can also be used in each case; however, it is extremely time-consuming, expensive, and destructive. The nital etching and microhardness techniques are quick and easy, but they can only detect B- and D-class damage. Furthermore, hardness testing is destructive and nital etching is subjective. Figure 4 shows some of the features of Barkhausen noise analysis compared to the most widely used grinding-burn detection technique, nital (temper) etching (Refs. 2 and 9).

It was seen in Figures 1 and 2 that the Barkhausen signal increased for decreasing hardness and for increasing tensile stresses. This is the exact scenario for retempering grinding burn as seen in Figure 5. Since grinding damage affects the hardness and stress in ways which increase the Barkhausen signal, detection of grinding damage by the Barkhausen noise analysis is quite simple. If the amplitude increases, then there is burn.

The exception to this rule is for rehardening zones. In the case of rehardening zones, the signal may decrease, but these zones are always surrounded by severely retempered zones, which exhibit large amplitudes of Barkhausen noise (MP).

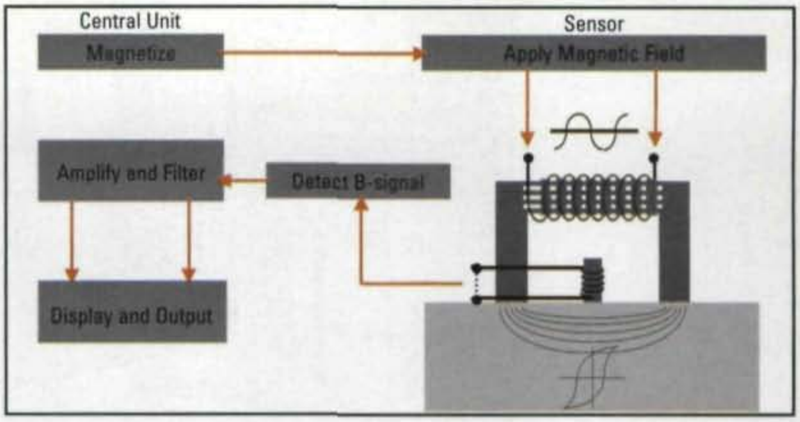


Figure 3—Instrumentation required for Barkhausen noise analysis.

Comparison of Inspection Methods			
	Barkhausen Method	Nital Etch	Microhardness
• Nondestructive	Yes	No	Yes
• Use of Chemicals	No	Yes	No
• Automated	Yes	No	No
• Reliable	Yes	No	No
• Evaluation Through Coatings	Yes	No	No
• Danger of Hydrogen Embrittlement	No	Yes	No
• Influenced by Both Stress and Microstructure	Yes	No	No

Figure 4—Comparison of nital (temper) etch to Barkhausen noise analysis.

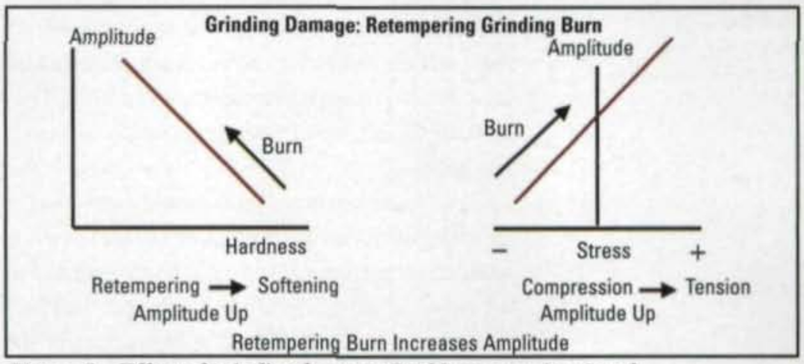


Figure 5—Effect of grinding burn on Barkhausen noise signal.

Instrumentation for Gears

There are several different methods to make the Barkhausen measurements. They are manual measurement by general-purpose or custom sensors, manual measurements made with the aid of fixturing, and semiautomated or fully automated methods.

Here we introduce semiautomated Barkhausen noise evaluation of transmission gears.

Outline of Instrumentation and System Operation

The inspection system, shown in Figures 6 and 7, consists of a linear x-y motion controlled sensor, a live center, a three-jaw chuck with software-controlled rotation, a Barkhausen noise analyzer, a computer, and data acquisition and analysis software. Parameters for rotation and x-y motion are programmed into the computer for each individual gear type. The operator then installs a gear manually,

Figure 6—Gear inspection system, with gear inspection stand and computer/ROLLSCAN™ cabinet.

selects the type of gear from the software and presses Start. The remaining operations are all automatic.

The sensor moves into place on the gear tooth—see Figures 8 and 9—then axially scans the preset locations on the tooth, up to four radial locations per tooth. The gear then rotates slightly, allowing the sensor to contact the opposite flank, which is then scanned in the same manner as the first flank. Next, the sensor moves away from the gear and the gear rotates, allowing the sensor to move in to test the next tooth. This continues for the preset number of teeth and the results for each scan are presented on the computer monitor with the status of ACCEPTED or REJECTED, based upon programmed rejection conditions.

The system can be set up to measure one tooth or all teeth, and it can be programmed to measure one tooth, then skip five and test the seventh tooth and so on. A typical setup is to use two scans per flank and to measure a total of four teeth at approximately 90° from one another. This type of setup drastically decreases the measurement time, compared with measuring each tooth, without sacrificing reliability. When the measurement is completed, the results can be saved to a file or output to a printer.

Getting Started with Barkhausen Noise Analysis

In order to get started with Barkhausen noise analysis, one must first obtain a correlation between the Barkhausen noise signal and some other measure of the severity of burn, e.g. nital etching. Based upon the correlation data, a criterion for rejection can be established for the Barkhausen instrument. One simple inspection method is based upon the fact that the MP values can be directly related to the results of a visual nital etch inspection. By measuring a variety of production parts and comparing them with nital etch inspection, a correlation can be made and the level of burn can be quantified using the magnitude of the Barkhausen signal, or magnetoelastic parameter (MP).

By examination of the correlation, a criterion for rejection is established. The rejection criterion is then entered into the computer program for the type of gear being used. Once the rejection criterion has been entered, Barkhausen noise analysis of production samples may begin. An example of the setup used for one gear type on a motorcycle transmission gear system is shown in Figure 10.

The figure illustrates a correlation between the magnetoelastic parameter, MP, and the visual indication of burn from nital etching. The left graph is a correlation for the maximum MP values measured on all scans of a gear, while the right graph is a correlation for the difference between maximum and minimum MP values measured on all scans of a gear. On each graph, a cross has been added to indicate the rejection criterion. In each case, the lower left quadrant indicates acceptable samples while the upper right quadrant indicates unacceptable samples. Therefore, by setting the maximum rejection limit to 60 MP and the difference rejection limit to 20 MP, all parts rejected by nital etching will also be rejected by the Barkhausen noise analysis.

The example given indicates some scatter in the data, and it is only for a relatively small group of parts. Based upon this example, it would be wise to choose rejection criteria that are slightly lower than those indicated. This would be taking a conservative stance, but you would be 100% positive that no rejectable parts are passed. In order to increase confidence in results, all final correlations are being done with 60 sample groups tested by three different users. This technique will further increase confidence in the rejection criteria and limit the need for further analysis of the gears.

When a gear measures near or above the rejection criteria, it is common practice to check the gear further using nital etching. This type of "extra" analysis is excellent for confidence building, especially if the rejection criteria were established using a small group of parts. Over time, operators would become more confident that the analysis system and the established rejection criteria are reliable and true.

Benefits of Automated Barkhausen Noise Inspection

Early detection of damage. Grinding damage usually occurs as a result of wheel wear, but may also occur due to incorrect feed rate, wheel speed, or various other changes, as mentioned before. In a production cycle that outputs large numbers of parts every hour, it is essential that errors are detected quickly. Nital etching techniques can take several minutes and are not always conveniently located with respect to the grinders. Because of this, etching is typically done once an hour or less; therefore, detecting errors is by no means fast. This can be a huge loss in time and money on damaged product. The Barkhausen technique can be established such that detection is always within a matter of minutes of the error, resulting in thousands of dollars in savings. Some users have reported a return on investment in as little as three months.

Record of results. The Barkhausen noise amplitudes (MP values) are recorded for each individual gear, and the data can be saved and recalled for review, if necessary. Nital etching has no record of the results unless the operator keeps a logbook, and the etch results still are subject to human error.

Quality-Performance Control Chart. The Barkhausen results can be used for statistical analysis, if necessary.

Decrease warranty repairs. Barkhausen noise analysis can aid in monitoring and preventing the possibility of generating undesirable surface conditions in manufactured components. This is due to the increase in confidence when measuring burn. By eliminating etching and using a proper Barkhausen noise analysis, one can significantly enhance process capability, thus reducing risk of producing parts that challenge specification compliance.

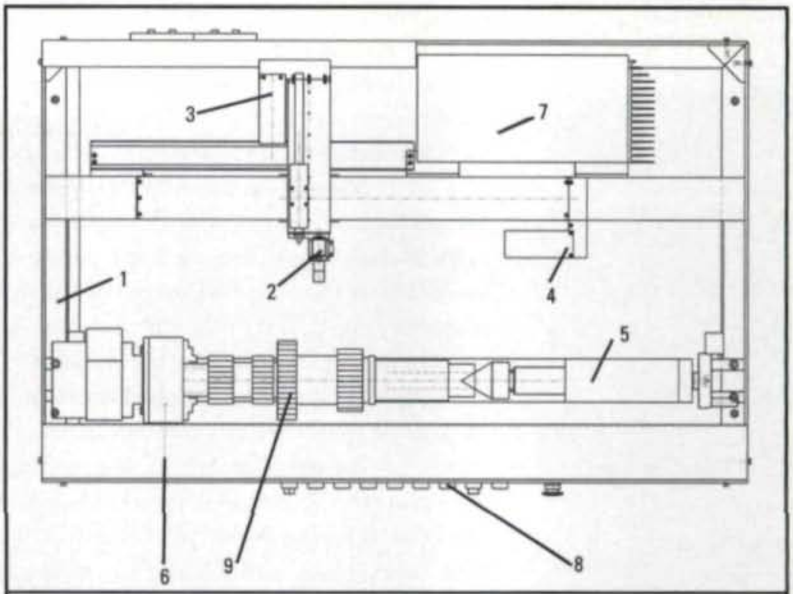
No consumables, low maintenance cost. Barkhausen noise uses no chemicals or consumables of any sort, whereas the acid etch technique requires close monitoring and is difficult to maintain with today's increasing environmental standards.

Setting Up the Grinding Process Using Automated Barkhausen Noise Inspection

For an application such as transmission gears, it is not unlikely for the same grinding machine to be used to grind several different types of gears. This is true of many applications, especially when one facility is required to produce hundreds of different types of similar parts. In these cases, quickly setting up the grinder and changing from part to part is essential.

As mentioned earlier, nital etching takes several minutes, and the etch facility may be located hundreds of feet from the grinder. A typical setup requires that the operator set up the grinder for a particular part number and then run a test sample. Then the part is etched and, based upon the results of the etching, changes are made to the grinder. This iterative process continues until the operator is satisfied with the results of the etching. This procedure can take from several minutes to an hour or even more, even for an experienced operator.

Setting up a grinder using Barkhausen noise analysis is based upon the same principle. But the



1. Gear-stand frame	2. Sensor	3. Axial motion
4. Horizontal motion	5. Live center	6. Drive head
7. Control logic box (SL)	8. Operation panel	9. Sample

Figure 7—Gear inspection stand.

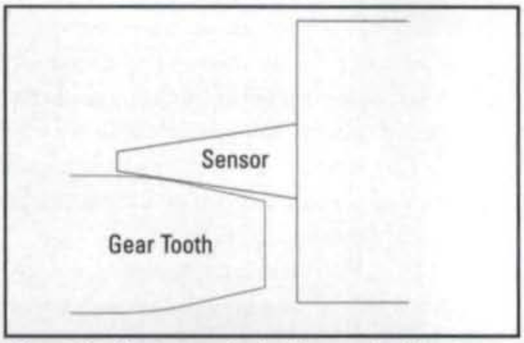


Figure 8—Sensor contact with gear tooth.

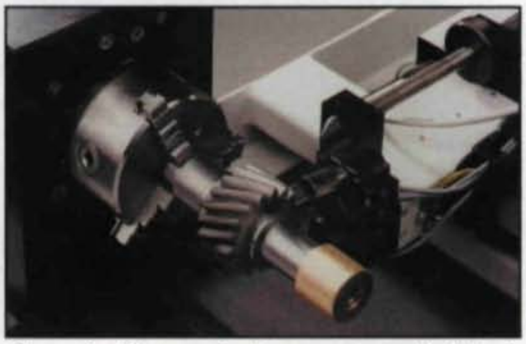


Figure 9—Photograph of gear contact with helical-type gear. (Photo courtesy of Stresstech Oy, Finland.)

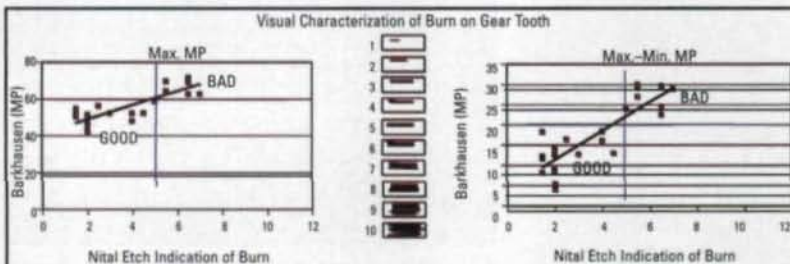


Figure 10 —Maximum MP correlation with nital etch (left) and maximum–minimum correlation with nital etch.

instrumentation is usually located very near the grinder and the feedback is immediate. Changes can be made to the grinder within a minute or two of the grinding operation on the test sample, and the time it takes to complete the iterative process is drastically reduced. In addition, the data is quantified, so that the operator has some idea of the changes necessary, rather than guesswork based upon etch results. It is not hard to see that using Barkhausen noise analysis simply for setup can save a lot of time and money.

Monitoring the Grinding Process Using Automated Barkhausen Noise Inspection

After the initial setup of a grinding machine, it is wise to monitor the machine by testing production samples at periodic intervals or by as much as 100% inspection, if feasible. This type of analysis can be done quickly and easily using an automated Barkhausen noise analysis system. By testing as many parts as deemed necessary, based on the rate of production, this type of testing is used to insure that quality parts are being produced and to find any problems, such as a worn-out wheel, before they become costly. The typical Barkhausen noise analysis system can be an invaluable tool for monitoring finish-grinding operations during production, whether the throughput is two parts per hour or 200. It is a fast, easy and nondestructive technique of determining whether the grinder is correctly performing its function.

Interpreting the Results

Interpreting the data from the analysis system is done by falling back on some of the basic theory of Barkhausen noise and the influential parameters that affect the signal. With a slight knowledge of gear design and processing, and a basic understanding of Barkhausen noise, a person can make some observations regarding the results of the analysis system. First, we know that Barkhausen noise increases when hardness decreases and when compressive stresses are relieved. In general, Barkhausen noise increases

Figure 11—Measurement screen and data from a typical setup using four scans per flank on four teeth from Stresstech's GEAR software.

based upon the amount of damage done in grinding.

Intuitively, it makes sense that the worst defects will occur near the tip of the gear tooth, since there is less material there to dissipate the heat generated in grinding. Figure 11 shows the data output on the computer screen. The output represents a measurement on a gear using four scans per flank on a total of four teeth. The data is presented in a way that mirrors the image of a tooth.

The graph consists of two curves. One is for the maximum data points and the other is for the minimum data points. If we focus on one plot, the first data point on the far left is for the outermost point, radially, of the first flank. Then, moving to the right, the next three points are for the 2nd, 3rd and 4th scans of the first flank. Continuing rightward, we move to the innermost point on the opposite flank and then out to the tip of the opposite flank with the 8th point of the plot. That completes measurement of the first flank of tooth 1 and the opposite flank on tooth 2.

Moving on, the next tooth measured is the first flank of tooth 7 and then the opposite flank on tooth 8. This continues, until the final point on the opposite flank of tooth 22. This gear happens to have 27 teeth, and the setup is to test between teeth 1 and 2, 7 and 8, 14 and 15, and finally 21 and 22. This corresponds to testing at about every 90°. Now, returning to the type of damage we would expect on a gear tooth and reviewing the plots, it is evident that the larger MP values come from the tips of the gear teeth. This would validate the expectation that more burn will be evident near the tip, due to decreased heat dissipation.

There are two other observations that can be made with respect to the measurement in Figure 11. One is that the data for the maximum and minimum at any given point are very close. This indicates that at any given radial position, the change in the Barkhausen noise signal is negligible and therefore the change in microstructural properties and residual stresses, at that radial position, are also negligible. The second observation is that the data from flank to flank and from tooth to tooth are very similar. This indicates that the Barkhausen noise signal does not vary from tooth to tooth or on opposite flanks.

These observations can be very important in determining the cause of damage. For instance, if there is a variation from flank to flank that rejects one flank and not the other, it may be that the grinding wheel is not centered between the teeth and one tooth has more material removed than the other. These types of observations and thought processes can be a very valuable troubleshooting tool, resulting in time savings.

Another observation that can be made during measurement is an increase in the overall signal level of a part. The difference between the maximum and minimum values may remain small, but the level may increase from normal levels of 40–50 up to levels of 70–80. If this type of change occurs, it may not be the result of grinding damage. In fact, this type of change may be the result of prior processing. Several parameters could change, but the most common is a change in heat treatment. If the heat treatment changes, affecting the hardness or the amount of retained austenite, the Barkhausen signal observed after grinding will be changed (Ref. 8). If these kinds of changes are common, the difference between maximum and minimum rejection criteria becomes the best tool for detecting grinding damage.

But, if the maximum rejection criterion is used, these types of changes will be flagged. Using this type of rejection is preferred, because it scans for other changes in processing that could be potential problems. Once a potential problem is identified, it is then up to the process engineer to review the plots and troubleshoot the probable causes.

For example, a gear is tested that indicates high readings. The operator signals the process engineer, who requests that the gear be etched for further analysis. The gear does not have any visual indication of burn using the nital etching technique. The process engineer then evaluates the plots to find that the maximum values have exceeded the rejection criterion, but the maximum–minimum rejection condition is well within limits. The process engineer then decides to have a hardness test done.

The hardness test indicates a slightly lower hardness than usual. This may be the reason for the increase in signal. The process engineer then decides to check the retained austenite level and to cut a sample and investigate the case depth. The results indicate that the austenite level has decreased from normal levels and case depth is close to normal. The engineer concludes that the gears can be passed through quality control, but the furnace should be checked and retained austenite levels should be monitored.

As you can see from this example, such a system can be much more than a "grinder burn" detection system. That is precisely why it is referred to as a Barkhausen noise analysis system.

Other Successful Applications of Barkhausen Noise Analysis

Barkhausen noise has been successfully applied in many areas, of which grinding is the most widespread application. Other applications include detecting defects in hard turning and heat treating, measuring the effectiveness of shot peening, measuring residual stresses, and predicting fatigue life. Some examples are detecting grinding damage on cam lobes, crankshaft journals, racks and pinions, bearings, and aircraft landing gear (even through chrome); measuring shot peen effectiveness on welds; and measuring the effects of straightening on camshafts and crankshafts.

Conclusions

Barkhausen noise analysis is a very useful tool for measuring damage in ground steel components. The principles behind the measurement technique are sound, and application to measuring gears has proven to be not only useful for determining the amount of grinding damage, but also as a troubleshooting tool for process quality control. Barkhausen noise analysis is much faster than the existing method of nital etching, in addition to being a superior technique in terms of sensitivity to damage and objectivity of results.

The measurement technique and software are very user friendly. The system can save time and money in setup and monitoring, as well as in troubleshooting. When the Barkhausen system is fully implemented, etching facilities can be reduced to small quantities for use in a metallurgical laboratory. Overall, it has been shown that an automated Barkhausen noise analysis system can effectively monitor undesirable surface effects caused by grinding in a manner superior to any other in an easy-to-use, cost-effective device that has been shown to give a return on investment in as little as three months. ○

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