ELECTROMAGNETIC TESTING TECHNIQUES FOR QUALITY GRADING OF NONFERROUS ROD AND WIRE

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INTRODUCTION:

Electromagnetic nondestructive inspection is widely used as a technique for grading the quality of nonferrous rod and wire. The inspection is performed without disruption to the manufacturing process. The two individual inspections of eddy current flaw detection and ferrous inclusion detection are performed with a single non-contact encircling coil.

Eddy current inspection is a very sensitive technique to detect cracks, monitor the general surface condition, and detect defects occurring on or near the surface of the material. By interrogating the entire outer circumference of the rod or wire, it also provides an early indication of die wear. Ferrous inclusion inspection detects ferrous particles that become imbedded in the rod or wire during the manufacturing process. This technique provides an early indication of roll wear. Early detection of ferrous inclusions helps to eliminate many of the wire breaks that occur during further size reduction processes. It is interesting to note that as the line speed increases, as is typically the case in reduction processes, the detectability of ferrous inclusions also increases.

The electromagnetic inspection process provides a very effective method of ascertaining the product quality of non-ferrous rod and wire. The quantity and density of individual surface flaws and inclusions are continuously compared to user defined pre-established quality grading parameters. It will provide the customer with an incremental progress report and a proper technique to determine the product’s overall quality. The electromagnetic test is also a very effective tool for process control monitoring of the manufacturing process. Proper implementation of the electromagnetic test technique can insure decreased downtime, improve product yield, and help produce a better quality finished product. Standard features of the electromagnetic test include compatibility with plant software, permanent records of the test results, and documentation for each coil of rod or wire, each customer order, and each production run.

COMBINATION TEST (SINGLE COIL INSPECTION):

The electromagnetic technique performs a continuous inspection of the non-ferrous rod and wire during the actual manufacturing process. The product passes through an encircling test coil and holder apparatus without contact. Since the rod and wire do not come into physical contact with the test coil, the inspection does not interrupt or slow down production. Both electromagnetic inspections (eddy current inspection and ferrous inclusion detection) are performed simultaneously with the same encircling test coil. Since the encircling coil completely surrounds the product, the entire outer circumference of the rod or wire product is inspected. The advanced filtering capabilities for the electromagnetic inspection do not impose any restrictions on the speed of the manufacturing process. Testing can take place at line speeds up to 20,000 feet per minute (100 meters per second).

Figure 1 – Combination Eddy Current and Ferrous Inclusion Test Coils

The rod or wire is fed through the transmitter system, which consists of a single encircling coil and a magnetizing coil holder. A shielded coil cable sends the test responses to the combination eddy current and ferrous inclusion test electronics. The magnetizing coil holder has steel guides at both the inlet and outlet sides. The guides concentrate the magnetic field into the rod or wire product to magnetize the ferrous particles to provide for detection. Magnetization is not a requirement for the eddy current inspection. The signal from the coil will be transmitted through a shielded coil cable into the ferrous inclusion detection electronics first and then into the eddy current electronics.

Figure 2 – Magnetizing Coil Holder with Permanent Magnets

Pictured above is a magnetizing coil holder using permanent magnets to provide magnetization for the ferrous inclusion inspection. Although the permanent magnet system does not have the field strength of electromagnets, it is less expensive and less costly to operate than the electromagnet. Pictured below is an electromagnet coil holder. The electromagnet provides significantly more magnetizing field strength. The detectability of ferrous inclusions increases with increased magnetizing field strength.

Figure 3 – Magnetizing Coil Holder (Electromagnet)

The electromagnetic inspection can take place in the process directly after the casting and before the cooling bed. In this case, a water-cooled test coil and holder apparatus is placed inline as shown in the simple process diagram shown below. The water-cooling protects the coil windings from the excessive temperatures of the process.

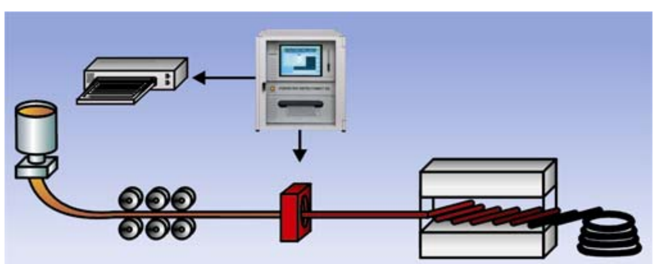

Figure 4 – Hot Testing Process Diagram

The test coil can also be placed after the cooling system using standard ambient temperature coils. Typically in copper processing, this initial manufacturing process produces rod to a finished diameter of 5/16” (7.9mm). A simple process diagram is shown below. The test coil is located after the cooling bed and just prior to the coiling operation.

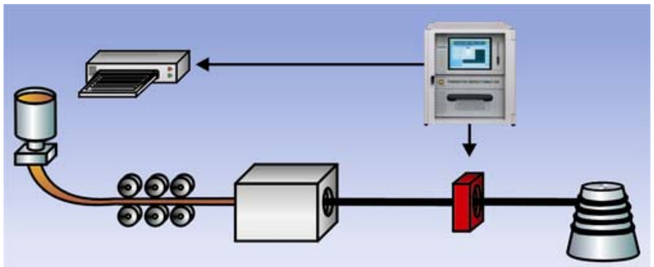

Figure 5 – Testing After Cooling Operation

In the next process, non-ferrous rod may be further reduced through a first drawing operation to produce an intermediate diameter. A first pass reduction, for example, may reduce the rod size to 7/32" (0.228", 5.8mm). The purpose of the electromagnetic tests at this point in the process is to detect any defects and ferrous inclusions severe enough to cause a wire break during the *next* reduction process. If the first reduction pass is made, for example, to 7/32" (0.228", 5.8mm), a 30% reduction from the rod size, virtually all inclusions that would cause a wire break will have been already detected. It is claimed that for reductions less than 50% of wire diameter, no inclusions capable of causing a wire break will escape detection of the ferrous inclusion test. Tests performed during one operation, therefore, will determine the success for the next drawing pass.

In addition to detecting inclusions and defects in the material, the focus of the inspection is to grade the quality of the rod or wire product and determine its suitability for future sizing and end use. Before elaborating on the method and techniques used for the grading of non-ferrous rod and wire, details regarding the actual inspection techniques will be investigated. Eddy current inspection detects stress cracks that occur during the casting process in addition to scaling and laminations that occur during the rolling process. Ferrous inclusions can be introduced during the rolling process or during the casting process if ferrous materials are inserted into the scrap.

EDDY CURRENT SURFACE CONDITION AND FLAW INSPECTION:

Eddy current inspection is the more traditional of the two electromagnetic test techniques used for the nondestructive inspection of nonferrous rod and wire. Eddy current inspection is a very sensitive method for detecting cracks and other defects found on or near the surface of the material being inspected. It is also a very effective method for monitoring the general surface condition of the rod or wire product.

In eddy current inspection, an alternating electrical current is provided at a fixed frequency into a test coil's primary field windings (excitation coil). This alternating current produces an alternating magnetic field. As the rod or wire passes through this magnetic field, eddy currents are induced into the product along its circumference. These eddy currents generate a secondary magnetic field in opposition to the coil's primary magnetic field. The secondary magnetic field from the eddy currents induces a current into the coil's secondary measure windings (receiver coils). The eddy current instrument electronics interrogates these returned signals and compares them to defined threshold limits. If these signals exceed the define threshold limits, they are counted as flaws. The density and quantity of flaws are used to determine the rod or wire quality. The figure below shows the field windings (excitation coil) and the measure windings (receiver coils). The orientation of the magnetic field from the field windings is also shown.

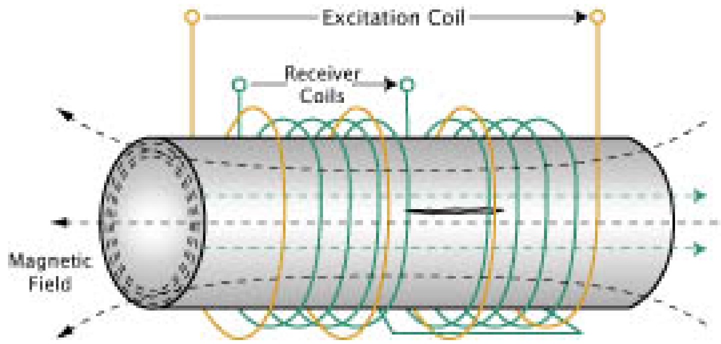

Figure 6 – Eddy Current Coil Configuration

There are no test standards available for the inspection of continuously manufactured non-ferrous rod and wire. Producers do not have the luxury of using saw cuts, drill holes, or EDM notches in the material to produce a consistent and repeatable indication. Once the product leaves the test coil, the same material cannot be tested under the same conditions. The only possible set up technique involves making a basic setup, establishing a typical baseline signal display, and then comparing subsequent results to that pre-established baseline.

The product quality is then determined on the basis of how these signals compare to this established baseline signal response. An initial setup is made during mill operation to establish the instrument screen display amplitude to 15-20% for assumed good product. The baseline eddy current signal is adjusted with the sensitivity (gain) control. As additional rod or wire passes through the coil, the signal amplitudes are compared to this initial setup. If the product quality is good, then the signals obtained from the product are fairly uniform and consistent. Disruptions in the surface quality of the rod or wire create alterations in the returned signals from the coil's measure windings. Disruptions to this "normal condition" can be interpreted, depending on their severity and pattern, either as defects or as deteriorating surface quality.

The measure windings in the test coil are wound in differential. Because one measure winding is continuously compared to the other measure winding, the coil is extremely sensitive to small surface cracks and quickly occurring defects in the product surface. Cracks and other sharply generated defects cause an immediate and abrupt disruption to the flow of eddy currents in the rod or wire. Therefore, an immediate and abrupt increase to the eddy current signal amplitude will be displayed. Medium or large defects in the material will trip the pre-established thresholds in the instrument's evaluation electronics.

Differential measure windings will, however, tend to balance on a continuous longitudinal defect such as drawing process scratches. These scratches show up as a cluster of higher density and lower amplitude signals. If the surface condition degrades gradually, the signal will also degrade gradually at an amplitude higher than the normal surface noise pattern. The use of flaw density analysis and flaw counting is used to accomplish detection of these conditions. The severity and density of these disruptions are monitored through the use of several eddy current threshold amplitudes and through section length analysis. The number of flaw counts exceeding each threshold per section will provide information about the severity and density of these flaws. An experienced eddy current operator will recognize these trends and be able to identify the reasons why they occur. In much the same way that ferrous inclusion detection will be shown to structure a roll replacement schedule, the eddy current patterns can predict the breakdown of dies. A preventive maintenance schedule can help eliminate these problems before they occur and increase the overall yield of higher quality manufactured product.

Test frequency selection depends on whether the depth of penetration or the defect size is more critical. Test frequencies of 100 KHz or 30 KHz are typically used for the electromagnetic inspection. Higher test frequencies will detect smaller defects but with less field penetration. Lower frequencies provide better field penetration but sacrifice some flaw detectability. Both 30 KHz and 100 KHz are successfully implemented in non-ferrous rod and wire test lines.

FERROUS INCLUSION DETECTION:

The detection of ferrous particles is a very important inspection for producers of non-ferrous rod and wire product. Ferrous particles are usually introduced during the manufacturing process. The purpose of the inspection is not only to detect the ferrous particles, but also to provide the manufacturer with information that will assist in their elimination. Most ferrous inclusions that cause wire breaks during further reduction processes is due to the deterioration of mill rolls.

The ferrous inclusion inspection requires the ferrous particle to be magnetized. The coil holder must provide a DC magnetizing field strength of sufficient strength to magnetize any ferrous particles that may be imbedded in the material. The diagram below shows the ferrous particle being magnetized. According to Lenz' law, the magnetized particle (dipole) induces a voltage into the coil windings as it passes through the receiver coil. The resultant induction signal generated from the ferrous inclusion is then interrogated by the ferrous inclusion electronics. The amplitude of the returned signal is compared to pre-defined threshold limits. Along with the eddy current data, the ferrous inclusion data is used to define the material's quality grade. The ferrous inclusion signal amplitude is affected by the line speed of the process, the mass of the particle, its orientation in the rod or wire, the magnetizing field strength provided, and its proximity to the coil windings.

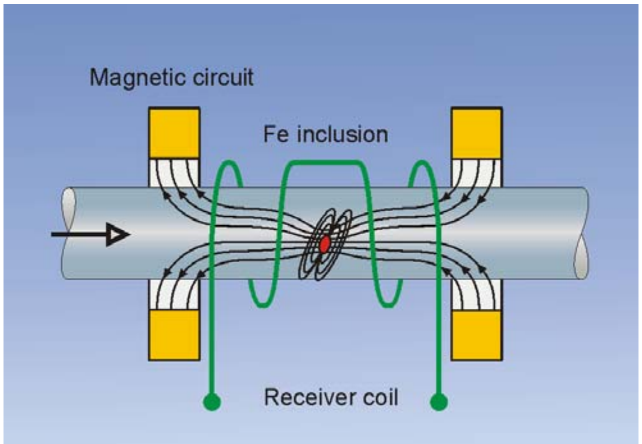

Figure 7 – Principle of Ferrous Inclusion Inspection

Ferrous inclusion detectability improves as the line speed increases. The faster that the differential voltage is generated into the material, the greater the signal amplitude. Since faster processing speeds are typical of the further reduction processes, the producer can be assured that as the line speed increases and the product diameter becomes smaller, the detectability of ferrous particles increases. The figure below shows the linear relationship between the product's line speed and the signal amplitude of the ferrous inclusion.

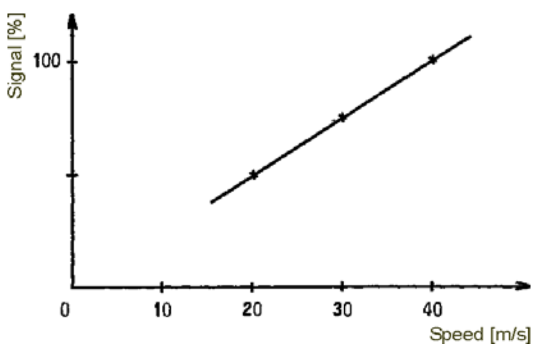

Figure 8 – Effect of Line Speed on Ferrous Inclusion Detectability

The larger the mass of the ferrous particle, the larger the signal amplitude it will produce. Iron particles with a mass of 0.1 mg are easily detected. Ferrous inclusions as small as 0.02 to 0.03 mg mass have been detected. The physical size of the actual ferrous particle is difficult to predict. Material tracking is difficult and wire breaks occur due to many other reasons. The effect of ferrous particle mass to the signal amplitude is pictured below.

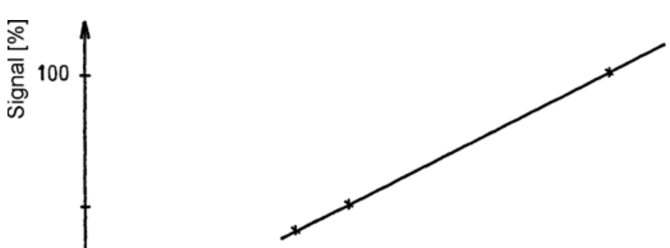

Figure 9 – Signal Amplitude as a Function of Particle Size

The stronger the magnetizing field used to magnetize the ferrous particles, the better the detectability. Stronger magnetizing fields will help detect smaller ferrous inclusions. Since the inclusions become more magnetized, they will produce a larger differential voltage into the receiver coil, and therefore produce a larger amplitude signal. Both permanent magnets and electromagnets are used to magnetize the ferrous particles in the rod or wire.

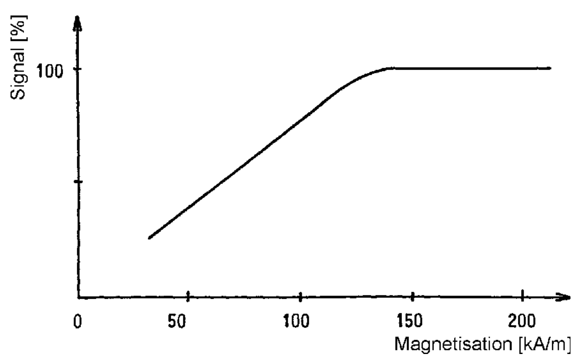

Figure 10 – Signal Amplitude as a Function of Magnetization Level

The location of the ferrous particle in the rod or wire product is also critical to its detectability. Ferrous inclusions are easiest to detect when they are near the surface. The following diagram illustrates the relationship between the signal amplitude and the spacing of the ferrous inclusion from the coil windings.

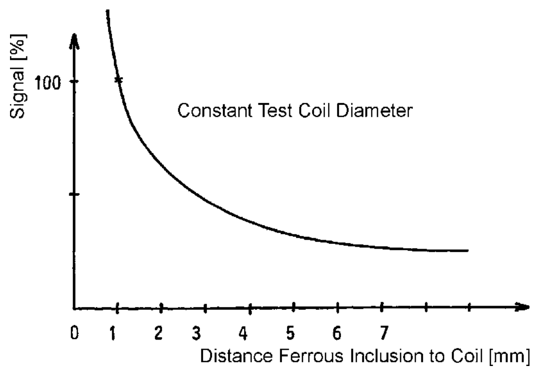

Figure 11 – Signal Amplitude as a Function of Particle to Coil Winding Spacing

In general, the orientation of the ferrous inclusion that creates a magnetic dipole providing the greatest differential voltage as it passes through the coil will provide the highest signal amplitude. The normal elongation of a ferrous particle that occurs during rolling and drawing process may actually assist in its detectability.

Since ferrous particles in the rod and wire product are the primary reason why wire breaks occur, their detection and elimination is critical. Most ferrous inclusions are caused by the breakdown of the sizing rolls. The ferrous inclusion detection system is then an early indicator of roll wear. Roll life is predicted by analyzing the ferrous inclusion data and determining the cycles between these high density clusters of ferrous inclusion signals. By developing a preventive maintenance schedule based on this data, the rolls can be replaced prior to their predicted breakdown. The number of wire breaks that occur during further size reductions can then be greatly reduced by minimizing, eliminating, or at least knowing when these ferrous inclusions occur.

Early detection and subsequent elimination of ferrous inclusions during the early wire processing stages helps the producer manufacture larger and heavier coils in the finished product sizes. Because ferrous particles are not the only cause of wire breaks, a direct correlation between ferrous flaw counts and the finished drawing weight has not been found. We know that inclusions with an area approximately 30% of the product diameter cause wire breaks. The producer can use statistical data from previous wire passes to determine the drawn product smallest size without a break due to a ferrous inclusion.

Many processing improvements have been implemented over the years to reduce the introduction of ferrous particles into the material. In addition to preventing inclusions through routine roll replacement, steel is being replaced in the process where possible. Although ferrous inclusions are still present in the process, awareness of the problem through its detectability has proven to be the first step towards its elimination.

TECHNIQUES FOR DETERMINING PRODUCT QUALITY GRADING:

Electromagnetic testing performs the task of determining the product quality of non-ferrous rod and wire product very effectively. Eddy current and ferrous inclusion data are obtained simultaneously and used together to determine the product quality. Testing criteria such as frequency, phase, sensitivity (gain), filter settings, and threshold limits are entered into the instrument electronics or into the testing software program as shown below. The grading criteria are also defined by the user. The number of flaws for each section and coil permitted for each quality grade are inputted for both the eddy current and ferrous inclusion channels. The section length, line speed, alarm limits and other important process details are also entered into the testing software program.

Figure 12 –Instrument Specific Setup Information

Section analysis is the best way to evaluate trends in the process condition and monitor defect density. The system software subdivides the continuous test for each coil into equal length sections. Each section is displayed on the display screen with the number of flaws and inclusions for each section. Typically, three individual amplitude threshold limits are used for the eddy current test and two amplitude threshold limits are used for the ferrous inclusion test. Alarm limits will indicate when the number of flaws or inclusions per section exceeds a predetermined limit. Each section is graded and displayed on the section grading analysis page. In a similar manner, the grading criteria for each manufactured coil or rod or wire is programmed into the test software package. Each coil is graded according to these pre-established grading criteria. The user determines the number of grades to be used and the names associated with these grades.

As the test is being conducted, the number of flaw counts is displayed either per section or per coil. When the cut signal is sent from the coiling process to the combination test instruments, the data from the just completed coil is compiled and a new coil is started. The actual number of individual flaw counts and inclusion signals found during the actual inspection are compared to the pre-established quality grading parameters for the just completed coil. Grading is performed for each section and for each coil. Statistics are provided indicating the average number of flaws per section and per coil. The diagram below shows actual section data for a coil under test. The number of flaw counts per section is shown for both the eddy current and ferrous inclusion tests. The screen display also shows if any alarm counts are exceeded and the grade for the tested section.

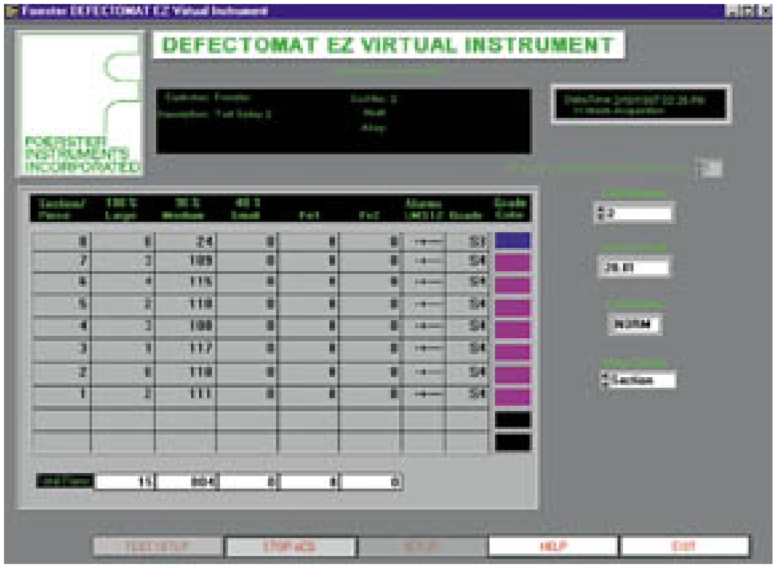

Figure 13 – Section and Coil Analysis Screen

Determining the location of flaws in the coiled rod or wire is done by a couple of methods. Since the length of each section is known, the location of the section with the highest density of defects or severe indications can be calculated. The newest generation equipment uses a more graphical format to display the exact location of eddy current defects and ferrous inclusions in the material. The exact location in the coil is pinpointed by using a Piece Image of the entire tested coil. The Piece Image for the last four tested coils are displayed in the bottom section of the following diagram. The exact location of eddy current defects and ferrous inclusions is shown with respect to the length of the whole coil. This information can greatly assist the end user by predicting what can be expected when further material processing is performed.

The top strip chart display shows the eddy current response for the last tested coil. The bottom strip chart display shows the ferrous inclusion response for the same coil. A signal appearing in the eddy current channel alone would be a crack, split, or other surface defect. A signal appearing in the ferrous inclusion channel alone would be a subsurface ferrous inclusion. A signal appearing in both channels at the same time would be a ferrous particle located near the surface of the material.

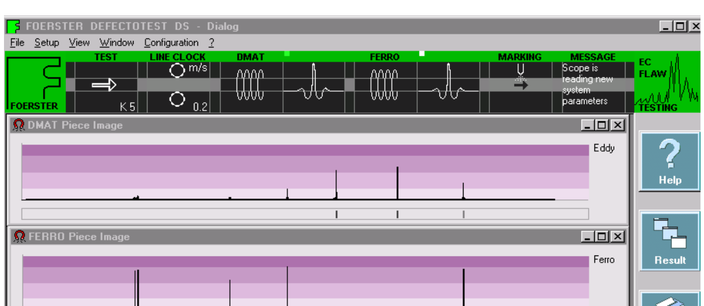

Figure 14 – Display of Piece Image Locations

CONCLUSIONS:

Electromagnetic inspection is a very effective tool to monitor the integrity of the manufacturing process. Initially designed primarily to grade the quality of non-ferrous rod and wire during the manufacturing process, it has become a mechanism to improve preventive maintenance, monitor process trends, and improve product quality. The electromagnetic inspection and quality grading process is a statistically based production technique. The effective use of the information provided by the combination eddy current and ferrous inclusion detection techniques is part of an ongoing process improvement process. It will detect incremental changes in the process and provide the manufacturer with the required information to make informed decisions and take the appropriate corrective action.

The electromagnetic test is not a perfect test solution. It will not detect every condition important to the manufacturer. It cannot define exactly the type of defect it is seeing or tell the manufacturer if and when the drawn wire will break. The electromagnetic inspection is, however, only inspection technique available capable of performing an in-process inspection of 100% of the product during the actual manufacturing process. The inspection alerts the user to conditions that deviate from a normal production pattern and to changes occurring in the process that warrant analysis and correction. The eddy current and ferrous inclusion tests completely complement the destructive tests performed in the quality labs. The ability to correlate the electromagnetic results with process conditions will directly improve the manufacturing process, provide better preventive maintenance scheduling, improve production output, and improve the product quality.

The electromagnetic inspection is a very effective technique for grading the quality of the rod and wire during the actual manufacturing process. The primary benefit of the combined eddy current and ferrous inclusion detection techniques is in their ability to be a continuous non-intrusive inspection and provide 100% product coverage at line speed. It helps the manufacturer of non-ferrous rod and wire products produce a better quality product without detriment to the manufacturing process. It is a valuable and effective process control tool for acquiring processing details, making continuous process improvements, as well as grading the product. The combination eddy current and ferrous inclusion detection inspection should be an integral part of a continuous process improvement program for all producers of non-ferrous rod and wire.

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