Process improvements on rod mills

The eddy current tester has proven to be useful in detecting various surface defects on hot-rolled wire rod and bar coils

By Brian Roberts and Tim Leahy

This paper appeared in the September 1999 issue of Welding Journal International and has been reprinted with permission. It was originally presented at the Wire Association International's 68th Annual Convention, Cleveland, Ohio, USA, June 1988.

Consumers of hot-rolled wire rod are always demanding better surface quality, and any producer who wishes to remain a supplier is always trying to improve it.

In a modem high-speed rolling mill, where steel temperature exceeds 1,000°C (1,800°F), production speeds surpass 100 m/s (20,000 fpm) and coils can be 10 km (6 miles) long, it is impossible to visually inspect the entire surface of any coil for defects. This is especially true when the defect in question is a seam—a tightly rolled discontinuity in the rod surface that is typically invisible to the naked eye but all too obvious to the end user. Efforts to improve the quality of shipped product have necessarily moved away from mere inspection and toward process improvement.

Hidden away within the melting, casting and rolling processes are potential sources of surface defects. Finding them requires ingenuity. Anyone familiar with process improvement understands the importance of a good response variable by which the effects of changes to the process can be reliably measured. It does little good and frequently much harm to adjust process variables when there is no clear way to measure the results of the change. Given the mill conditions described above, the response variable for surface quality has been elusive, but an inline eddy current surface inspection system has shown promise.

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This article describes the use of an inline eddy current tester (ECT) to detect surface defects and improve operating processes in a hot-rolled rod and bar mill. The authors describe its current and future capabilities as well as its limitations.

Description

Rolling mills have traditionally attempted to detect surface defects, seams included, with the only available methods, however crude: visual inspection, etching and filing and upset testing. Visual inspection is impractical given the quantity of material produced by a modern plant and the ambient conditions under which an inspector must work. The latter two tests will detect surface defects, but only on short samples taken from a coil that may weigh as much as 2,750 kg (6,000 lb). Since the samples can only be taken from the ends of the coil, they are not sufficiently random to be considered rational subgroups. Nonetheless, such tests have been all that was available for many years, and process improvements along the way relied on the correct interpretation of the dubious data collected from these tests. It is every roller's dream that a better way be found. Every inspector, meanwhile, wants a tool that can see the entire coil surface and warn of the presence of defects.

The trial installation

In 1985, Charter Steel attempted for the first time to use an ECT to monitor the product and process, but with little success. The original equipment had only an oscilloscope for a readout, and no capability for storing or reviewing data. The interpretation of its signal thus depended on the attention span of the inspector, who had to stare at the readout constantly to observe the blips that marked surface discontinuities. Any time spent inspecting the coil for the cause of the blip meant that the signal for the next coil was missed. The equipment manufacturer provided all documentation in a foreign language with practically no service. It was impossible under such conditions to correlate results, and after a respectable period of time, the unit was quietly taken off-line and forgotten.

Ten years later, a different manufacturer invited Charter to observe the operation of its eddy current unit at a wire rod mill in Europe. Charter personnel were hopeful that the technology had improved to the point at which it was time to try again. In 1995, company engineers visited a mill that was having some success detecting surface anomalies with an ECT. The design consisted of two individually wound coils contained in a single bobbin which induced an eddy current field in the steel that passed through them. The manufacturer's software interpreted differences in the signal strength as changes in the quality of the rod surface. The operators to whom the engineers spoke were confident that this eddy current tester was detecting many (if not all) surface defects on their product.

Despite differences between the European mill and its own, Charter leased the ECT for a trial period and installed it on Charter's former rolling mill in January 1996. Installation consisted of attaching the unit to a rigid frame that was wedged into the short 56 cm (22 in.) space between the exit of the finishing mill and the entrance to the first water cooling box. After running the fiber optic cable from the eddy current coil to the processor, and connecting the processor to a PC, the unit was ready for operation. The ECT worked correctly on the first coil to pass through it.

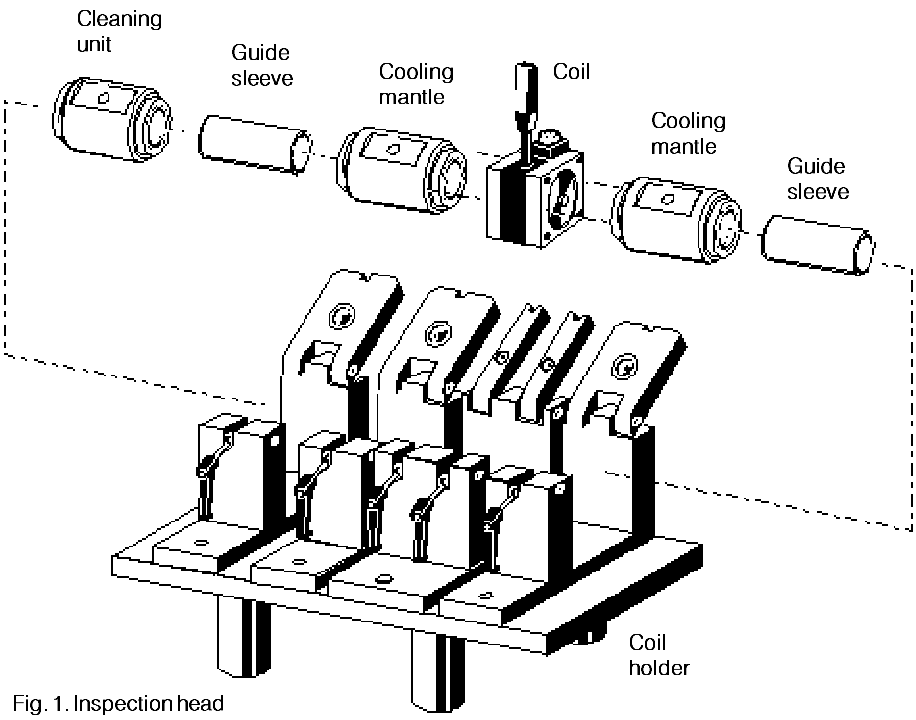

Fig. 1. Inspection head

The Eddy Current Tester

The system as installed at Charter Steel's plant in Saukville, Wisconsin, is comprised of five sections:

Inspection head. See Fig. 1. This is of extremely robust, water-cooled construction and accommodates encircling transducers with guide bushings and air strippers. It is mounted at the exit of the no-twist mill. For smaller sizes, the transducers are fitted with protective ceramic sleeves to minimize risk of damage. A hot metal detector (HMD) signals the approach of each coil. The transducer induces high frequency eddy currents to flow in the cross section of the material to a depth of 1.5 mm (.060 in.). Variations in cross-section resistivity caused by surface anomalies, are sensed by multi-differential windings within the same transducer.

ECT electronics. See Fig. 2. This is of modular construction, housed in an environmental cabinet, which has to be located within 20 m (65 ft) of the inspection head.

The electronics provide high frequency excitation of the transducer and process detected signals from their analog state to a digital format which can be handled by an external high-speed processor. Communication to the processor is by means of a fiber optic cable which provides complete immunity to electrical interference and can be of any length without alteration or distortion of signals.

Charter has a single-strand operation, but elsewhere the electronics have been expanded to handle multiple strands simultaneously.

Processor. The most popular choice is a regular personal computer such as a Pentium, with 16-bit expansion slots to accommodate special interface and analysis AT cards. Location is in a clean room environment well away from the mill.

Set-up parameters for each material and rod size are stored on hard drive and down-loaded to the Eddychek on demand. Signals from the Eddychek are processed and categorized according to amplitude, periodicity and length. A standard color monitor displays the surface quality of the current material in real time, with the preceding two coils also shown. First and last turns of each coil are expanded for review in subframes, as is a relative quality number related to the distribution of surface defects along its length.

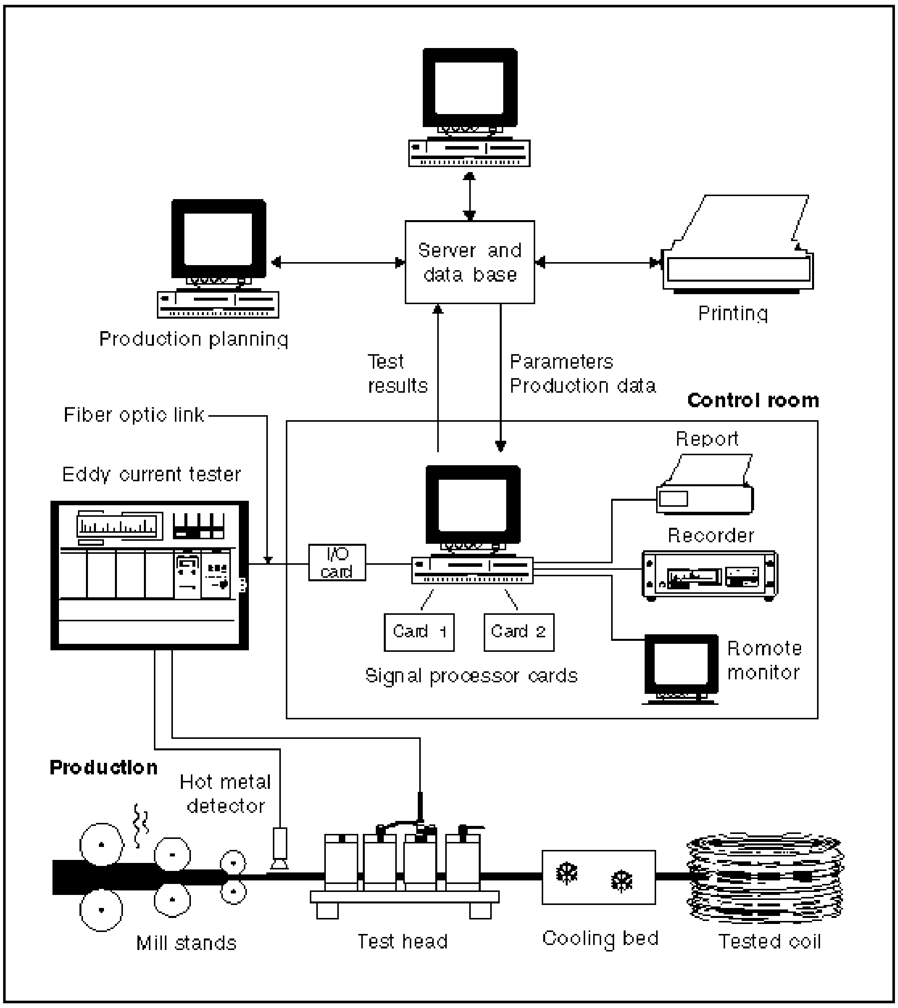

Fig. 2. ECT system

The system can be programmed to detect a regular periodicity of defect signals resulting from roll damage and identify the actual mill stand creating the problem.

Each coil is given an individual I.D. and all data are archived for later review. Histograms and trend analysis may be developed using standard software such as Excel.

Remote displays. Auxiliary monitors may be located at any venue such as quality control, production control, tool rooms, etc. Printers and strip chart recorders are similarly available.

Host computers. An Ethernet link allows communication between the company's network and the Eddychek PC on a "file to file" basis, so that setups and material data are down-loaded automatically and complete results are archived in a much larger capacity store than the PC hard drive.

In one installation, complete information on each coil is sequentially stored for five years and can be retrieved in seconds.

This system is likely to be the next stage of development at Charter.

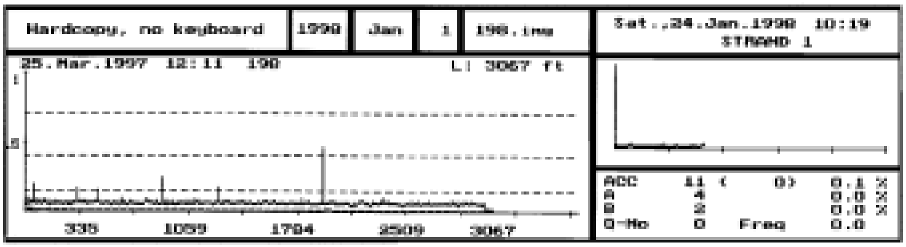

Fig. 3. Typical eddy current pattern.

The signal display

The software gives an inspector a realtime graphic view of the rod coil under test. The display (see Fig. 3) consists of a bright yellow horizontal timebase with flaw signals displayed vertically along the length. The timebase starts as soon as the front end of the rod passes through the ECT. The display is identified with an image number that appears near the top and is time stamped, using the internal clock. Spikes or peaks in the line represent defects or changes from the previous measurement. The height of the peak is proportional to signal strength, on a scale of zero to 100 percent of full scale. See Fig. 4. Single indications of surface anomalies appear as one peak, while clusters or multiple defects are indicated not only with peaks indicating magnitude, but also with colored bars below the peaks that represent their frequency.

Three dotted horizontal lines stretch across the display. These settings can be adjusted by the user and represent the signal strength required for a spike to be considered a defect. The software recognizes three categories of defects (B, A and ACC in decreasing severity) based on detected signal strength. For a signal to be counted as a "B type" defect on the set-up at Charter requires that the peak exceed 70 percent of fullscale. Any peak that exceeds a 40 percent threshold will be counted as an "A"; similarly, ACC type defects are those that exceed 15 percent over an accumulation period. Any defect that registers as a B type will also register as an A type and an ACC.

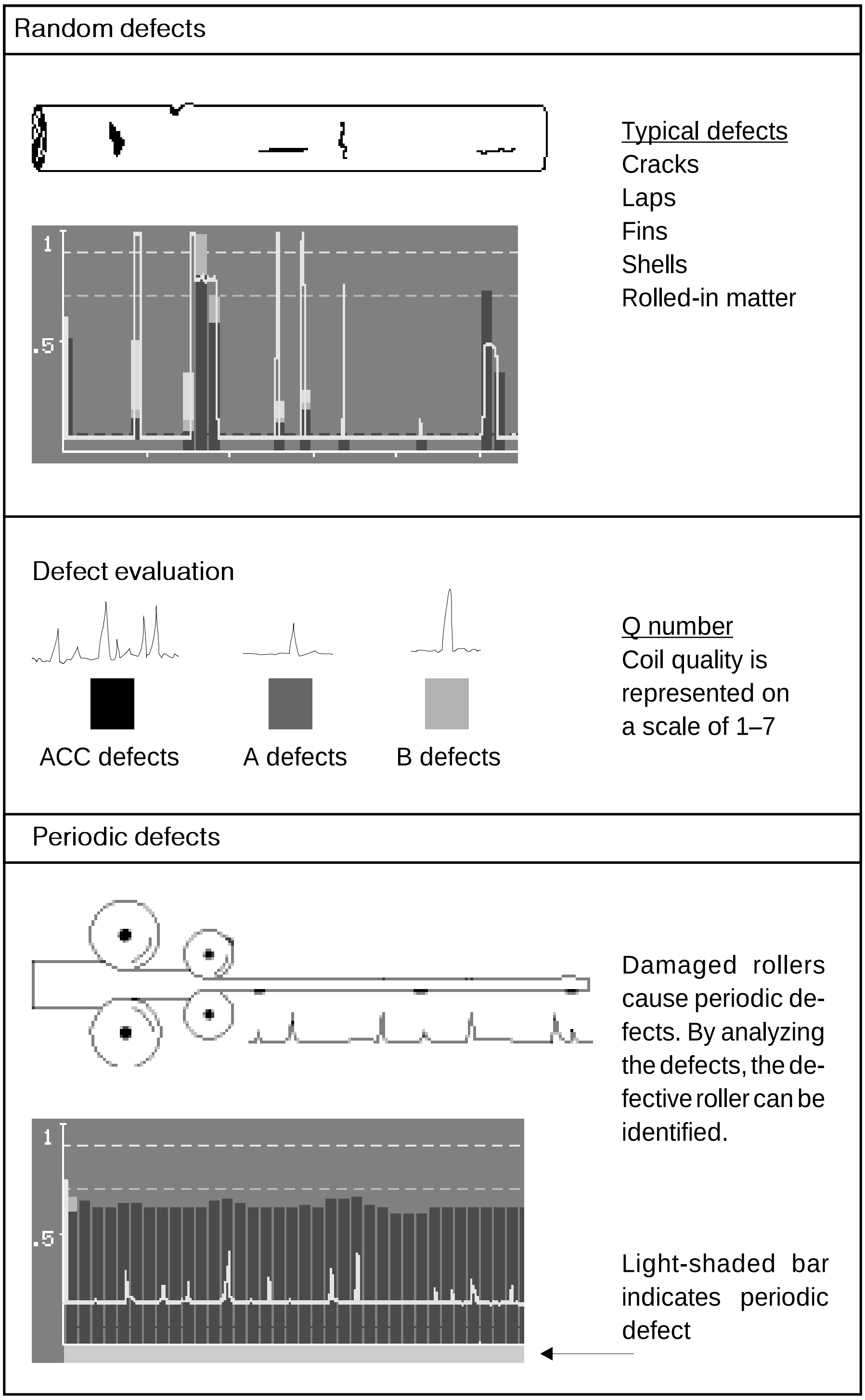

Fig. 4. Defect types

The gain setting is adjusted to raise or lower the background noise level from good material to a value of about 5 to 10 percent. After each coil has been run, the software summarizes the counts for each type of defect on the right side of the screen next to the graphic image.

The software subdivides the coil into 55 units of equal length, which the manufacturer refers to as Single Evaluation Units (SEUs) but which the authors call “windows.” In this case, each window corresponds to approximately 1.5 seconds of rolling time. The yellow signal line, which is updated once per window, displays the strongest signal measured during that time. However, the ECT may detect more than one defect within a window. When this occurs, it represents them with colored vertical bars underneath the signal line (see Fig. 5) whose height indicates the relative number of defects. Some bars are barely visible above the X-axis. Others are so high that the inspectors immediately know that there must be a large number of defects clustered in one area of the coil.

Three panes appear simultaneously on the computer screen. See Fig. 6. The lower pane displays the present coil, the middle panel displays the coil that immediately preceded it and the top pane displays the coil before that. As each coil finishes, its image jumps to the middle pane to make room for the next coil, and displaces the prior two images. At any time, the inspector can view results of the last three coils rolled. To see earlier images, he or she simply presses a function key and then steps backward with “page up/down” keys.

The data for each coil are collected in a text file which, along with the image file, is written to the PC hard drive as soon as the coil end is reached. The software writes both files quickly enough to recover before the front end of the next coil arrives, as little as four seconds later.

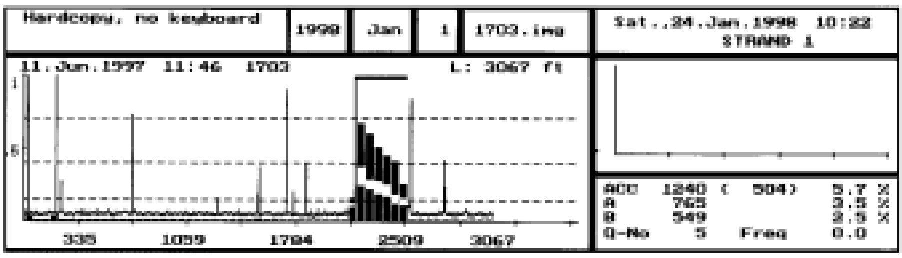

Fig. 5. Eddy current signal with vertical bars indicating multiple defects

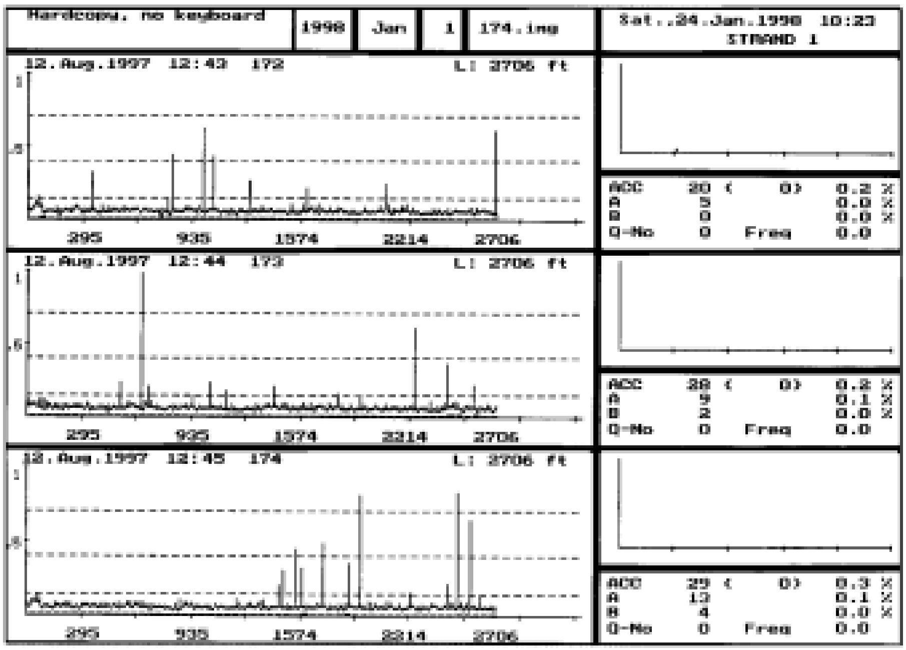

Fig. 6. Three eddy current signals in different panes

Early efforts

The real test of the unit lies in its ability to locate injurious defects when standard inspection techniques fail. Correlating the eddy current signal with the quality of the coil surface was an obvious necessity. Initially, each rod coil was torn apart to look for the source of the scattered peaks, but it quickly became apparent that associating a single spike with a particular defect would never work. In the first place, locating a particular spot on a coil requires opening the coil, counting and peeling off the required number of rings. Given the weight of the coils produced today, this is a tedious task. Furthermore, one can never be certain that any defect, once found, is in fact the one that produced the observed signal. Efforts to find the source of every individual spike in the eddy current signal usually have been fruitless.

The author (Leahy), however, soon noticed something which suggested that the unit was indeed working as advertised. Within one hour of operation the inspector had confirmed the presence of light surface defects on three separate coils in the approximate position specified by the eddy current. In each case, the eddy current had displayed red bars below the signal line, and the number of “B” defects was significantly higher than on other coils. Higher numbers of “B counts," as the authors refer to them—especially if the pattern indicated that they were clustered in one or two spots on the coil—implied defects that could usually be confirmed by the inspector.

Over the next several weeks the inspectors became confident that vertical bars on the eddy current display usually meant that something was to be found on the rod coil surface at that spot. Although it was not possible to predict the exact nature or source of the defects, it was clear that the ECT could detect defects that could be seen with an experienced eye. The instrument's advantage was that it could inspect the entire length of every coil and tell the inspector where to look to find significant areas. The inspectors, who initially doubted the ECT, were impressed with the results and began to use it for this purpose.

Tracing a defect on a coil back to an observed signal on the screen was only one way of demonstrating capability, however. There was also a need to test in reverse: could the ECT warn the authors of a defect before they knew it was there? To find out, multiple holes about 3.0 mm (0. 125 in.) were drilled into the surface of seven test billets to a depth of approximately 12.5 mm (0.5 in.). After measuring the distance from the front of the billet to the location of the holes, which differed on each billet, the author calculated how many seconds it would take from the start of the eddy current signal to the point at which the damaged surface would pass through the unit. Verifying their presence was a simple matter of counting the time from the beginning of the coil to the specified point. In six cases the eddy current signaled the presence of these defects in the correct location (see Fig. 7); the defects were later confirmed visually. Some slivers were found on the one coil with no significant signal. Still, the unit was already demonstrating its ability to accurately flag the majority of defects on the coil.

During this trial period there were other occasions when the eddy current exhibited surprising performance. On one occasion, the yellow signal line suddenly jumped and tall red bars appeared across the bottom of the image, indicating an enormous number of defects. The author interrupted production to check the mill for the cause, because he suspected that the ECT was malfunctioning. Before the last rod coil had gone through the eddy current, however, the author was startled to hear the inspector on the intercom reporting that he had found marks on the rod surface left by a broken guide roller. At this point the author had proof that the ECT could wam about this type of defect as soon as it occurred. The ECT made several converts that day.

The final installation

The success they had achieved by the end of the trial lease was enough to convince Charter to purchase the eddy current system. However, it was apparent that the first installation was limited. The support frame which secured the inspection head was not adjustable. This proved to be troublesome during operation when the authors discovered that minor changes in speed and set-up affected the position of the passline enough to wear out the protective stainless sleeve during routine operation. Charter engineers designed a table that would permit minor vertical and horizontal adjustments to the head position, so that it could be correctly aligned with the passline under all conditions.

As Charter was in the midst of a major revamp of its rolling mill, the author decided to postpone installation of the ECT until after the start-up. The new table was designed as promised, and the ECT installed in December 1996. Because of delivery problems with the fiber optic cable that connects the processor and the controlling PC, the mill was forced to temporarily locate the PC immediately next to the processor. This meant that the screen with the image of the coil was more than 200 m (650 feet) from the inspector, so

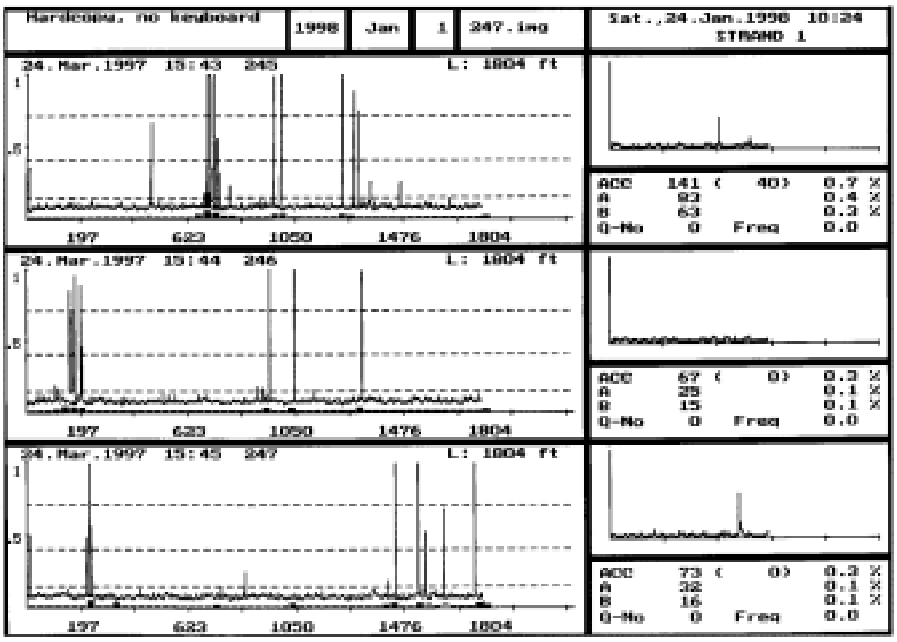

Fig. 7. Eddy current signals from billets with induced defects

the author had to observe images from this remote location and communicate his findings by radio. This proved to be beneficial, as it allowed the author to train observers in relative solitude and it fostered cooperation between him and the inspector on the floor. The mill operated in this manner for several months until the fiber optic cable had been delivered, and he could move the PC to the inspection area, where the screen is visible to the employee responsible for the disposition of the coil. The first three months of 1997 were spent completing the testing of the ECT before placing it on-line essentially full-time in March.

Process improvements

As useful as the ECT could be as an inspection device, it was always the intention to use it to improve the melting, casting and rolling processes. The author was hopeful that it would provide the elusive dependent variable, the measure by which changes to the processes could be accurately evaluated. In the course of one afternoon, the ECT proved its worth as a process improvement tool in dramatic fashion.

Shortly after commissioning, the author decided to analyze the casting process by graphing the B counts for each billet from randomly chosen heats of various grades. Data were plotted on an individual/moving range graph where each point represented the B count for one billet. With this method, changes in the casting or rolling processes—whether naturally occurring or deliberately introduced—could be detected. In March 1997, the author examined the data from an order of a heat of AISI 6150 and had no reason to suspect that there was anything unusual about this heat. Forty-five billets had been rolled consecutively without any delays on the mill. When the B count totals were initially viewed, they appeared to be random; that is, some coils had higher values than others, and some less, but most varied normally around an average of 9.4. See Fig. 8. When the data were arranged in casting order, however, it was immediately evident that all billets with the higher B counts had been cast on strand one of the four-strand caster. See Fig. 9. Billets from the other three strands had much lower B counts. The difference was unmistakable and quite enlightening. There was no conceivable way that the ECT could have erroneously measured higher values only on coils from that particular strand; the difference had to be real. Other inspection methods detected no differences between any of the coils, but the plot of ECT data showed otherwise. Unfortunately, in this particular case, no assignable cause for the difference was ever identified.

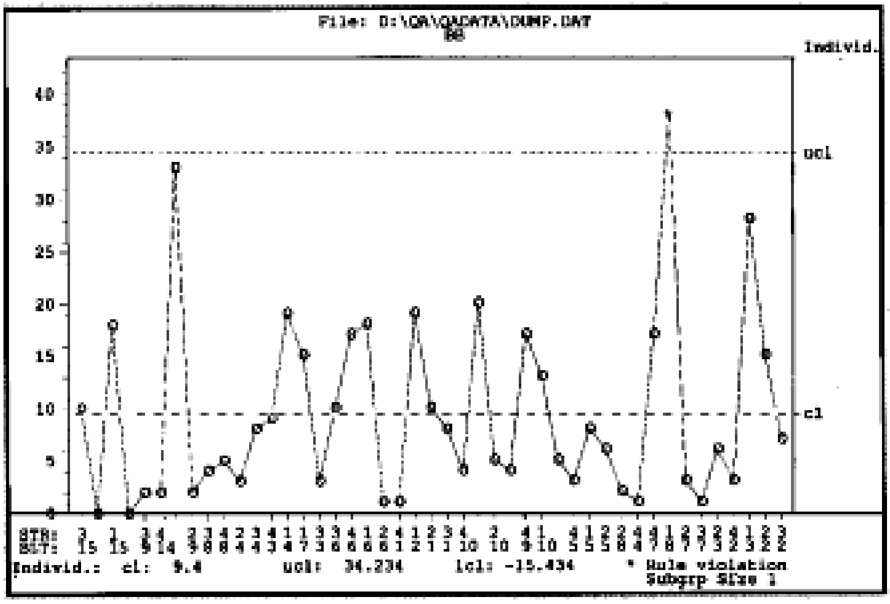

Fig. 8. B counts for heat of AISI 6150 arranged in rolling order

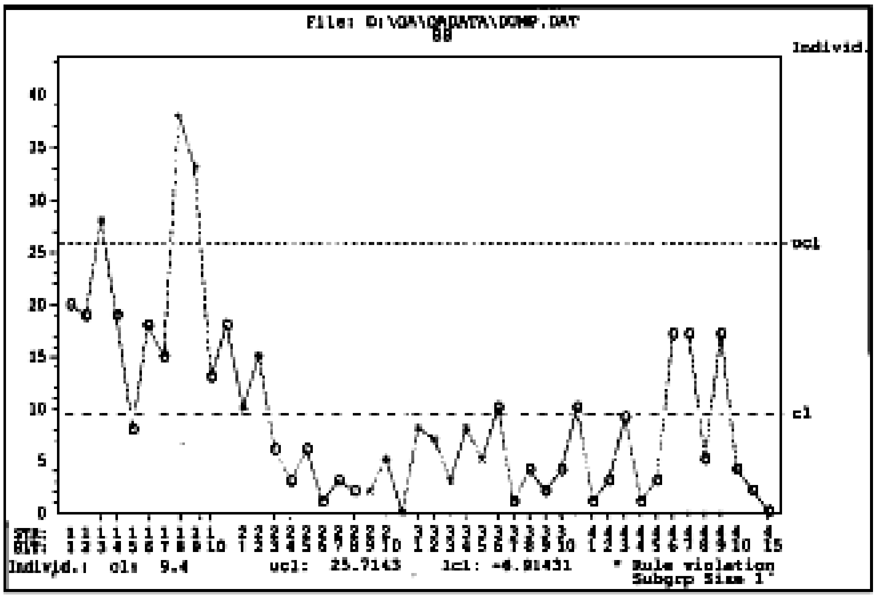

Fig. 9. B counts for heat of AISI 6150 arranged in cast order

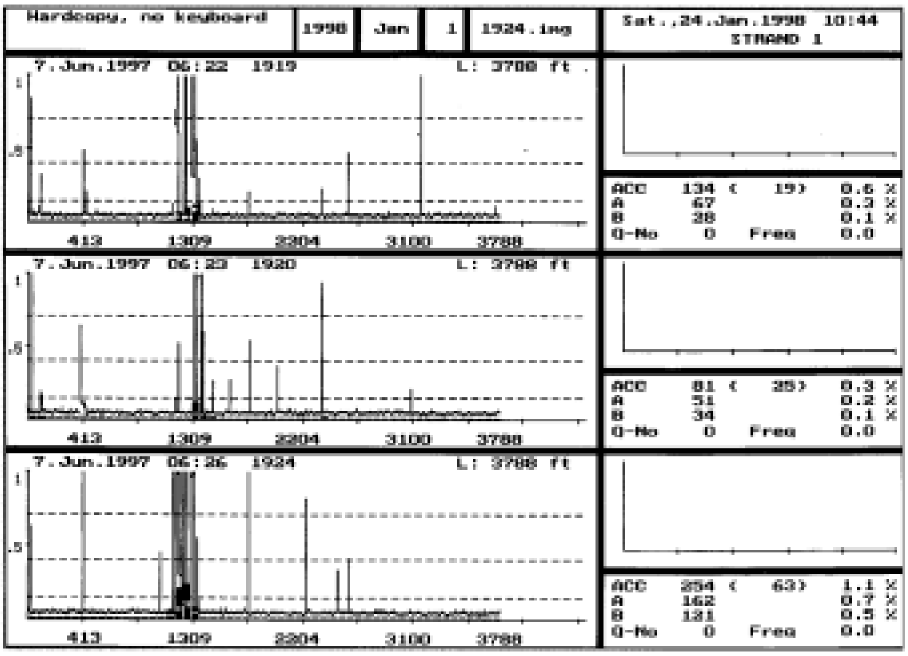

Fig. 10. Eddy current signals indicating defects induced by furnace floor refractory

This finding set off a search for additional examples. In several cases, charts again indicated differences attributed to the strand on which the billet had been cast. In others, it was found that the billets from a specific location in the heat had higher B counts than the rest of the billets. Certain grades were found to have consistently higher B counts than usual. The author had always suspected that such patterns might occur but their traditional measuring techniques had lacked the necessary sensitivity to detect them. The author was convinced that the eddy current tester had a level of sensitivity unsurpassed by any other such device.

Within a short time the rolling mill was regularly reporting such findings to the melt shop, which then reviewed production and quality data for that material. These investigations did not always yield the hoped-for evidence, but there were cases in which the ECT data confirmed long-revered "folk lore" about what really happens when a heat is cast. Fronts and backs of heats, for example, were found to have generally higher (but not necessarily injurious) B counts than at the middle of the heat where casting conditions were in a steady state.

But if science can affirm cherished beliefs, it can also be used to refute them. One popular legend held that billets from certain grades that were rolled after short, unintentional mill delays (during which time the billets would soak in the reheat furnace a little longer than average) "always" had better surface quality. Data were collected from numerous billets rolled after such delays and B counts compared to those from randomly chosen billets of the same heats that had rolled normally: there was no statistically significant difference in their mean values. This determination ended the expensive and ultimately futile practice of delaying production to heat the billets more than necessary, in the belief that this would somehow correct a problem with the surface quality.

The ECT provided opportunities to improve the rolling process as well. In 1997, Charter commissioned a new furnace and roughing mill as part of the revamp of the entire rolling line. Prior to this start-up, the authors discovered a surface quality problem that was traced back to gouges on the billet originating from rough spots on the refractory hearth in the soak zone of the pusher-type furnace. Small chunks of refractory would break off the floor from the weight of the passing billets, and the billets would contact the sharp edge of the resultant depression in the floor. The scabs and slivers that appeared on the coils would appear in one location on every coil until the steel had rubbed the rough spot in the floor smooth again. The usual reaction was to change the location from which the billets exited the furnace until the damaged spot in the furnace floor could be repaired. The ECT proved remarkably adept at signaling the beginning of one of these occurrences. The resulting pattern, with a spike or bar at the same location on almost every coil, was a tell-tale indication of the origin of the defect (Fig. 10). By referring to the image, it became much easier for the operator to pick a spot on the furnace floor from which a billet could be charged safely.

The ECT has also detected one condition that neither the author nor the manufacturer ever expected. Guide failures in the finishing mill can sometimes be predicted by a rise in the accumulated (ACC) defect level, indicating increasing vibration. If the operator knows that a guide failure is imminent, it is a simple matter to replace it before it fails and either causes a cobble or induces surface defects in the steel. The authors first realized the ECT's ability to anticipate guide failures in March 1997, when a gradually rising trend in the ACC signals reached unprecedented levels. See Fig. 11. The ACC levels dropped back to normal immediately after the finishing stand guide was replaced (Fig. 12).

Limitations to the ECT

The ECT has proved useful both as an inspection aid and, more importantly, as a process control tool. However, its limitations prevent it from being the ultimate instrument for either use.

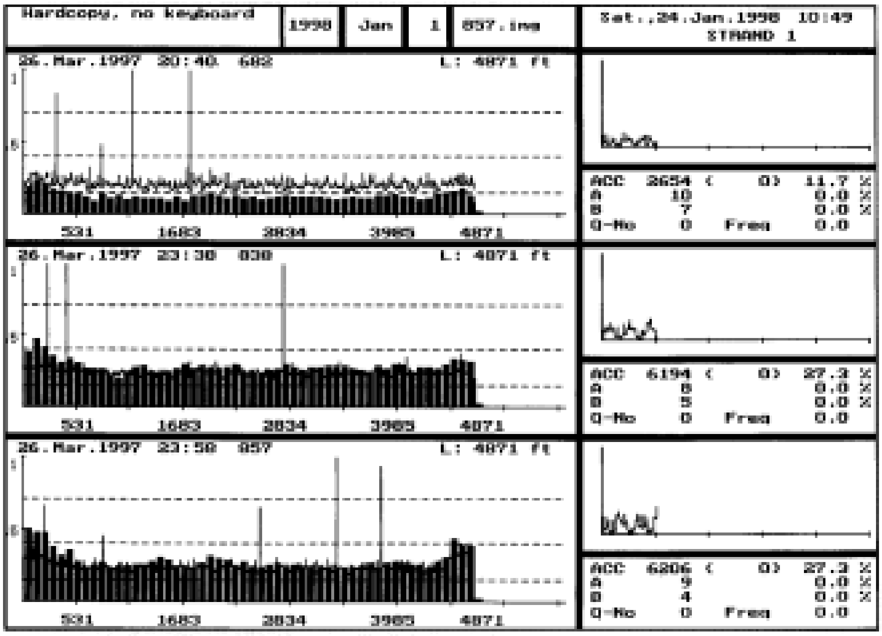

Fig. 11. Eddy current signals indicating imminent guide failure

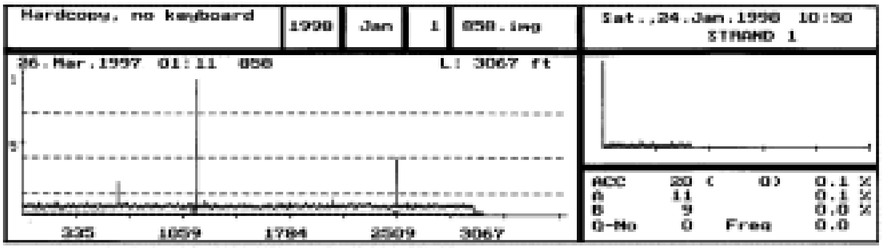

Fig. 12. Eddy current signal after guide was replaced

Some of these restrictions, the author believes, can be overcome with more research and work. Others will probably have to wait for a later generation of in-line inspection methods.

Everyone who sees the ECT in operation for the first time invariably asks about the depth of defects that can be detected. This is a natural question, but the author believes that the depth of defect is not significant. The eddy current inspection system can best detect those surface defects that are visible to the naked eye. The greater the disruption to the surface, regardless of the actual depth of the defect, the more likely it is that the eddy currents generate a signal. Determination of defect depth is best left to subsequent testing on cold material, after drawing or grinding operations to improve surface finish.

Unfortunately, this means that the mill has not been able to turn the ECT into a seam detector—the most useful of all imaginable inspection tools. As explained earlier, this unit uses windings to measure the difference in signal strength between adjacent sections of rod surface. The onset of a surface defect creates a disturbance in the eddy current field (see Fig. 13) which is measured as a differential signal. The same occurs when the end of the defect passes through. In between, the signal may vary if the defect itself does so, or it may appear as a flat line if the defect is relatively consistent. Scabs, slivers, broken roll marks and laps do tend to vary and are thus easier to detect.

Seams, however, are perversely consistent in the one area in which consistency is no virtue. In theory, the ECT should detect the beginning and end of a seam, since there is some change to the surface at those points. The rest of the defect, however, creates lesser signals, as the disruption of the seam along its length remains almost constant. Therefore, a seam might appear as two peaks separated by a short length of background noise. See Fig. 14. It is possible that seams are being detected, and perhaps flagged in this way, but the author has not been able to correlate signals with defects. The matter is complicated by the fact that seams can be quite short—a length of 50 cm (20 in.) or less is not rare. The beginning and end of a seam may occur so quickly that the two peaks happen within the same window and thus appear drawn as a single line. In that case, the characteristic signature of the seam does not appear on the screen.

Although the software provided by the manufacturer is adequate, the author still hopes to improve upon it by coupling it to the network system so that any image can be linked to the coil that generated it. At present, the author can trace the unique number assigned to the data and image files back to the parent coil, but it is a manual and time-consuming method. An integrated system allows for faster evaluation of the generated data and thus improvements to the process. The manufacturer has reported some success recently in this direction which the authors hope to incorporate as a lot of work is still ahead.

It is also necessary that the data generated by the ECT be displayed on a control chart for statistical evaluation. The author has written an Excel macro that summarizes the eddy current results for a 24-hour period; these re-

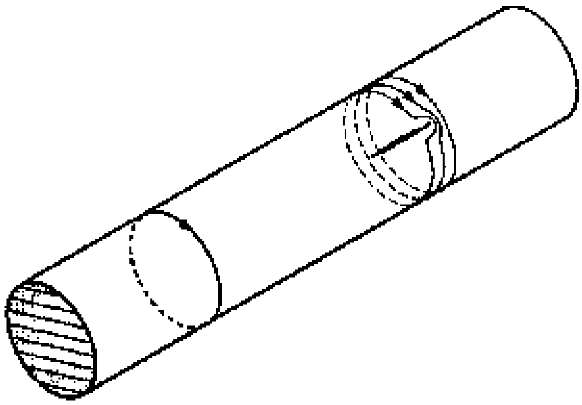

Fig. 13. Eddy current flow patterns

sults are easily imported into the relevant software and have been useful for evaluating day-to-day performance. For example, a recent problem related to an inconspicuous condition in the rolling mill caused a gradual increase in the percentage of coils rolled each day whose B count exceeded 20. See Fig. 15. When the data for each day were extracted and plotted using a spreadsheet program, the trend was obvious as was the immediate effect when the condition was corrected. Unfortunately, the manufacturer's present software does not automatically allow for such analysis of the data.

Even better would be real-time control charts that warned of changing conditions to which mill operators could respond. The vendor's software can display the relative ACC defect values for the last 20 coils, but the chart contains no control limits and is therefore of limited use. Furthermore, our experience shows that the B defect value provides a more accurate forecast of coil quality.

The ECT is generally capable of withstanding the harsh environment that surrounds it. It has never exhibited problems related to the high temperature of the steel that passes through it, and has survived all cobbles. The stainless steel sleeve that protects the measurement coil, however, is subject to wear from intermittent contact with the steel as it passes through. When enough wear has occurred, the sleeve ruptures and water leaks out. The coil must then be removed and the sleeve replaced before operation can resume. The problem was attributed to misalignment of the eddy current with the passline, or with excessive "flutter" (vibration) of the rod after it leaves the finishing stand.

The table that the engineers designed minimized the first problem by allowing for incremental adjustments in the horizontal and vertical planes to match the passline. The second problem has been harder to correct, especially on rod diameters under 6.5 mm (.250 in.) where speeds up to 100 m/s (20,000 fpm) occur. Since the ECT is located after the final stand, the steel is actually being pushed through it, and at temperatures exceeding 1,000°C (1,8000°F), it tends to deviate from the straight-line path wherever it is not constrained by a guide.

The manufacturer responded to a request for assistance by supplying a trial coil with a ceramic insert to protect the sleeve. This ceramic shield holds up well in operation and has extended life over the stainless steel sleeve about

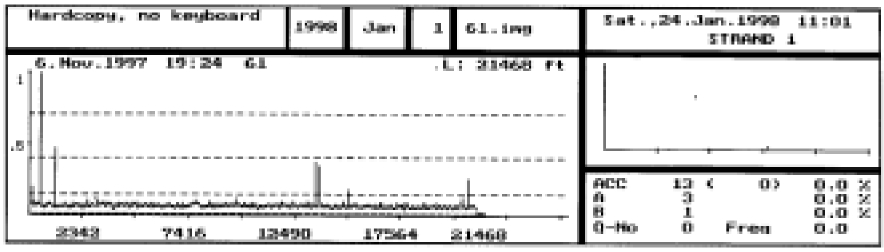

Fig. 14. Eddy current signal indicating possible seam (at center)

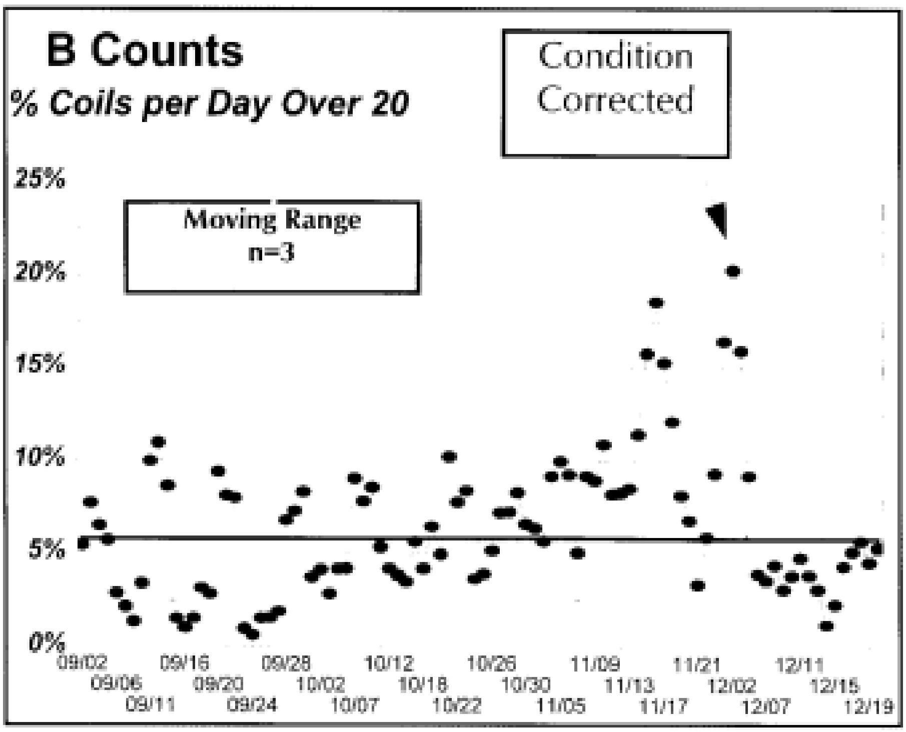

Fig. 15. Percentage of coils rolled ech day whose B count exceeded 20

fivefold. The engineers also improved the original design of the air stripper on the eddy current by including a static entry “bellmouth.” On smaller sizes, this additional guide further restricts the “flutter” and permits the sleeve to last longer before rupturing. Even with these design modifications, however, the authors still have had problems operating the ECT when rolling 5.5 mm (.219 in.) diameter rod that have not been fully overcome.

Conclusion

The eddy current has proved to be a very useful device for finding many types of surface defects on hot-rolled wire rod and bar coils. It is not yet clear whether it can detect tightly rolled seams. Even more impressive, however, has been its ability to indicate the effects of deliberate or unplanned changes in the processes that produced the coil. Further improvements in the communication between the eddy current software and the plant’s network are needed before this benefit can be fully realized.