

On-Line Hardness Assessment of Cold-Rolled Motor Lamination Steels

Z.S. Soghomonian, P. Beckley, and A.J. Moses

It is important to be aware of variations in the mechanical hardness of strip emerging from the strand anneal lines, which are used to anneal continuous steel strip during production. Lamination stamping, punching, and handling characteristics can depend on the hardness of the materials. A novel technique for the nondestructive determination of the hardness of nonoriented electrical steels has been developed. This technique exploits the measurements of structure-sensitive magnetic parameters, which are measured continuously on-line in real time. The magnetic data being produced are then processed through appropriate algorithms to provide an evaluation of material mechanical hardness. Variation of hardness along the length of coils then can be readily examined.

Keywords
non-oriented steels, on-line mechanical hardness

1. Introduction

COLD-ROLLED electrical steel intended for motor laminations is produced so as to conform to strict standards of power loss and permeability as embodied in the International Standards. Various mechanical properties are featured in specifications that are agreed upon between producer and user. One of the more important of these is mechanical hardness expressed in terms of values obtained from the Vickers or Rockwell hardness test methods. Usually hardness is measured on samples taken from the end of a production coil of steel. These same samples may be used to assess magnetic properties and to yield data for inclusion in a commercial test certificate. Increasingly, the practice is to monitor magnetic properties continuously along the length of coils of steel to guard against unwanted variations in properties remaining unobserved. It has long been desired to have convenient means of continuously assessing steel hardness so that any unwelcome variations may be noted and acted upon. This paper describes a system for providing such information.

2. Hardness Assessment

The capabilities of traditional methods for hardness assessment are reviewed.

2.1 *Vickers Test*

A well-known method, the Vickers test, employs a pyramidal diamond indenter, which produces an impression in the steel under a known load. The linear dimensions of the impression then can be measured to derive a hardness value. Statistical analysis shows that on thin electrical steel (approximately 0.5 to 0.7 mm), as assessed by one indentation, hardness is characterized by the uncertainty arising from a standard deviation of 2 VPN_{10} (Vickers pyramidal number using a 10 kg test load). Normally, a commercial test is based on one measurement, and that level of uncertainty is accepted.

Note the typical variation in hardness that can be observed on a cold-rolled product. Figure 1 shows a three-dimensional plot based on an extensive series of hardness measurements. Clearly, a test method that creates a mean value for the whole strip width would be extremely valuable industrially.

2.2 *Rockwell Test*

The Rockwell test is used more in the U.S.A. than in Europe, and well-established relationships have been developed connecting the Rockwell and Vickers tests (Ref 1). The work described in this paper is based on the Vickers method of hardness measurement.

3. Continuous On-Line Systems

Over the last 30 years, various methods have been used to obtain hardness measurements along the length of a coil of steel strip (Ref 2).

3.1 *Mechanical*

Ingenious methods of carrying out repeated indenter measurements on moving strip have been produced. These suffer from the problems of maintenance and spatial resolution. Rebound damping techniques have also been used for nondestructive hardness assessment.

3.2 *Magnetic*

Various systems have been developed in which correlations were sought between hardness and a magnetic property that could be measured on a strip processing line. Coercive force and remanence values were often employed because the measurement of coercive force involved forcing a premagnetized state back to a condition of $B = 0$ (zero magnetization), and the remanence measurement involved observation of remaining flux after release of a preimposed magnetizing field.

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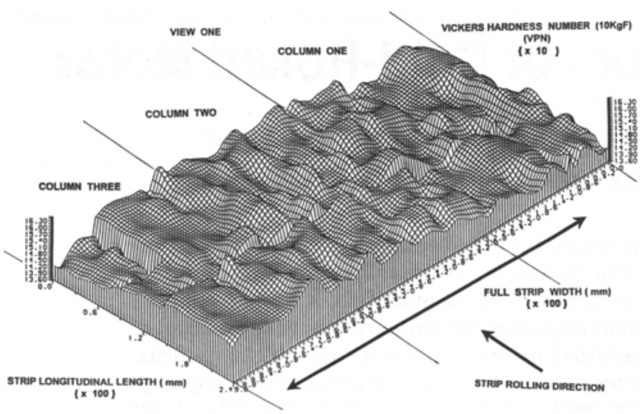

Fig. 1 Profile of finite hardness variation across the full strip width of a typical nonoriented material (silicon content, 0.2%). Area: 900×240 mm^2

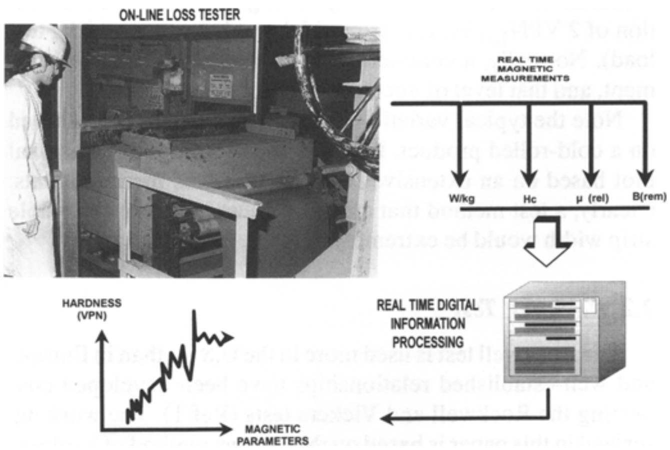

Fig. 2 Continuous mechanical hardness measurements through the utilization of an on-line loss tester

These methods encountered two main difficulties: (a) problems of measuring remanent flux and zero flux when unfavorable magnetic circuits had to be used for practical reasons perhaps utilizing components mounted in a drum over which the strip passed; and (b) problems of poor correlation between hardness and the chosen magnetic property. The methods worked, but with an unfavorable uncertainty surrounding a given result.

4. Algorithmic Prediction of Hardness

4.1 *On-Line Power Loss Testers*

Power loss is the key technical quality parameter for electrical steels. Over many years, on-line power loss testers have been developed to the point where they are a reliable and accurate integral part of the quality control of electrical steels. Further, the more recent models now employ digital signal handling so that complete magnetization (B) and applied magnetic field intensity (H) data are available for the whole of each magnetization cycle (50 Hz operation in Europe). This makes it relatively easy to obtain remanent flux density, tesla (B_{rem}); coercive field strength, A/m(H_c); specific power loss, W/KG (W);

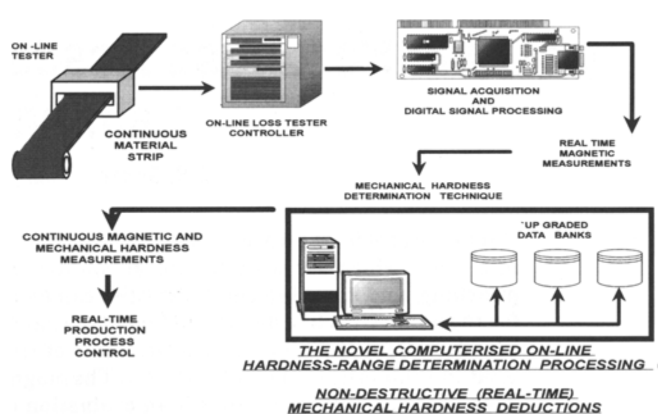

Fig. 3 Operational structure of the hardness determination technique

and permeability kg/Oe, (μ) from operations carried out on the data available.

Difficulty in accessing accurate, continuous real time data on B_{rem}, H_c, μ, and W prevented any of these being used as an indication of hardness. Further, it soon became apparent that the uncertainty involved in inferring hardness from any one magnetic parameter, no matter how accurately known, was too great.

4.2 *Multiparameter Operation*

Experiments were carried out to test the hypothesis that if several magnetic parameters were measured simultaneously, and their values were used in conjunction with a set of known hardness-versus-parameter relationships within a special voting optimization algorithm, a more certain value for hardness could be produced. Figures 2 and 3 outline this procedure. After considerable investigation, it was found that H_c, μ, and W could, among them, give the most useful result. In the determination of the mechanical hardness, a computational technique was invented to run synchronously with the on-line data acquisition hardware of the on-line loss tester.

With respect to the deduced mechanical and metallurgical characteristics, the technique is capable of indicating the magnitude and location of mechanical or magnetic defects within the material and allowing corrective measures to be taken in real time to minimize its progression along the continuous length of a coil.

The operation of the technique is categorized into three different sections in which different predetermined interactive analytical tasks are performed:

- The measurement of the magnetic properties of the material in real time (during production)
- The correlation of the required magnetic measurements and for the deduction of mechanical hardness (in real time)
- A facility for upgrading the system database in order to progressively improve the resolution of the deduced values of mechanical hardness

This facilitates the gradual upgrade of the preprocessed magnetic information that is used in the logical magnetic data mapping processes performed in section 2, as well as improving the

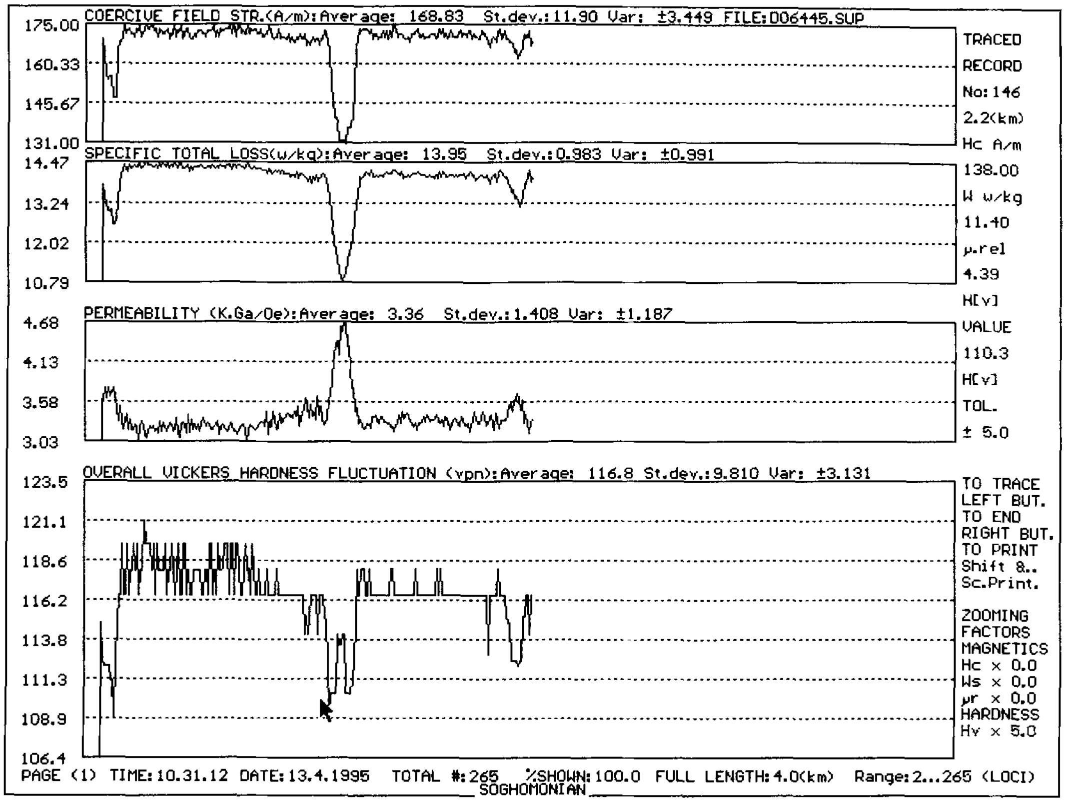

Fig. 4 Continuous real-time plots on magnetic and hardness variations along the full length of a nonoriented coil illustrating a region of decreasing mechanical hardness

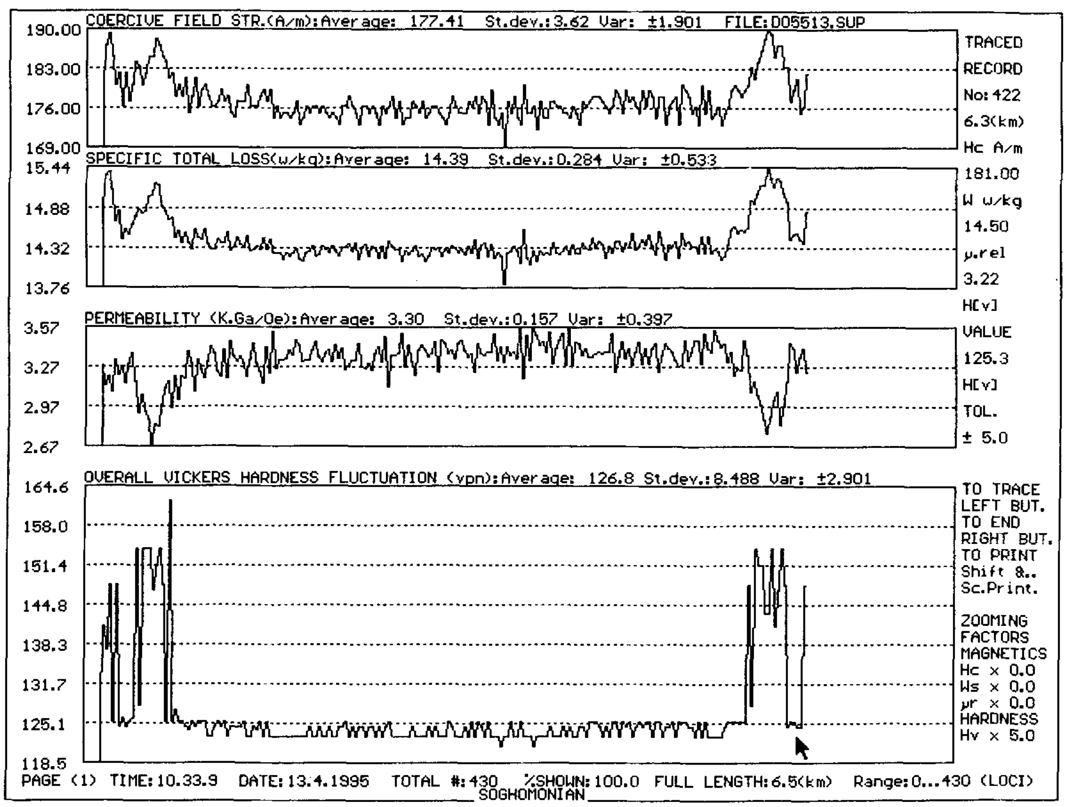

Fig. 5 Continuous real-time plots on magnetic and hardness variations along the full length of a nonoriented coil illustrating regions of increasing mechanical hardness

resolution and accuracy of all the mechanical property being determined in real time.

5. Developmental Steps

The key developmental steps have been (a) exploitation of accurate digital information from modern on-line power loss testers, and (b) the development and use of a multiparameter optimal voting algorithm (the subject of patent protection, Ref 3 and 4).

6. Results

A careful statistical assessment of the reliability of the system shows that absolute VPN_{10} may be predicted to within 5 points. The magnitude of any local variation will be correctly expressed to ±1 VPN_{10} point. This performance applies over a basic range of silicon content in steel varying within a range of 0 to 2%. Figures 4 and 5 show plots chosen to illustrate the ability of the system to detect hardness variations.

Figure 4 shows a region of softening within a coil, and Fig. 5 shows areas of increased hardness. The interplay of H_c, μ, and W may be examined for comparison. Figure 6 shows a plot encompassing a wide range of results covering a large range of metallurgical states of the material. With respect to these variable metallurgical conditions, the interactive hardness deduction technique allows separate categorization for different metallurgical states of "cold rolled and recovery," "gradual recrystallization," and "ferrite grain growth" for the material, thus allocating different tolerance levels of ±5 VPN_{10}, ±10 VPN_{10}, and ±5 VPN_{10}, respectively, to the real-time hardness deductions. The nondestructive (real-time) deductions of the hardness along with other on-line magnetic parameters jointly established the necessary foundations for further process control and condition monitoring possibilities.

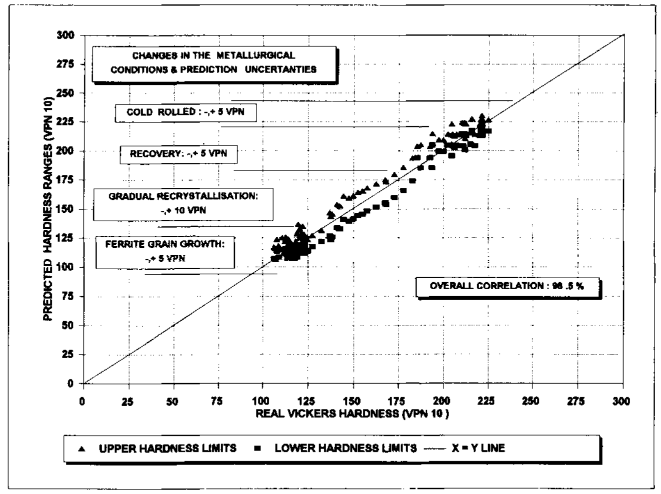

Fig. 6 Overall characteristics response of the novel hardness determination technique for different nonoriented compositions

7. Alternative Application Prospects of the Invention

Currently, the developed technique is being used with conventional on-line magnetic testing systems for real-time monitoring of the magnetic and mechanical properties of different compositions of nonoriented silicon steel grades. This has been achieved successfully on a commercial level with minimal implementation costs and without interruption to the natural process flow.

As the current software implementation of the technique has been fully tested for its accuracy and continuous performance on silicon steels, it is expected that it could be employed by other manufacturers of steel strip to monitor specific mechanical properties over a wide range of alloying compositions and metallurgical conditions. Such applications could include galvanized steel strip or tin-plated materials.

8. Conclusion

By the suitable use of existing on-line power loss testers and an optimized multiparameter algorithm, an accurate, continuous on-line hardness monitor may be made available. This nondestructive, noncontact hardness determination system also can be applied to the processing of steels other than electrical steels where power loss testers would not normally be used. The predevelopment of loss testers for electrical steels means that the real time determination of the mechanical hardness monitor is relatively inexpensive when compared with costs that would have arisen if the project had been separately developed.

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