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On-Line Measurement of the Microstructure and Mechanical Properties of Steel

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I - INTRODUCTION

One of the greatest challenges of the steel industry is the consistent production of large quantities of steel with well controlled uniform mechanical properties. An essential step in meeting this challenge is the development of reliable sensors which can non-destructively monitor these properties on-line. Although some developments exist in this area, most mechanical property determinations in steel plants are still based on time consuming and costly destructive tests done off-line. In addition to causing shipment delays and being costly, destructive testing provides information on only a small fraction of production and provides no information on possible variations. Mechanical properties can vary from ingot to ingot within a heat, and even within an ingot due to changes in chemical composition or variations in subsequent thermomechanical processing. With the tightening of customer specifications, e.g. from the automotive industry, pressure is increasing for the capability to accurately measure 100% of shipped material. The non-destructive measurement of mechanical properties would also provide the important possibility to control and optimize the process.

The mechanical properties of steel depend on microstructural parameters such as chemical composition, the concentration, shape, and dispersion characteristics of precipitates, grain boundaries, dislocations and point defects such as interstitial or substitutional impurities and vacancies. The accurate and reliable determination of mechanical properties therefore requires the use of sensors sensitive to such microstructural variations in a predictable manner. Because of the complexity of the problem, the approach generally taken is to establish empirical correlations between a physical measurement and the desired mechanical property. Such correlations are usually valid only for limited material parameter changes and to improve and extend their range of applicability information such as chemical composition, processing parameters, and the use of multiple sensors may be required as shown schematically in Figure 1.

In this paper, the various physical mechanisms which have been used to develop techniques for nondestructively measuring microstructural parameters such as grain size, annealing condition and mechanical properties such as tensile and ultimate strength, hardness, fracture toughness and deformability, will be briefly reviewed. Electromagnetic and ultrasonic techniques will then be discussed in greater detail since these offer at present the greatest potential for on-line use.

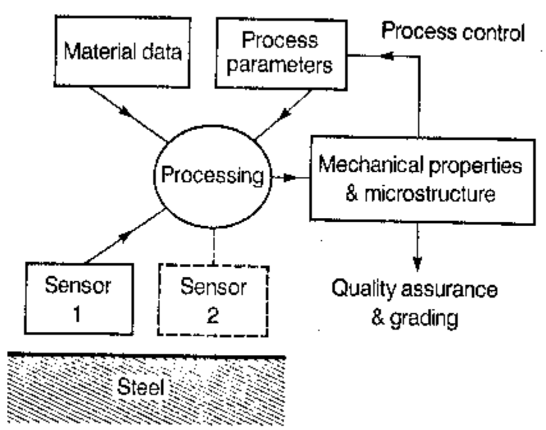

FIGURE 1:

Schematic representation of the integrated use of mechanical property and microstructure sensors.

II - OVERVIEW OF NON-DESTRUCTIVE CHARACTERIZATION TECHNIQUES

A large number of physical measurements can be used to characterize the microstructure and mechanical properties of metals. A number of these are listed in Table I. X-rays for instance are useful for monitoring stress-relaxation, state of anneal - and has recently been shown to be a potentially useful technique for on-line measurement of grain size in moving steel strip[2]. Small angle neutron scattering can yield information on structural defects with a size ranging from less than 10 nm to ≈ 1 μm and can be used to study precipitates, microvoids, dislocations, and growing or dissolving particles[3]. Similarly, positron annihilation can be used as a non-destructive tool to study defects introduced by plastic deformation, fatigue and creep[4]. Mossbauer spectroscopy has been shown to yield useful information at nearly every stage of the steelmaking process, e.g. in particular for the determination of structures and percentages of the principal metallurgical phases in common low alloy steels, investigations of dual phase, precipitation-strengthened and high alloy steels[5]. Thermal measurements have recently been evolving as a new tool for non-destructive measurements. In particular, thermal imaging can provide visualization of grains and thermal conductivity measurements can provide information on hardened layers. The above techniques, however, are in most cases far from being applicable to the on-line monitoring of mechanical properties. Electrical conductivity measurements which can provide a wealth of information on chemical composition, phase transformations and annealing state offers the possibility of monitoring annealing especially for batch annealing where the requirement of non-contact is not present[6]. For on-line measurements of hardness, grain size, ultimate strength and formability, techniques based on magnetic and ultrasonic measurements offer the greatest potential and in some cases have already been installed in steel plants as discussed below.

TABLE I: Techniques useful for the nondestructive measurement of microstructure and mechanical properties.

• Mechanical	• Thermal
• X-Rays	• Neutron Scattering
• Resistivity	• Mossbauer
• Magnetic	• Positron Annihilation
• Ultrasonic	• Etc.

III - ELECTROMAGNETIC MEASUREMENTS

a) Magnetic Measurements (hysteresis)

Electromagnetic techniques of monitoring microstructure include measurements of magnetic properties in the frequency range of 0 to ≈10 kHz, Barkhausen noise and electrical resistivity. Figure 2 shows a typical magnetization curve for steel together with some of the parameters which can be used to characterize magnetic properties. Among these are saturation and remnant magnetic inductions B_m and B_r respectively, initial and maximum permeability μ_o and μ_m, and coercive force Hc. Among the various magnetic parameters, some are relatively insensitive to changes in microstructure such as the Curie temperature, crystallographic magnetic anisotropy and saturation magnetization. These properties will change with chemical and phase composition, whereas properties related to the magnetization such as permeability, coercive force, hysteresis loss and Barkhausen noise are strongly dependent on defects which also affect mechanical properties.

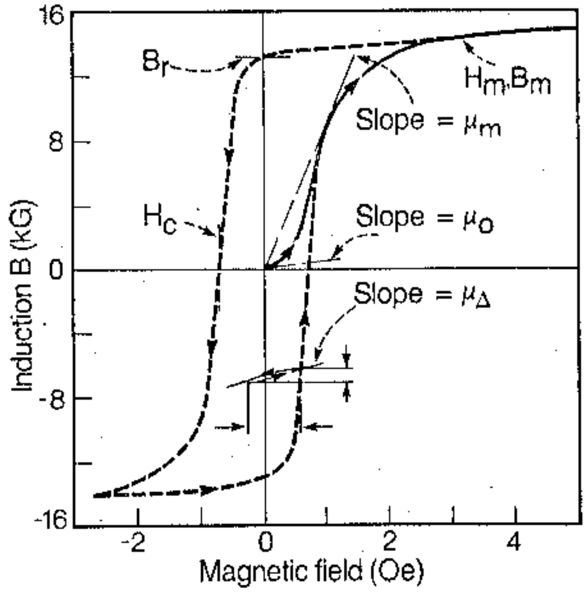

FIGURE 2:

Typical hysteresis loop of steel illustrating parameters which characterize it.

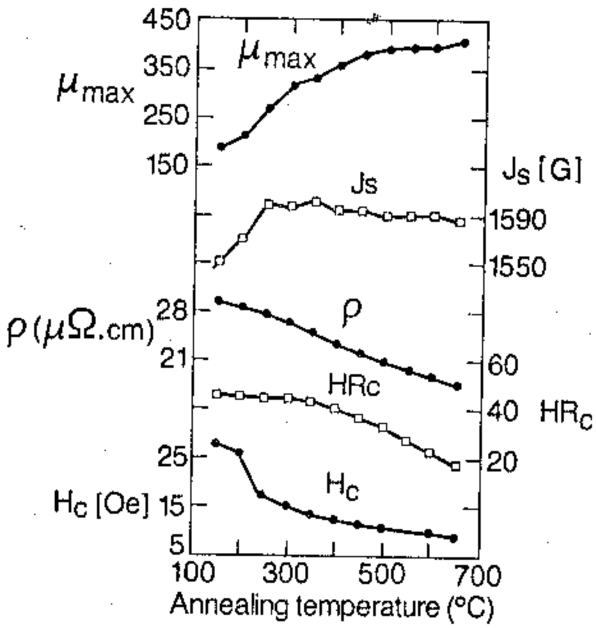

FIGURE 3:

Variation of Rockwell hardness HRC, Magnetic permeability μmax, saturation magnetization J_s, coercivity, Hc, and electrical resistivity, ρ, with annealing temperature for a carbon steel (from ref. 7).

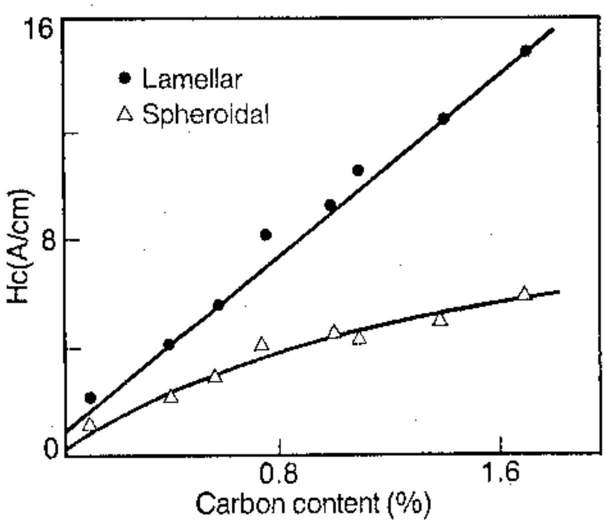

FIGURE 4:

Variation of coercive force with carbon content for lamellar and spheroidal precipitates. (from ref. 10).

This is illustrated in Figure 3 where the magnetic properties μm and Hc are shown to vary smoothly in accordance with hardness for a carbon steel annealed at different temperatures[7]. As expected, the saturation magnetization (J_s) varies only slightly under the same conditions. Similarly, the details of hysteresis loops will depend on composition and microstructure. The non-linear behavior of the magnetization of steels can be analyzed by decomposing the magnetization response (or voltage response of a coil encircling the material) into harmonics. The phase and amplitude of these harmonics depend on the detailed shape of the hysteresis loop which in turn depends on composition and microstructure. This type of analysis has been extensively studied for sorting of materials according to composition and heat treatment[8,9].

Most of the work aimed at on-line monitoring of mechanical properties of steel has concentrated on measurements of coercive force, Hc, and residual magnetic induction Br (or magnetization). Accurate values of Hc can be obtained even for non-ideal geometries, and relative values of Br can be obtained by measuring the external field, Hex, at some location near a sample that has either been magnetized entirely or locally. This latter measurement has the advantage of being essentially independent of the speed of the relative motion between the probe and steel material. The theoretical behavior of Hc in the presence of defects such as dislocations, inclusions and grain boundaries has been studied extensively and was recently reviewed by Mikheev and Gorkunov[10].

Although the coercive force Hc of industrial steel products will be the result of a complex synergistic interplay between microstructural defects, it is useful to understand its behavior when each of these is taken separately. The following relations were found to be valid respectively for dislocations and grain boundaries:

$$Hc \alpha \sqrt{N} \tag{1}$$

where N is the dislocation density and $N \leq 10^6 - 10^7$ cm^{-2} and

$$Hc = A + B/d \tag{2}$$

where A and B are constants and d is grain size.

In the case of inclusions, the following expression:

$$Hc = P\ Keff\ V^n\ /\ M_s \tag{3}$$

is generally found to be valid, where V is the volume of the inclusion, P is a factor dependent on the degree of dispersion of the inclusions, Keff is an effective anisotropy constant and n is an exponent which depends on the form of the inclusions and has values of order 1. Figure 4 illustrates equation (3) for lamellar and spheroidal cementite inclusions in steel. For lamellar forms, Hc increases linearly with the volume, whereas for spheroidal inclusions Hc α $V^{2/3}$ ([10]).

The effects of stress have not been considered above although they may be dominant in practical applications. Because steels are magnetostrictive, stress will tend to modify their effective anisotropy and significantly affect Hc.

In fact, changes of magnetic properties with stress form the basis of a number of techniques to non-destructively measure residual stresses[11,12].

A study by Pyatunin and Slavov[13] has shown that microstresses, as measured by the distortion of the crystalline lattice, $\Delta a/a$ in α-iron play a major role in determining both the coercive force and the tensile strength σ_t of hot rolled steels. A universal linear relationship was found between $\Delta a/a$ and σ_t for both hot rolled rimmed and killed carbon steels. However, two different linear relations were found between $\Delta a/a$ and Hc for the two types of steels, leading to two different relations between σ_t and Hc for these two steels - see Figure 5. This difference in magnetic behavior was attributed to different textures (as determined by x-rays) for the two different types of steels (which are close in chemical composition). In the case of rimmed sheet steel, a larger fraction of grains have the (magnetically difficult) direction in the plane of the sheet leading to a larger coercive force for a given σ_t. In a more recent paper, Timoshenko et al.[14] were able to regroup 67 types of rolled products into 9 groups having identical relationships between mechanical property (tensile strength) and coercive force. The classification depends on texture. In order to further refine the correlations factors such as chemical composition, thickness etc. can be included in a regression analysis[15].

One of the most promising applications of real time mechanical property determination using magnetic measurements is in the monitoring of annealing of strip or tinplate in a continuous annealer. In a continuous annealing furnace which operates at speeds of 150 to ≈600 m/min. the degree of anneal is controlled by temperature and speed. Economy of time and energy as well as product quality dictate that annealing not be taken much further than is necessary to obtain full recrystallization. Usually a maximum Rockwell hardness is specified and the objective is to keep below but as close as possible to this. A number of instruments that relate magnetic measurements to mechanical hardness have been built and installed in steel plants. Hansen[16] has built an instrument that magnetizes a moving strip of

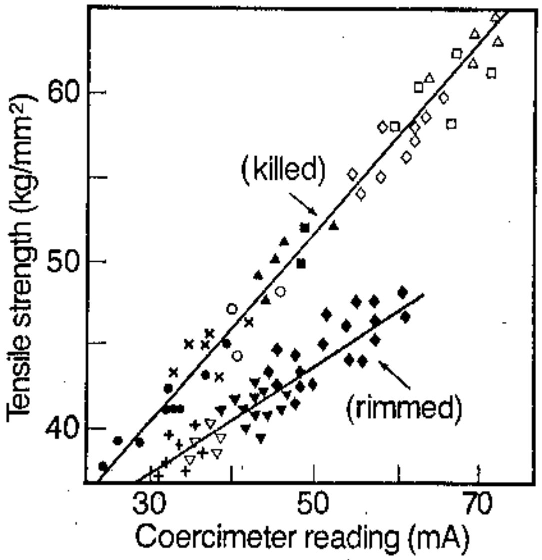

FIGURE 5:

Relation between tensile strength and coercive force for hot rolled rimmed and killed carbon steels of different compositions. The difference in behaviour between killed and rimmed steels is attributed to differences in texture (from ref. 13).

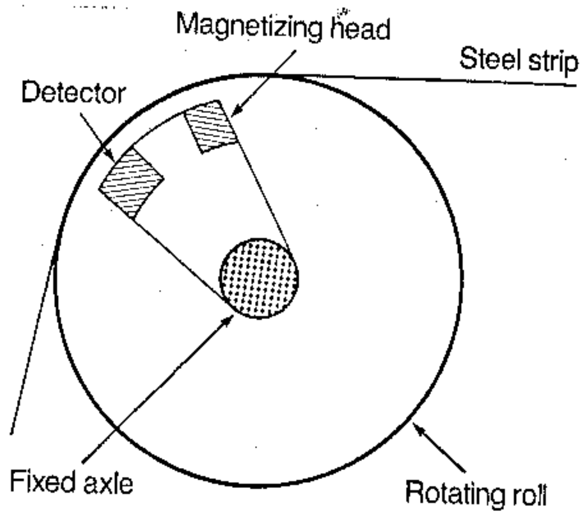

FIGURE 6:

Magnetic sensor configuration used in England for on-line monitoring of hardness (from ref. 18).

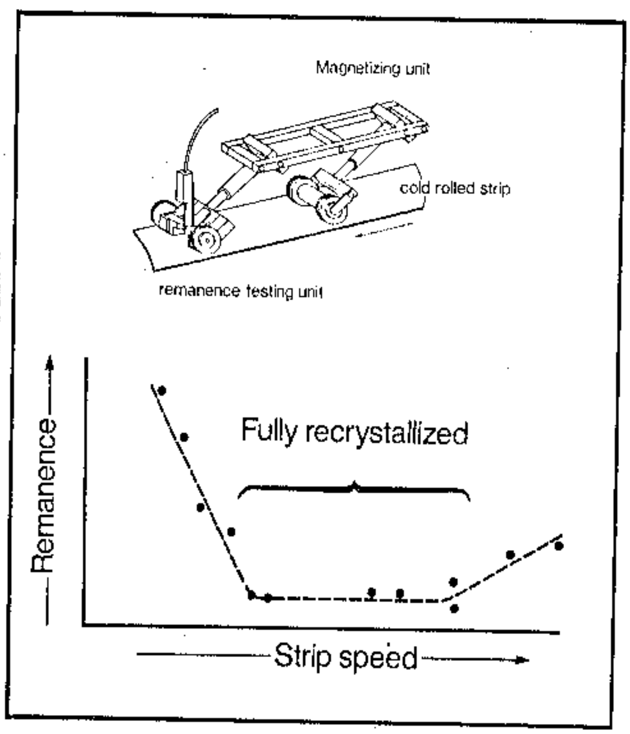

FIGURE 7:

On-line magnetic measurement of the degree of recrystallization of ferritic stainless chromium steel strip (from ref. 19).

sheet steel as it leaves the annealing furnace and measures the remnant magnetization by means of the external field of the sheet; the remnant magnetization is then correlated to hardness. Similar systems have been installed in England[17]. One arrangement of magnetizing and sensing heads is shown in Figure 6 (ref. 18). Recently, the same principles have been applied by Krupp in Germany to monitor the microstructure and degree of recrystallization of continuously annealed ferritic stainless chromium steel strip[19]. The equipment is depicted schematically at the top of Figure 7. The remanent magnetization is related to the degree of recrystallization which depends on strip speed as also shown in Figure 7. Magnetic hardness sensors have also been installed by Kawasaki steel[20].

b) Barkhausen noise

Another magnetic measurement that offers potential for non-destructive evaluation of materials and that has attracted interest in recent years is Barkhausen noise. Barkhausen noise results from the irreversible steplike change in magnetization that results when domain boundaries are suddenly depinned and break away from microstructural defects under the influence of a varying external field. A typical experimental setup is shown in Figure 8. A biasing magnet is cycled at low frequency (generally less than 100 Hz). Noise is detected inductively by a coil placed close to the material surface and analyzed in the frequency range of ≈1-300kHz. A typical result showing Barkhausen noise bursts is shown in Figure 9. A maximum in noise usually occurs at or near $B \approx 0$. Barkhausen noise (BN) can be analyzed in several ways. One method adopted by Finnish investigators is to analyze the noise amplitude distribution and to determine an average value[21,22]. Another technique is to detect the envelope of the noise and to determine the maximum value of the envelope[23]. Although BN is very sensitive to stress, making it an important non-destructive tool for residual stress measurements it is also affected by a number of mechanical properties and microstructure and researchers in Finland have made extensive studies of the relation between BN and microstructure in various types of steels[21,22]. It was argued that most of the pinning points for domains are either grain boundaries themselves or located at grain boundaries. The noise pulse amplitude is thus affected by average grain size. A number of low carbon ferritic and ferritic pearlitic steels were studied. Best results between optically determined and BN determined grain sizes were obtained after temper rolling over the recrystallized state. A linear dependence on a logarithmic grain scale was obtained with the ±1 ASTM band including 25 of 28 samples in the 11-3 ASTM range (see Figure 10). Using about 500 samples of low-allow, low-carbon steel in soft annealed and temper rolled condition a correlation coefficient of 0.92 with a standard deviation of 5.9 μm at the 95% confidence limit was obtained. Barkhausen noise was also shown to be sensitive to precipitation, pearlite morphology and carbon content[23]. Since the Barkhausen noise maximum occurs at the B=0 crossing the experimental setup of Figure 8 can also be used to determine Hc; this has been extensively exploited by Theiner and co-workers of the Fraunhofer Institute who have studied correlations between Hc and hardness of high alloy steels in quenched, tempered and plastically deformed conditions[24]. Correlations with other parameters related to acoustic Barkhausen noise and incremental permeability were also investigated.

Commercial instruments are presently available which allow measurements on material that is either stationary or moving at speeds of up to 5 m/s[25]. Typical depths probed by these instruments are ≈0.2 mm.

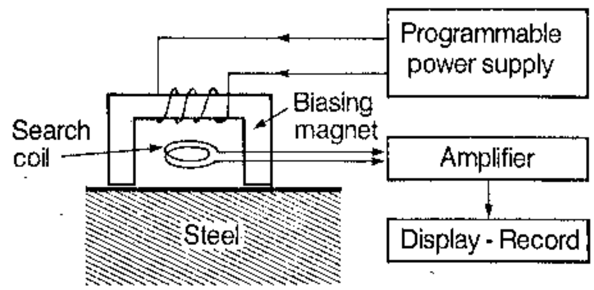

FIGURE 8:

Typical experimental setup for measuring Barkhausen noise in steel (from ref. 23).

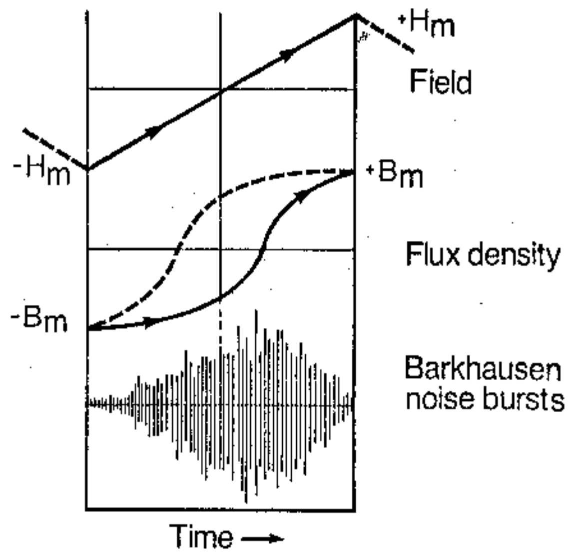

FIGURE 9:

Schematic of change in magnetic induction and production of Barkhausen noise bursts during a linear scan of magnetic field (H) with a system such as shown in Figure 8 (from ref. 22).

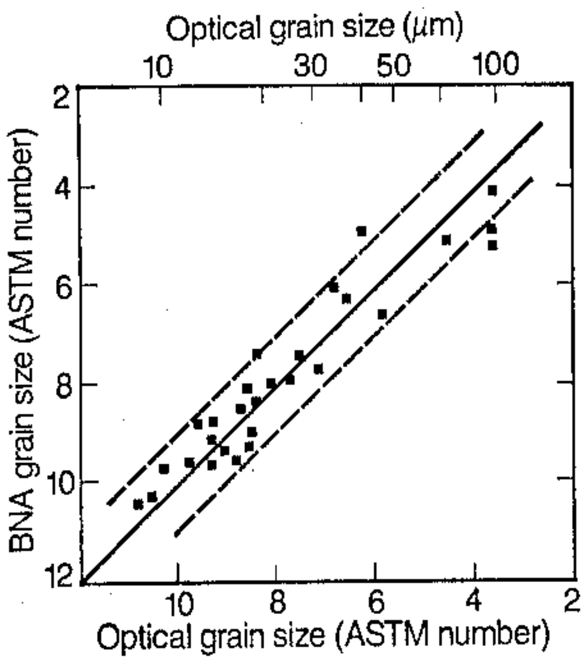

FIGURE 10:

Comparison of grain size obtained from Barkhausen noise and metallographically for low-carbon temper-rolled steel sheet (from ref. 22)

IV - ULTRASONIC TECHNIQUES

a) Introduction

Because of the sensitivity of ultrasonic propagation characteristics to microstructural parameters (through direct interactions with the crystalline lattice) and the possibility of safe on-line measurement systems, ultrasonics is potentially one of the most promising techniques for the nondestructive characterization of material properties. Ultrasonic velocity has been used to measure Young's modulus as a function of composition for iron-based binary alloys [26], see figure 11. Variations are nearly linear with composition except for carbon. However, because elastic properties depend on other factors such as thermomechanical processing, ultrasonic velocity cannot be uniquely related to composition. An example of the effect of processing on velocity is shown in figure 12 which shows a close correlation between hardness and ultrasonic velocity. Measurements were made along the length of an end quenched Jominy bar. Changes of hardness are associated with a change of microstructure from martensitic at the quenched end to pearlitic at the other end. This correlation can also be used to determine case hardening depth by probing surface layers of variable thickness with Rayleigh waves [28]. Measurements of velocity can also be used to measure residual stresses [29]. However the changes in velocity resulting from stress are very small and would be difficult to measure on moving steel.

b) formability:

A more promising application of velocity measurements in the steel plant is for determination of anisotropy and texture which can then be related to the formability of cold-rolled steel sheet. Drawability is related primarily to plastic anisotropy which in turn is dependent on crystallographic texture. The plastic strain ratio, r, defined as

$$r = \varepsilon_\omega / \varepsilon_t \qquad (4)$$

where ε_w and ε_t are the natural strains measured in the width and thickness directions of a tension specimen, is the customary measure of anisotropy. For most commercially produced carbon-steel sheets, $\bar{r}$ varies with test direction and is measured at 0,45° and 90° from which an average value $\bar{r}$ is obtained. The variation of $\bar{r}$ in the plane of the sheet correlates with the tendency of sheet to form "ears" upon drawing and is characterized by the value Δr defined as:

$$\Delta r = \tfrac{1}{2}(r_o - 2\, r_{45} + r_{90}) \tag{5}$$

Determining r and Δr values from tension specimens is tedious and costly. Recent measurements however, based on a study based on 230 steel samples covering a wide range of commercial cold-rolled low carbon steel sheets indicates that general correlations exist between $\bar{r}$ and E and Δr and ΔE, where Young's modulus E was measured from a resonance technique (30, 31) (see figures 13 and 14). The correlation coefficients and standard errors were found to be essentially the same for experimental and commercial steels of different types. Much of the scatter in the data is believed to be due to errors involving the measurement of $\bar{r}$ by tension tests (which were done by several operators using slightly different test methods). It was concluded that Young's modulus provides a more sensitive measure of the small changes in crystallographic texture that result from changes in processing than to measurements of $\bar{r}$. In a more recent study, Hitagawa (32) has also shown the existance of a good correlation between the square of the through thickness longitudinal velocity, v^2_ℓ and the average plastic strain ratio, $\bar{r}$ (see figure 15). The correlation is explained theoretically on the basis that v_ℓ increases monotonically with increase of $\langle 111 \rangle$ axis density normal to the rolling plane and the experimental observation that this density is proportional to $\bar{r}$. By using non-contact ultrasonic techniques, such as electromagnetic-

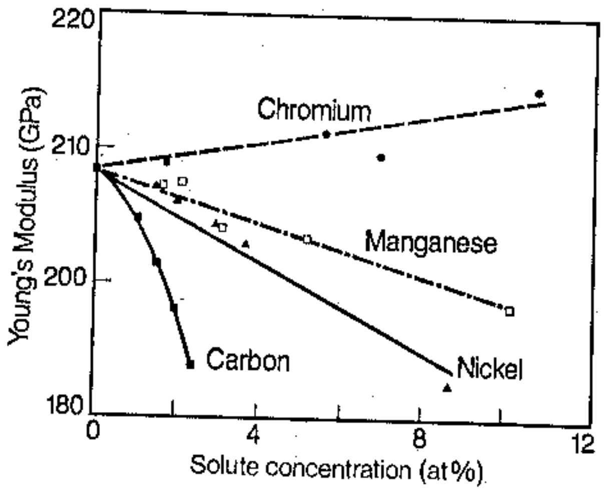

FIGURE 11:

Variation of Young's modulus with solute content for various iron based binary alloys (reproduced from ref. 26, using data of ref. 27).

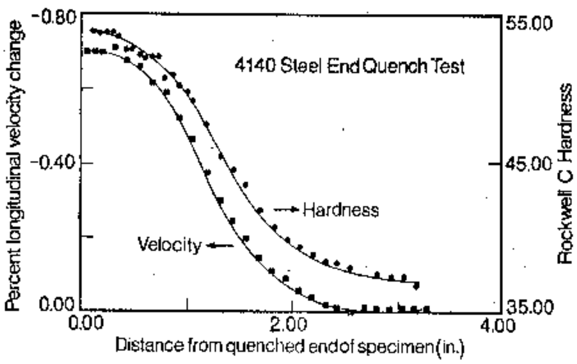

FIGURE 12:

Change in longitudinal ultrasonic velocity and Rockwell hardness along the length of an end-quenched steel Jominy test bar. (from ref. G.S. Kino et al., J. Nondest. Eval. 1, 67 (1980).

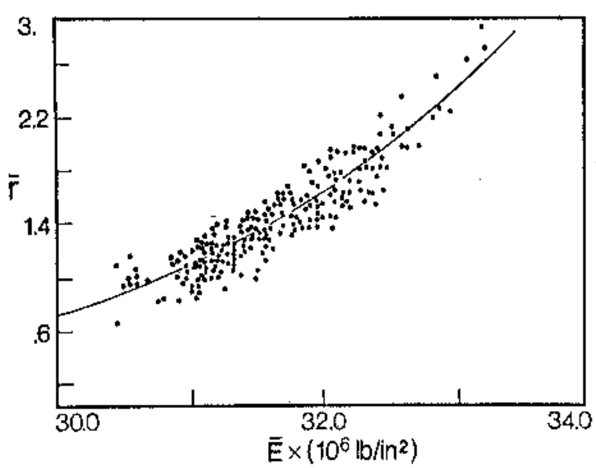

FIGURE 13:

Relation between the average plastic-strain ratio, r and the average Young's modulus, E on cold-rolled low carbon steel sheet (from ref. 30).

acoustic transducers, it is probable that on-line measurements of $\bar{r}$ and Δr could be implemented in steel plants. Work at Bethlehem Steel is being done in this direction [33].

c) <u>grain size, tensile strength, fracture toughness:</u>

Another area of application of ultrasonics to the steel industry has for long range goal the development of practical on-line methods to predict properties such as yield strength, tensile strength and fracture toughness. One approach, taken by researchers at Bethlehem Steel [26, 33-35], is to take as a starting point the well known Hall-Petch relations

$$M = M_0 + M_1 d^{-\frac{1}{2}} \qquad (6)$$

which relate mechanical property, M, to grain size, d, (where M_0 is a constant dependent on composition, phase morphology, etc., and M_1 is a constant), and estimate grain size nondestructively from ultrasonic attenuation measurements. Ultrasonic attenuation in steel, α, for the case where the wavelength, λ ,is in the range $0.03 < d/\lambda < 0.3$, where d is grain size can be described by

$$\alpha = \alpha_0 + B\, d^3\, f^4 \qquad (7)$$

where α_0 is due to absorption or any contribution not associated with grain boundary scattering, B is a proportionability constant and f is ultrasonic frequency. The term Bd^3f^4 is the contribution due to grain boundary scattering. Klinman and co-workers (34) have shown that by a judicious choice of frequency (typically 5 - 10 MHz) the attenuation due to grain scattering can be used as a proxy for the metallographically measured grain size in the estimation of yield strength, tensile strength and transition temperature. This is illustrated in figure 16 for yield strength estimated using an extended Hall-Petch relation which includes chemical composition. For the estimation of yield strength,

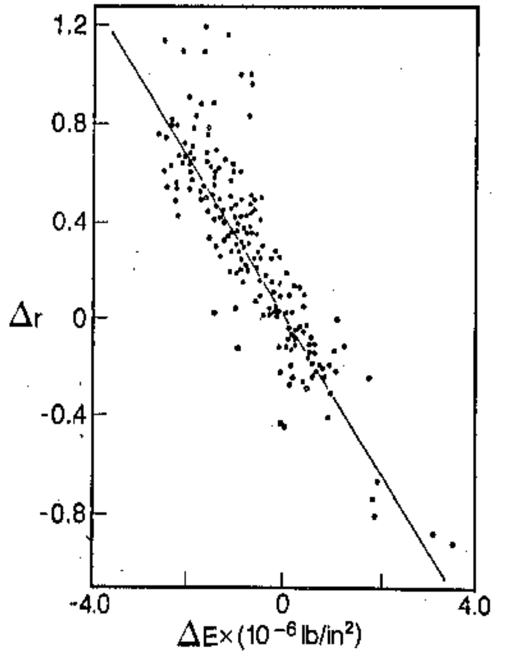

FIGURE 14:

Relation between the planar variation in plastic-strain ratio, Δr, and the planar variation in Young's modulus, ΔE for cold-rolled low carbon steel sheet (from ref. 30).

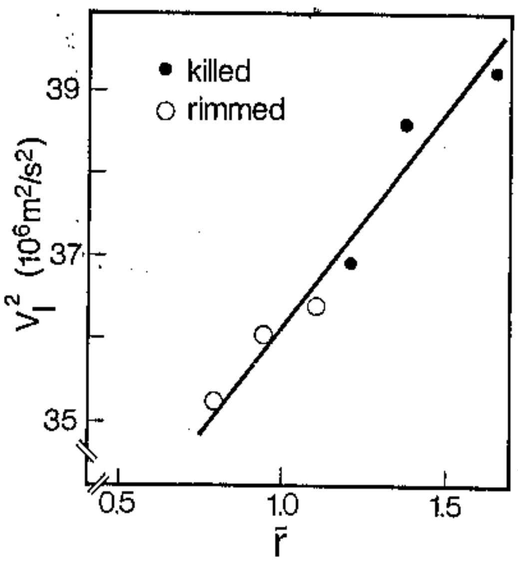

FIGURE 15:

Relation between the average plastic-strain ratio, $\bar{r}$, and the through thickness ultrasonic velocity of longitudinal waves v_ℓ in killed and rimmed carbon steels (from ref. 32).

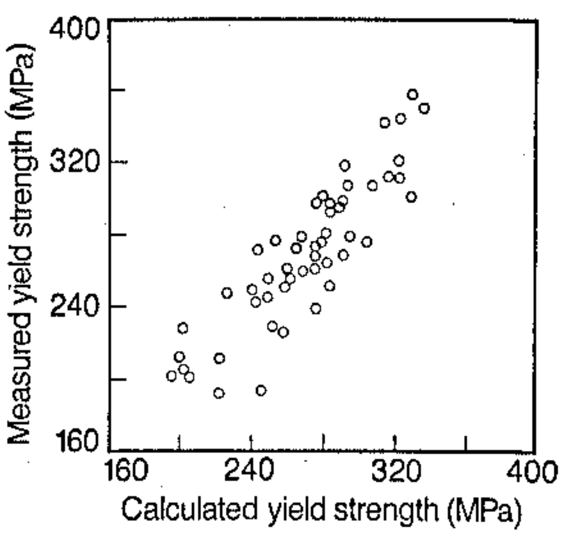

FIGURE 16:

Comparison of measured yield strength and yield strength calculated from an extended Hall-Petch relation using ultrasonic attenuation instead of grain size and including chemical composition. The materials are plain carbon-manganese ferrite-pearlite steels. The standard error is 19.6 MPa (from ref. 35).

chemical composition by itself explained 56 percent of the variance and gave a 95 percent confidence internal of $\pm$ 55 MPa. Addition of $d^{-\frac{1}{2}}$ to the regression markedly increased the variance explained (to 80 percent) and tightened the confidence internal to $\pm$ 31 MPa. Using the attenuation results instead of the metallographically determined d dropped the variance to 79% and opened the confidence internal to $\pm$ 39 MPa. Similar results apply to tensile strength and transition temperature estimations.

Grain size can also be measured ultrasonically with backscattering measurements [36]. These measurements consist in analysing the ultrasonic signals reflected from individual grains instead of the attenuation of ultrasound due to the same. Although good accuracy can be obtained and the technique has the advantage of not requiring parallel surfaces, a good surface finish is required and signal to noise can be a problem.

Another approach to ultrasonic mechanical property measurement was taken by A. Vary [37], who suggested a general empirical relation between fracture toughness, K_{1c}, yield strength σ_y and ultrasonic attenuation. Using attenuation measurements in the 10 to 50 MHz range, good results were obtained for two maraging steels and a titanium alloy aged at various temperatures. Other studies, however, indicated the doubtful applicability of the general relation for Fe-C alloys [38] and for a 403 stainless steel whose K_{1c} was varied by changing the temperature, thus keeping grain size and microstructure constant [39].

Another aspect of ultrasonics which is still largely unexplored for material characterization is the study of non-linear elasticity. Third-order elastic constants have been shown to depend strongly on texture [40] and has been shown to be a possible nondestructive tool to characterize the state of anneal of aluminum [41]. The techniques required, however, are difficult to apply in an industrial environment.

At present, an ultrasonic technique to measure grain size has been installed on a cold strip line by Krupp in Germany (19). Similar techniques are being explored by Nippon Steel and Bethlehem Steel.

CONCLUSION

Among the various physical techniques included in table I, which can be used to nondestructively characterize on-line the microstructure and mechanical properties of steel, the use of techniques based on x-rays, magnetic and ultrasonic measurements appear to be the most promising. Since information on the on-line use of x-rays is at present very scarce, the above presentation concentrated on magnetic and ultrasonic techniques. Magnetic techniques are extremely sensitive to stress, microstructure and mechanical properties and offer the possibility of rapid non-contact measurements. Limitations are associated with the complexity and ambiguity of the relation between microstructure, magnetic properties and mechanical properties. However, some progress has been achieved in this area, for instance by regrouping carbon steels of varying composition according to texture, yielding groups which have identical correlations between hardness and H_c. A number of magnetic based sensors have been installed in steel plants to monitor hardness of steel strip on-line.

Ultrasonic techniques have been developed more recently and show great promise. In this case, a clear relationship can be established between texture, anisotropy and ultrasonic velocity. This property has been used to reliably measure properties of low carbon steel sheets such as drawability. The relationship between attenuation and grain size is also well established and can be used to determine grain size or in cases where mechanical properties are closely related to grain size - to predict mechanical properties directly.

Reliability would probably be enhanced by the use of several complementary techniques; for instance, ultrasonic methods for determining grain size and anisotropy may be combined with magnetic measurements to narrow the uncertainty in yield strength predictions obtained from ultrasonic attenuation.

Research is required to develop still unknown or presently "exotic" techniques and to improve understanding of the relations between traditional measurements and mechanical properties.

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REFERENCES

1) R.C. Booth and R.N. Cressman, "Nondestructive Testing Needs in the Steel Industry", Materials Evaluation 39, 1130 (1981).

2) C. Rinik, J.E. Hilliard, and J.B. Cohen, "SOL-X : An On-line nondestructive Method for Measuring Grain Size with x-rays", J. of Nondestructive Evaluation 2, 133 (1981).

3) J. Weertman, "Identification by Small Angle Neutron Scattering of Microstructural Changes in Metals and Alloys in Nondestructive Evaluation" in Microstructural Characterization and Reliability Strategies", edited by O. Buck and S.M. Webb TMS-AIME Conf. Proceedings, (1981), p. 147-168; H. Walther and P. Pizzi, "Small angle neutron Scattering for Nondestructive Testing", in Research Techniques for Nondestructive Testing, Vol IV, edited by R.S. Sharpe, Academic Press 1980, p. 341.

4) C.F. Coleman and A.E. Hughes, "Position Annihilation", in Research Techniques for Nondestructive Testing, Vol III, p. 355 (1977).

5) G.P. Huggman and F.E. Huggins, "The Use of Mossbauer Spectroscopy in the Analysis of the Raw Materials and Products of the Steel Industry", in Physics in the Steel Industry, American Institute of Physics Conf. Proceedings No. 84 (1982), p. 149.

6) S.J.P.Durham, R.A.C. Drew, W.B. Muir and W.M. Williams, "Differential Resistivity Measurements for Monitoring Annealing", CSIRA Workshop (this report).

7) F. Forster and W. Stumm, "Application of Magnetic and Electromagnetic Nondestructive Test Methods for Measuring Physical and Technological Material Values", Materials Evaluation (1975) p.5.

8) R.C. McMaster, Nondestructive Testing Handbook, Vol II, The American Society for Nondestructive Testing, Inc., Columbus, Ohio (1959).

9) "Electromagnetic Sorting and Testing", in Metals Handbook Vol XI Nondestructive Inspection and Quality Control, American Society for Metals, Metals Park, Ohio, 1976, p. 93-105.

10) M.N. Mikheev and E.S. Gorkunov, "Relationship of Magnetic Properties to the Structural Condition of a Substance - The Physical Basis of Magnetic Structure Analysis (Review), Soviet J. Nondestructive Testing, translated from Defektoskopiya No.8, pp. 5-22, (aug. 81).

11) R.A. Langman "Measurement of the Mechanical Stress in Mild Steel by means of Rotation of Magnetic Field Strength", NDT International 14, No. 5, 255 (1981).

12) D.C. Jiles and D.L. Atherton, "Theory of Ferromagnetic Hysteresis", J. Appl. Phys. 1984 [Conference on Magnetism and Magnetic Materials, Pittsburgh, Nov. 1983].

13) G.A. Pyatunin and V.I. Slavov, "Nature of the Relationship between Mechanical and Magnetic Properties of Carbon Steel", Soviet J. NDT, translated from Defektoskopiya, Nov. 1978 (No. 11), pp 98-103.

14) N.N. Timoshenko, G.A. Pyatunin and V.I.Slavov, "Method of Magnetic Inspection of the Mechanical Properties of Rolled Sheet". Ind. Lab. 47 (2) 184-6 (1981).

15) L.O. Devyatchenko and L.E. Valyaeva, "Improving the Accuracy of Magnetic Inspection of the Mechanical Properties of High-Quality Steel", Soviet J. NDT translated from Defektoskopiya No. 2, pp 52-57, (1983).

16) H.J. Hansen, J. Metals 18, 1131 (1966).

17) G. Syke and I. Murray "Some magnetic Methods of Non-Destructive Examination: Part 1; Measurement of Hardness in a Continuous Annealer, in Non-Destructive Examination in the Steel Industry, ISIPublication No. 103, The Iron and Steel Institute 1967, p. 109.

18) Publication No. 103, The Iron and Steel Institue 1967, p. 109.
N. Davis "Magnetic Analysis Techniques", in Research Techniques in Nondestructive Testing Vol II, pp 121-149, Academic Press (1973).
*See also: M.N. Lapper "Apparatus for the magnetic testing of metal strip, British Patent 1311907 (28 March 1973).

19) A. Randak, "On-line Inspection of Semi-finished and Finished Steel Products for Surface Defects and Internal Quality" in On-line Inspection of Steel Products, International Iron and Steel Institute, Committee on Technology, Brussels 1983 p.1.

20) E.W. Leaver, Report on Product Quality Scissors Used by the Japanese Steel Industry (May 6 to June 3, 1983).

21) S. Titto, M. Ottala and S. Saynajakangas, "Non-destructive Magnetic Measurement of Steel Grain Size", Non-destructive Testing, Vol 9, No. 3, 117 (1976).

22) O. Sundström and K. Torronen, "The Use of Barkbausen Noise in Nondestructive Testing", Materials Evaluation, Feb. 1979, p.51.

23) G.A. Matzkanin, R.E. Beissner and C.M. Teller, "The Barkhausen Effect and its Applications to Nondestructive Evaluation, Southwest Research Institute Report NTIAC-79-2 (1979).

24) W.A. Theiner and H.H. Willems, "Determination of Microstructural Parameters by Magnetic and Ultrasonic Quantitative NDE", Proc. of a Symposium on Nondestructive Methods for Material Property Determination, Hershey, Pa., April 1983 (Plenum, in press).

25) American Stress Technologies, Inc., Pittsburgh, Pa.

26) B.E. Droney and R. Klinman, "Ultrasonic Techniques for Determining the Mechanical Properties of Steels, Physics in the Steel Industry (APS/AISI, Lehigh University, 1981), AIP Conference Proceedings No. 84, p. 210, edited by F.C. Schwerer, American Institute of Physics (1982).

27) G. R. Speich, A.J. Schwoeble and W.C. Leslie, "Elastic Constants of binary iron-base alloys", Met. Trans. 3, 2031 (1972).

28) C.Flambard and C. Lambert, Proc. 8th World Conf. on Nondestructive Testing, Institut de Soudure, Paris, Section 1c, pp 1-7, (1976).

29) D.R. Allen, W.H.B. Cooper, C.M. Sayers and M.G. Silk, "The Use of Ultrasonics to Measure Residual Stresses, in Research Techniques in Nondestructive Testing", Vol VI, R.S. Sharpe, ed. Academic Press (1982), pp. 151-209.

30) P.R. Mould and T.E. Johnson Jr., "Rapid assessment of drawability of cold-rolled low carbon steel sheets, Sheet Metal Industries, June 1973, p. 328.

31) C.A. Stickels and P.R. Mould, "The use of Young's Modulus for Predicting the Plastic-Strain Ratio of Low-Carbon Steel Sheets", Met. Trans 1, 1303 (1970).

32) H. Kitagawa, "Analysis of Elastic Anisotropy in cold-rolled steel sheet", Proc. of the sixth International Conference on Textures in Metals, Tokyo (1981), pp-1166-1178.

33) B.E. Droney "Use of ultrasonic techniques to assess the mechanical properties of steels", symposium on Nondestructive Methods for Materials Property Determination, Hershey, Pa., 1983, Plenum Press (in press).

34) R. Klinman, C.R. Webster, F.J. Marsh and E.T. Stephenson, "Ultrasonic Prediction of grain size, strength and toughness in plain carbon steel", Materials Evaluation, Oct. 1980, 26.

35) R. Klinman, and E.T. Stephenson, "Ultrasonic prediction of grain size and mechanical properties of plain carbon steel", Materials Evaluation, 39, 1116 (1981).