

# Review of magnetic methods for nondestructive evaluation

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This paper provides a guideline to the literature of magnetic techniques for nondestructive evaluation. Compared with other NDE methods such as ultrasonics or eddy currents, the literature for magnetic methods is relatively small, but one of the difficulties is that it is widely scattered. This review therefore presents a fairly comprehensive summary of works on Barkhausen effect, magnetoacoustic emission, magnetic hysteresis, residual field and magnetically induced velocity change methods that have appeared to date.

**Keywords:** magnetic techniques for NDE, Barkhausen effect, magnetoacoustic emission, magnetic hysteresis, residual field, magnetically induced velocity change

More iron and steel is produced each year than any other metal. In 1986 world production of crude steel was  $662 \times 10^6$  tons and of pig iron and ferro alloys  $484 \times 10^6$  tons. So economically steel must be considered one of the most important industrial commodities. It is of course under widespread use as a constructional material on large-scale projects such as pipelines, railroads and bridges while also being used for the fabrication of high-strength components. Consequently there is a growing need for nondestructive inspection of steel structures both for the detection of corrosion, cracks and other defects and for the evaluation of stresses, elastic and plastic deformation and the likelihood of failure due to creep or fatigue.

A number of nondestructive testing techniques have appeared over the years, but today the subject of NDE has assumed a vital role, as more industries become aware of the potential benefits of plant life extension, the cost effectiveness of only retiring defective components (retirement for cause) and the possibilities of avoiding potentially catastrophic failures by monitoring the condition of structures both for defects and the presence of high levels of stress.

While various NDE techniques may be used on steels, one group is unique to steel – the magnetic methods. These utilize the inherent ferromagnetic properties of the steel for nondestructive evaluation of a wide range of material properties from cracks to residual strain. In general the changes in magnetic properties that are observed are easily measurable and unlike ultrasonic methods do not need high-resolution electronics for their use. Nevertheless the magnetic methods have not yet been fully exploited when compared for example with ultrasound. Probably this is because other techniques can be applied to a wide variety of materials and previously there was more incentive for their development. Now, however, as the limitations of other techniques become apparent, as for example in the important area of detection and prediction of failure such as fatigue or

thermomechanical degradation (creep damage), attention has focused on the capabilities of magnetic methods applied to steels.

In the following discussion of the various techniques that are already available, there is a brief description of each method followed by a summary of the problems that have been successfully solved by the technique. Each section then ends with a recommended review paper or standard reference text. The review begins with the Barkhausen effect and then goes on to consider magnetoacoustic emission, magnetic hysteresis, residual field, remanent magnetization and magnetoelastic methods.

## The magnetic Barkhausen effect (MBE)

The Barkhausen effect was discovered in 1919<sup>[1]</sup>, but it was many years before its potential as an NDE tool was realized. It is now one of the most popular magnetic NDE methods for investigating intrinsic properties of magnetic materials such as grain size, heat treatment, strain and other mechanical properties such as hardness.

The Barkhausen effect consists of discontinuous changes in flux density, known as Barkhausen jumps (Figure 1). These are caused by sudden irreversible motion of

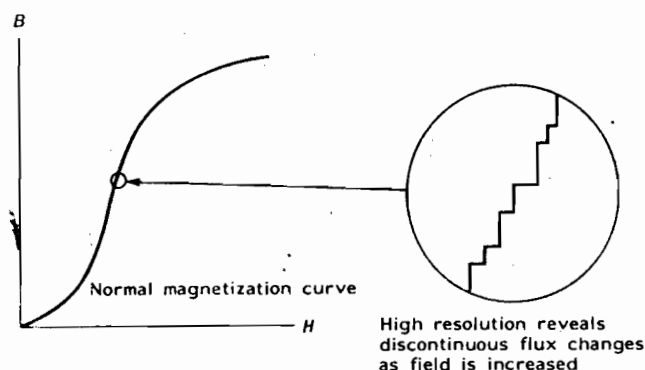


Fig. 1 Discontinuous changes in flux density  $B$  as the magnetic field  $H$  is changed

magnetic domain walls when they break away from pinning sites due to changes in magnetic field  $H$ . The Barkhausen spectrum, which is the number of events against pulse height, as shown in Figure 2, is dependent on the number density and nature of pinning sites within the material. These may be grain boundaries, dislocations or precipitates of a second phase with different magnetic properties from the matrix material, such as iron carbide in steels. Most Barkhausen activity occurs close to the coercive field  $H_c$ . Double peaks in the count rate can occur, as shown in Figure 3. Also the location and size of the peaks can shift as a result of changes in the defect distribution (see Figure 3) where results are for two specimens of the same material with different defect distributions.

The first attempt to use the magnetic Barkhausen effect to determine stress was reported by Leep<sup>[2]</sup>, but the method really only began to gain acceptance after the work of Pasley<sup>[3]</sup> who showed distinct variations in Barkhausen signal amplitude with applied and residual stress. As stress increased in tension the peak Barkhausen amplitude in steel was found to increase while in compression it was found to decrease.

Subsequently there were a number of investigations in Finland by Tiitto<sup>[4-6]</sup>, Sundstrom and Torronen<sup>[7]</sup>, Kettunen and Ruuskanen<sup>[8]</sup>, Ojala and Saynajakangas<sup>[9]</sup>, Karjalainen and Moilanen<sup>[10-12]</sup> and Ruuskanen and Kettunen<sup>[13]</sup>. Tiitto<sup>[4]</sup> investigated the effects of elastic and plastic strain on the MBE in silicon iron and the microstructural dependence of MBE in steels<sup>[6]</sup>. He was also able to show that MBE could be used to determine grain size in steels<sup>[5]</sup>. Sundstrom and Torronen<sup>[7]</sup> reported that MBE can be used for determination of microstructure, mechanical and electrical properties. Karjalainen and Moilanen<sup>[10,11]</sup> investigated the effects of plastic deformation and fatigue on MBE. Ojala and Saynajakangas<sup>[9]</sup> devised an MBE instrument for grain size determination.

The effect of tensile and cyclic loading on the RMS value of MBE signals in mild steel was the subject of an investigation by Karjalainen *et al*<sup>[12]</sup>. They found that residual strains in unloaded specimens could be identified from MBE. But changes occurring under cyclic loading (fatigue cycling) were very complex so that the Barkhausen

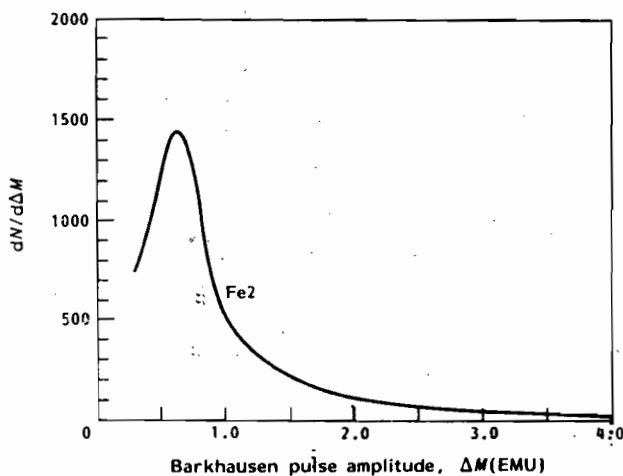


Fig. 2 Magnetic Barkhausen spectrum (pulse height distribution); after Tebble, Skidmore and Corner, *Proc. Phys. Soc.* A63 (1950) p 739

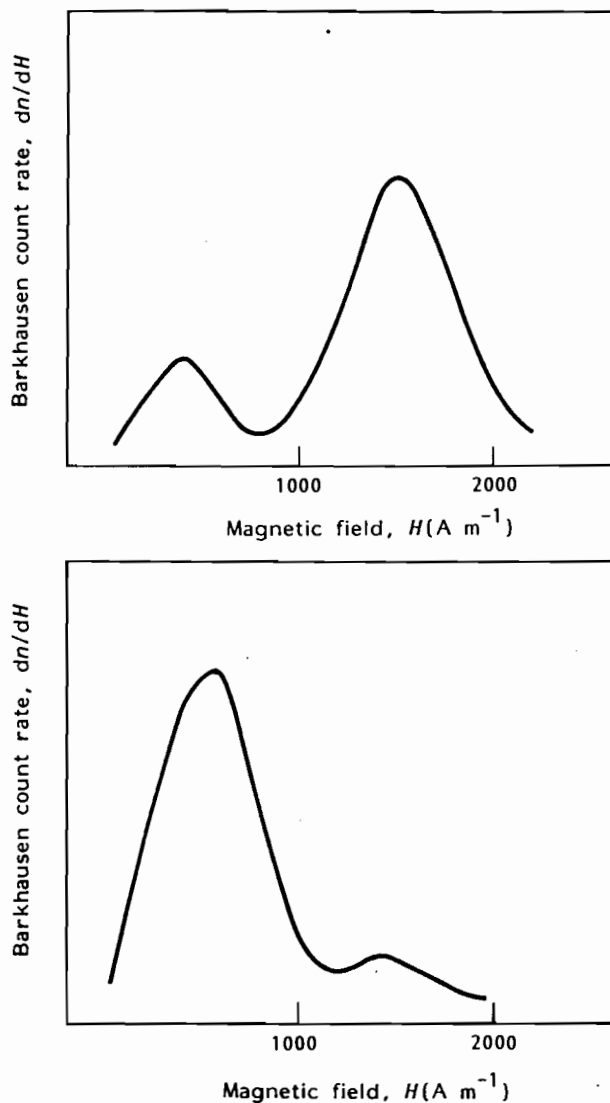


Fig. 3 Barkhausen count rate as a function of magnetic field  $H$  for specimens with two different defect distributions<sup>[26]</sup>

signals could not be simply related to the applied load. However, Ruuskanen and Kettunen<sup>[13]</sup> were able to demonstrate that the median Barkhausen pulse amplitude could be used to assess whether the applied stress amplitude was above or below the fatigue limit.

Lomaev<sup>[14,15]</sup> has reviewed the literature relating to nondestructive evaluation applications of MBE. In these papers he identified five mechanisms by which MBE is caused: (i) discontinuous, irreversible domain wall motion; (ii) discontinuous rotation within a domain; (iii) appearance and disappearance of Néel peaks; (iv) inversion of magnetization in single-domain particles; (v) displacement of Bloch or Néel lines in two  $180^\circ$  walls with oppositely directed magnetizations. The first of these mechanisms has been studied most intensively and is often, incorrectly, quoted as the sole mechanism for generation of MBE. It is interesting to note that in the early years of MBE the effect was attributed to mechanism (ii), irreversible domain rotation.

A number of other papers have appeared on MBE in the Soviet literature, usually in *Defektoskopia*. Klyuev *et al*<sup>[16]</sup> have reported that on the basis of their results there does not seem to be any single unambiguous correlation

between their MBE measurements and the parameters of magnetic hysteresis. This is an interesting and very significant result since it shows that the magnetic Barkhausen effect provides nondestructive information on the state of a material which is independent of that gained by bulk magnetic properties such as hysteresis.

Filinov *et al*<sup>[17]</sup> have shown that MBE can be used to probe surface plastic deformation of steel components by using different magnetizing frequencies. Such a technique can be used for evaluation of a variety of different types of surface condition such as case hardening or surface decarburization.

A combination of MBE at different frequencies and hysteresis measurements has been used by Mayos *et al*<sup>[18-20]</sup> for the determination of surface decarburization in steels. By this method different depths of the material were inspected to investigate changes in magnetic properties. Segalini *et al*<sup>[21]</sup> have used MBE for evaluation of heat treatment and microstructure of constructional steels.

In Germany Theiner and co-workers have used MBE in conjunction with incremental permeability and ultrasonic measurements for the evaluation of stress<sup>[22-24]</sup>. As they have noted, all ferromagnetic NDE methods are sensitive to both mechanical stress and the microstructure of the material. In order to determine stress it is therefore necessary to use two or three independent measurement parameters. They found that Barkhausen effect, incremental permeability, X-ray and hardness measurements were successful in estimating residual stress. As might have been anticipated, they found changes in the density of dislocations affected the MBE signals. They also found<sup>[25]</sup> that MBE could be used to distinguish between microstructures which cannot be distinguished on the basis of optical microscopy.

In the United States a large amount of work on MBE has been conducted at Southwest Research Institute by Matzkanin, Beissner and co-workers. Much of this work has been summarized in *The Barkhausen Effect and its Applications to NDE* by Matzkanin, Beissner and Teller<sup>[26]</sup> which remains the most comprehensive work on the subject to date. Other reviews are also available, the most notable being by McClure and Schroeder<sup>[27]</sup>.

### Magnetoacoustic emission (MAE)

Magnetoacoustic emission is an effect which is very closely related to the magnetic Barkhausen effect. It is caused by microscopic changes in strain due to magnetostriction when discontinuous irreversible domain wall motion of non-180° domain walls occurs. It therefore arises in ferromagnetic materials when subjected to a time-dependent field (Figure 4). The acoustic emissions may be detected by a piezoelectric transducer bonded onto the test part. The amplitude of MAE depends on the magnetostriction coefficient, being zero if  $\lambda = 0$  and increasing with  $\lambda$ . The amplitude of emissions is also a function of the frequency and amplitude of the driving field.

It is clearly apparent that MAE must change with applied stress, since stress alters the magnetocrystalline anisotropy. This results in a change in the relative numbers of 180° and non-180° domain walls. Since 180° domain walls do

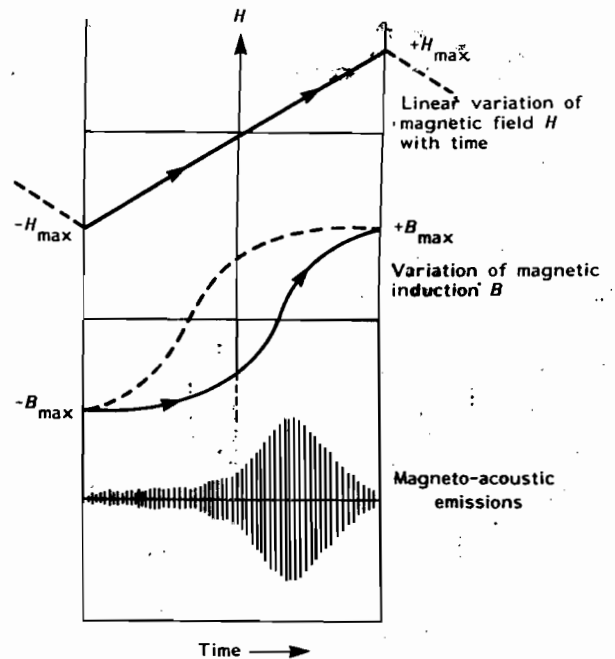


Fig. 4 Schematic diagram showing change in magnetic field  $H$  with time, variation in flux density over the same period and the emergence of magnetoacoustic emission pulses as flux density changes

not contribute to MAE, the amplitude of emissions and the total number of emissions will change with stress.

Despite its close relation to the magnetic Barkhausen effect, MAE has a much shorter history. It was first reported by Lord<sup>[28]</sup> during magnetization of nickel. Its significance for NDE was realized by Kusanagi *et al*<sup>[29]</sup> who were first to demonstrate the effect of stress on MAE. Shortly afterwards Ono and Shibata<sup>[30-32]</sup> reported MAE results on a number of steels. Their results indicated that the method could be used to determine the amount of prior cold work and differences in heat treatment.

Burkhardt *et al*<sup>[33]</sup> have also investigated the dependence of MAE on the mechanical and thermal treatment of steels. They found that MAE was very sensitive to the amount of plastic deformation. Theiner and Willems<sup>[34]</sup> used MAE in conjunction with other independent measurements such as incremental permeability, MBE and magnetostriction. Their results showed that the MAE amplitude decreased with the mechanical hardness of steels but increased with tempering.

Edwards and Palmer<sup>[35]</sup> have recently shown that MAE signals are affected not only by stress and frequency of field but also by such factors as sample shape. Ranjan *et al*<sup>[36,37]</sup> have used MAE and MBE for the determination of grain size in decarburized steels. They used two types of measurement, the MAE peak height and the total number of emissions, both of which were found to increase with grain size.

A related phenomenon has also been reported by Higgins and Carpenter<sup>[38]</sup>. Acoustic and magnetic Barkhausen emissions due to domain wall motion were observed in ferromagnetic materials when the applied stress was changed without changing the magnetic field. This can easily be understood in terms of the domain wall pinning

model. The magnetic Barkhausen emissions were also observed under dynamic stress by Jiles and Atherton<sup>[39]</sup> during their investigations of magnetomechanical effects, although they were not reported in the paper. This phenomenon of magnetomechanical emissions has received little attention but would appear to have significant implications for the detection of dynamic stresses in steels.

### Magnetic hysteresis

All ferromagnetic materials exhibit hysteresis in the variation of flux density  $B$  with magnetic field  $H$  (Figure 5). The hysteretic properties such as permeability, coercivity, remanence and hysteresis loss are known to be sensitive to such factors as stress, strain, grain size, heat treatment and the presence of precipitates of a second phase, such as iron carbide in steels. In addition, the measurement of hysteresis yields a number of independent parameters, each of which changes to some degree with stress, strain and microstructure. Since it has been remarked earlier that several independent parameters are needed in general to separate effects of mechanical treatment from microstructure, hysteresis measurements would seem to be ideally suited for the determination of intrinsic properties of steels because the several independent parameters can be obtained from one measurement.

Despite this economy of means, there are certain difficulties that need to be overcome with the magnetic hysteresis method. Firstly, the problem of demagnetizing effects due to finite geometries needs to be addressed, since results which may appear to be due to changes in sample properties can be caused by geometrical effects. Secondly, until recently it has proved impossible to adequately model hysteresis in ferromagnets so that it has been difficult to interpret changes in the hysteresis characteristics in terms of fundamental changes in sample properties. Of course this has also been true of other magnetic methods,

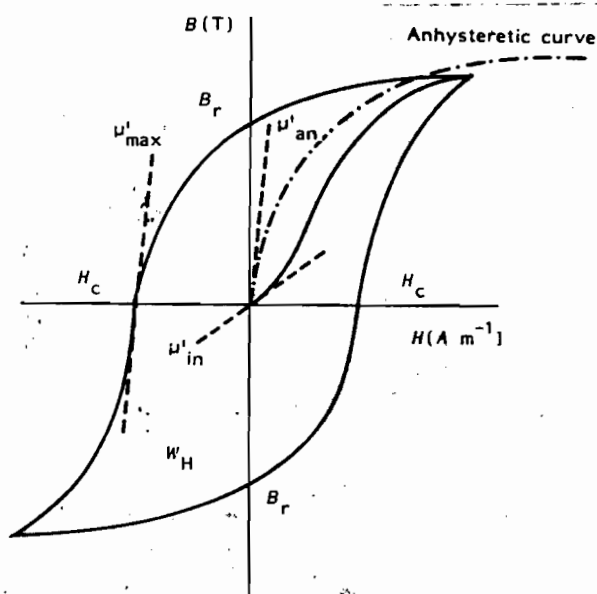


Fig. 5 Typical hysteresis loop of a ferromagnetic material showing the various hysteresis parameters such as coercivity  $H_c$ , remanence  $B_r$ , initial permeability  $\mu'_{in}$ , maximum differential permeability  $\mu'_{max}$  and total hysteresis loss  $W_H$ , which is the area enclosed by the loop

such as the Barkhausen effect, and has not prevented their use for NDE.

Evaluation of the condition of magnetic steel components has been one area where NDE via hysteresis has had great success. Numerous applications have been reported in the literature. Mikheev and co-workers at the Urals Science Centre have made many investigations of the quality of heat treatment of steels from magnetic parameters<sup>[40-46]</sup>, particularly the evaluation of hardnesses of various steels<sup>[47]</sup>. In most cases the magnetic properties were determined using a coercimeter and correlations made between chemical composition, microstructure, heat treatment and hardness and the principal magnetic parameter of interest, the coercivity. Mikheev has written two reviews on the subject<sup>[48,49]</sup> which may be used as an introduction to his work.

Kuznetsov and co-workers have also looked at the effects of heat treatments such as quenching, hardening and tempering on the magnetic properties of steels<sup>[50-54]</sup>. They have also devised a method for determining the depth of case hardening<sup>[55]</sup>. Similar work on determination of quality of steel component heat treatment has been carried out by Fridman *et al*<sup>[56]</sup>, Kononov *et al*<sup>[57]</sup>, Melgui *et al*<sup>[58]</sup>, Katsevman and Sandorskii<sup>[59]</sup> and Gorkunov<sup>[60]</sup>. Specific applications to sorting of components have been described by Sandorskii<sup>[61]</sup> and to determination of composition and microstructure by Khavatoev<sup>[62]</sup>. Zatsepin *et al*<sup>[63]</sup> investigated the variation of coercivity with heat treatment and mechanical properties, while Rodigin and Syrochkin<sup>[64]</sup> were able to use the effect of stress on coercivity to check mechanical hardness, thereby using hysteresis parameters as an accept-reject criterion for steel components.

The effects of stress on the magnetic hysteresis properties of steels are of interest because they have applications to nondestructive evaluation of structures such as railroad lines and pipelines. Typically the hysteresis 'signature' is changed by stress as shown in Figure 6. Vekser *et al*<sup>[65]</sup> showed that it was possible to measure the stress in rail steel from the permeability. Schchebinina *et al*<sup>[66]</sup> were able to detect defects in in-service railroad rails from inspection by fluxgate magnetometers.

Pyatunin and Slavov<sup>[67]</sup> investigated the effects of microstresses and texture in steel on the bulk magnetic properties and showed correlations between mechanical and magnetic properties for specimens of similar texture.

The dependence of magnetic properties on static and dynamic stresses was the subject of a study by Novikov and Fateev<sup>[68]</sup>. Similar work was performed by Pravdin<sup>[69-71]</sup> who drew distinctions between the effects of static and dynamic stresses. The results revealed that dynamic loading changed the flux density  $B$  by different amounts depending on the applied field  $H$ . This was very similar to the findings of Jiles and Atherton described below.

The effects of elastic stress on hysteresis have been reported by a number of investigators, including Jiles and Atherton<sup>[72,73]</sup>, Burkhardt and Kwun<sup>[74]</sup> and Pölanschutz<sup>[75]</sup>. The interpretation of results is difficult without a working mathematical model of hysteresis, since none of the direct hysteresis parameters such as coercivity, remanence, initial permeability or hysteresis loss is uniquely related to a single physical property. This

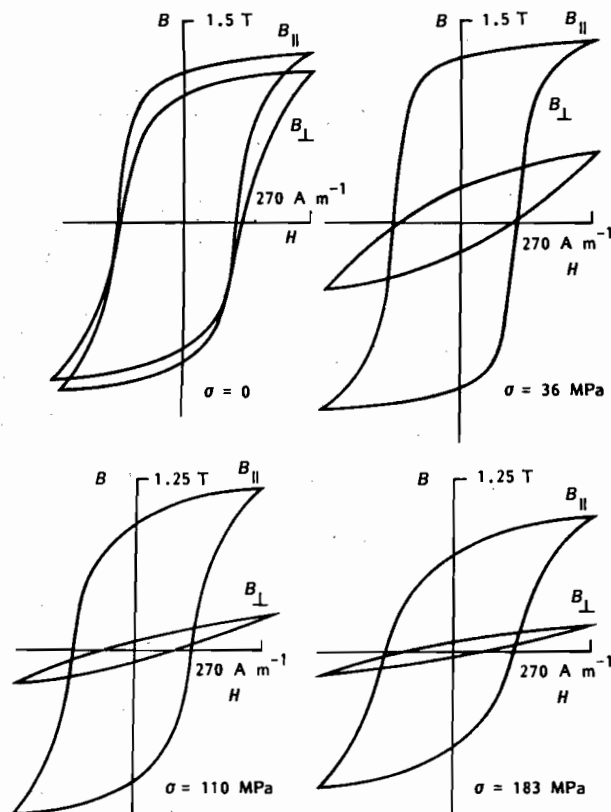


Fig. 6 Changes in magnetic hysteresis 'signatures' of mild steel with stress; after Langman<sup>[97]</sup>

was realized by Davis<sup>[76]</sup> who had NDE applications of hysteresis for evaluation of steel quality in mind. Subsequent attempts were made to utilize Davis's harmonic model by Willcock and Tanner<sup>[77,78]</sup>.

It is clear that any model which has a hope of being used for interpretation of NDE results such as effects of stress, elastic and plastic strain, creep and fatigue should have as few parameters as is reasonably possible. The stress or strain dependence of these parameters can then be determined. Such a criterion immediately excludes the Preisach model<sup>[79]</sup>. Some success has been achieved recently with the model of Jiles and Atherton<sup>[80]</sup>. Changes in the magnetic parameters with stress have been determined empirically by Szpunar and Szpunar<sup>[81]</sup> and from first principles by Sablik *et al.*<sup>[82]</sup> and used to model the magnetic hysteresis properties under stress.

Hysteresis measurements have also been used by Abuku<sup>[83]</sup> for evaluation of residual strain in steel rods. Changes in magnetic properties with stress cycling have been used to predict fatigue life of specimens by Sanford-Francis<sup>[84,85]</sup>, Bose<sup>[86]</sup> and Shah and Bose<sup>[87]</sup>. It was found that the hardness of the specimens, which can be inferred from coercivity measurements, began to change long before any crack failure appeared. Coercivity measurements have been used by Jakel<sup>[88]</sup> for evaluation of quality control of steel components.

A brief review of several NDE techniques including hysteresis measurements for on-line measurement of microstructure and mechanical properties of steel has recently been given by Bussière<sup>[89]</sup>.

## Residual field and remanent magnetization

This technique is closely related to the flux leakage method which has been reviewed by Beissner *et al.*<sup>[90]</sup>. However, whereas the flux leakage method is used to detect flaws from anomalies in magnetic flux, the residual field method is usually aimed at detecting changes in intrinsic properties such as strain, microstructure or heat treatment from variations in the magnetic field close to the surface of a ferromagnetic structure or component (Figure 7). The magnetometers used with the technique are often fluxgates (also known as ferroprobes), but Hall probes and induction coils are also used and in cases where the coercivity needs to be measured, a coercimeter is used.

The measurement of field intensity was used by Lees *et al.*<sup>[91]</sup> for detecting the accumulation of oxides within steel boiler tubing. Atherton and co-workers<sup>[92-94]</sup> used the same technique for detecting stresses in pipelines due to large-scale bending, while Konovalov *et al.*<sup>[95]</sup> determined the mechanical properties of steel pipes from a combination of coercivity and remanence obtained from measurements of field intensity close to the surface of pipes.

Suzuki *et al.*<sup>[96]</sup> used measurements of remanent magnetization for detection of stresses in pressure vessels. Langman<sup>[97-99]</sup> detected and measured stress levels in steel plates by a novel method of rotating the magnetic field  $H$  and noting any differences caused by stress-induced anisotropy. A detailed discussion of the variation of magnetic field and flux density with stress has been given by Langman in a subsequent paper<sup>[100]</sup>.

A number of techniques for sorting steel components on the basis of magnetic field measurements, usually from the determination of coercivity, have been reported by Mikheev *et al.*<sup>[101,102]</sup> and by Tabachnik *et al.*<sup>[103]</sup>.

No extensive reviews of the method have appeared in the literature. In general it is very similar in nature to the magnetic flux leakage method. The only differences lie in the interpretation of results, since the effect of stress on magnetic properties is complicated. Another additional feature is the use of the coercimeter in a number of instances. This device magnetizes the specimens to saturation in one direction, using an electromagnet, and then determines  $H_c$  by reversing the field until the flux density in the specimen is reduced to zero<sup>[104]</sup>.

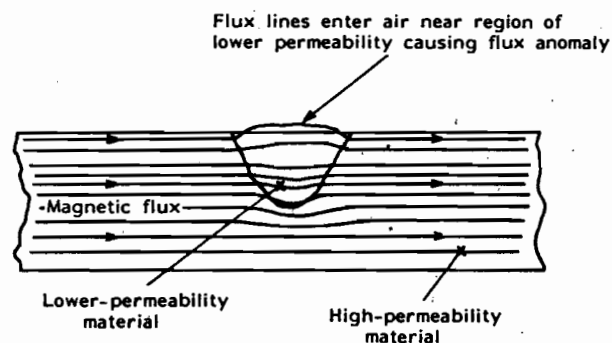


Fig. 7 Flux leakage into the air caused by a region of lower permeability within a piece of steel

## Magnetoelastic methods (magnetically induced velocity changes, MIVC)

This method relies on the measurement of acoustic velocity in the presence of a magnetic field to determine stress. Both magnetic field<sup>[105]</sup> and applied stress<sup>[106]</sup> change the velocity of sound in ferromagnetic materials such as steel (Figure 8). However, until quite recently few investigations of the effect of stress on the rate of change of acoustic velocity with field,  $(dV/dH)_\sigma$ , had been reported.

The first application of this method to NDE of stress in steels was by Kwun and Teller<sup>[107,108]</sup> who investigated the stress dependence of the velocity of ultrasonic shear waves. The method has also been used by Namkung, Utrata and co-workers<sup>[109-112]</sup>. One of the great advantages of this technique for NDE of stress is that it is possible to detect residual uniaxial stress without reference to calibration data. The results of Namkung and Utrata, who measure the slightly different parameter  $(dV/dB)_\sigma$ , have shown that this is negative under coaxial compression but positive under coaxial tension. The work has recently been extended to an investigation of grain size and heat treatment of 4140 steel<sup>[113]</sup>.

The most recent review of this technique has been given by Kwun<sup>[114]</sup>. Typical variations of the acoustic velocity in steel with stress and magnetic field parallel are shown in Figure 9 and with stress and magnetic field perpendicular are shown in Figure 10.

## Conclusions

A variety of magnetic methods for NDE are available and these have been critically reviewed here. With the upsurge of interest in this field there must certainly be new magnetic methods awaiting development in the near future. One of these may be the use of magnetomechanical emissions of the type observed by Higgins and Carpenter which would seem to be ideal for the detection of dynamic stresses in steel, but which has not even begun to be exploited. Compared with ultrasound, most of the magnetic methods are in their infancy and so offer wide scope for future development and growth. But, also in comparison with ultrasound, the instrumentation required for magnetic inspection is far simpler and therefore in many cases easier to adapt to applications.

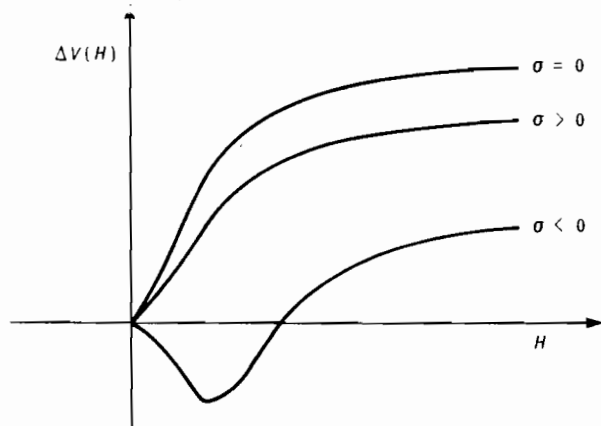


Fig. 8 Schematic diagram showing the change in ultrasonic velocity  $\Delta V$  with magnetic field  $H$  under various stress levels

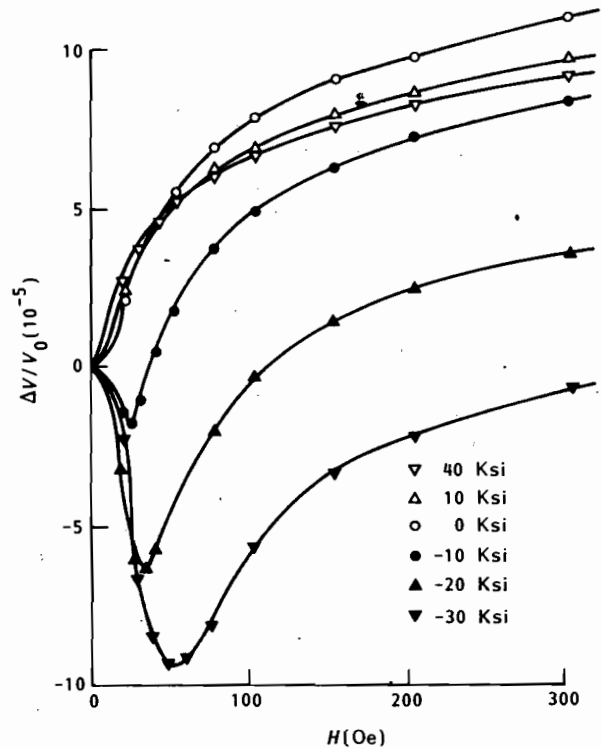


Fig. 9 Variation of acoustic velocity with magnetic field strength  $H$  for various stress levels applied parallel to the field; after Kwun<sup>[114]</sup>

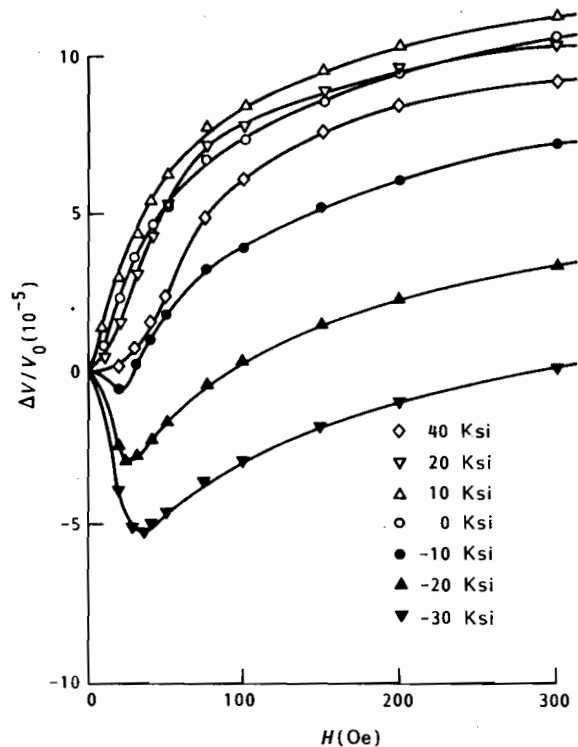


Fig. 10 Variation of acoustic velocity with magnetic field strength  $H$  for various stress levels applied perpendicular to the field; after Kwun<sup>[114]</sup>

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Chapter 2

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