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**A NATIONAL MEASUREMENT
GOOD PRACTICE GUIDE**

No. 88

The Measurement of
Residual Stresses by
Magnetic Methods - MAPS
and Barkhausen



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Measurement Good Practice Guide No.88

Determination of Residual Stresses by Magnetic Methods

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Abstract:

Residual stresses can be defined as those stresses that remain in a body after manufacturing or processing in the absence of external forces or thermal gradients. Virtually all manufacturing and fabricating processes introduce residual stresses into the manufactured article and extreme service loading may also change the state of residual stress in the component. The effects of residual stress may be either beneficial or detrimental, depending upon the sign, magnitude and distribution of the stress. For improved process and product control, design, performance and modelling it is increasingly important to have rigorous experimental procedures to determine the residual stresses to the best possible accuracy. A wide variety of residual stress measurement techniques exist, but without experience or detailed knowledge it is difficult for the user to choose which method is most appropriate.

Magnetic techniques for measuring residual stress have the advantage of being rapid, non-destructive and can be made in-situ on industrial plant and components. They can be applied to ferromagnetic materials, and measurements are carried out using a probe that both applies an alternating magnetic field to the component surface and contains one or more sensors to monitor electro-magnetically induced voltages. The techniques involve the measurement of a range of different magnetic properties and their correlation to the microstructural features and material properties like hardness and residual stresses. Several portable systems are available, but this GPG focuses on the MAPS (Magnetic Anisotropy and Permeability System) method and the MBE (Magnetic Barkhausen Emission) techniques. Practical advice on surface preparation, data collection, probe design, calibration issues, accuracy and uncertainty is presented. Examples of applying the techniques to different applications are also included.

This is the third NPL Good Practice Guide dealing with Residual Stress Measurement, the others, which are also available, focus on the X-ray Diffraction and Hole Drilling methods.

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Determination of Residual Stresses by Magnetic Methods

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1 Scope

Magnetoelastic methods have the advantage of being rapid, entirely non-destructive and applicable for in-situ measurement on industrial plant and components. However their high sensitivity to internal stress is complicated and historically poorly understood, and they are sensitive to other factors such as material microstructure, which can make the unambiguous interpretation of data difficult. Over the last ten years significant advances have been made in understanding the physical principles associated with these techniques, making the approach for practical measurement increasingly desirable, and today there are several portable systems in the market place that have taken advantage of developments in the field. It is not the purpose of this guide to review all these systems and approaches, particularly as currently very few have matured to a sufficient degree for general field application and are also in widespread use, but to focus on just two techniques: the multi-parameter MAPS (Magnetic Anisotropy and Permeability System) method and the MBE (Magnetic Barkhausen Emission) method. That is not to say that other techniques are unworthy of inclusion, and indeed many of the aspects of best practice considered are common to all magnetic methods, but it is a matter of convenience.

MAPS is a portable system designed for manual probe manipulation over a component. Measurements of a large number of magnetic parameters are made simultaneously with a controllable penetration typically in the range 0.1 mm to 5 mm (mild steel). The measurement is rapid, with a typical acquisition time of 1 minute for a complete biaxial tensor. For most industrial work, the MAPS system is calibrated against known stress levels, and then theoretical formulae are used to interpolate the calibrations. The variation of stress with depth below the surface can also be measured by mathematically deconvoluting measurements averaged to different sampling depths below the surface.

The MBE technique measures discrete changes in magnetisation, known as “Barkhausen jumps”, which can be seen as steps in the hysteresis curve and are considered to be direct evidence for domain wall movement during a magnetisation process. Further research has shown that analysis of the MBE signal can give an enhanced understanding of the magnetisation process. The size and shape of the MBE signal generated strongly depends on both the measurement parameters and the material properties, and as a result of the electromagnetic attenuation of the MBE signal, the depth of detection (skin-depth) of the MBE signal is restricted to the near-surface region of less than 1mm, but this strongly depends on the magnetic excitation frequency and permeability of the material. The MBE techniques are currently being used for the characterisation of microstructural changes caused by tempering and aging, evaluation of hardness and case-depth variations in case-hardened steels, estimation of surface and subsurface residual stresses, detection of texture orientation, assessment of progressive fatigue damage accumulation, detection of grinding damage etc. in a variety of ferromagnetic steels.

This is the third NPL Good Practice Guide dealing with Residual Stress Measurement, the others focusing on the X-ray Diffraction and Hole Drilling methods. The aim of this guide is to give an overview of the application of the two magnetic techniques and provide a practical guide to the procedures for component preparation, data collection, probe design, accuracy and uncertainty. It discusses the factors that an operator is most likely to encounter during a typical measurement programme and offers some insights into the interrelationship of operations or procedures and the recognition of operational problems.

2 Terms and Definitions

Symbol or Term	Definition	Units
NDT	Non-destructive Testing	
Standoff	The distance nominally set between probe base and test component surface for measurement.	mm
Lift-off	The true distance of the probe from the surface of the test component that may differ from the standoff due to surface roughness and geometry.	mm
MAPS	‘Magnetic Anisotropy and Permeability System’. It makes use of calibration <i>maps</i> relating the magnetic parameters <i>mapped</i> onto biaxial stress. It can also give a <i>map</i> of biaxial stress over a component.	
Flux Linkage Coil	A sensor wound on the (laminated silicon iron) core of the MAPS probe electromagnet. This coil links the flux generated by the drive coil.	
Flux Leakage Coil	A sensor coil positioned between the poles of the core of the MAPS probe, oriented so as to link the flux leaking directly between the poles rather than passing through the test component surface.	
Flux Rotation Coil	A sensor coil positioned between the poles of the core of the MAPS probe, oriented orthogonally to the leakage coil in the surface plane so as to be insensitive to the direct applied flux. This coil detects any rotation of the applied magnetic field induced by anisotropy in magnetic properties in the pipe wall.	
Impedance Plane	Signals on each sensor will have the same fundamental frequency as the driving electromagnetic field. However as the impedance of each sensor has both a resistive and inductive component the induced voltage signal will be phase shifted. This phase-shifted signal is split into a component in-phase with the drive and a component at 90°-phase (quadrature) to it. All measurements can therefore be represented as a point on the in-phase and quadrature impedance plane.	
DEP	Directional Effective Permeability parameter derived from MAPS linkage sensor data.	mV
PMD	Measurements from any sensor depend on both the lift-off of the probe and the stress level in the steel. A method is used for MAPS that separates each measured point on the impedance plane into a lift-off and stress component. The stress component is quantified on a scale from zero (0%) to unity (100%) with respect to two reference samples, the quantity being known as the delta parameter. To convert the delta values into stress levels for any particular steel type is a matter of calibration. PMD is the material delta value for the linkage sensor.	%
FMD	FMD is the material delta value derived from the flux leakage sensor data of the MAPS probe.	%
SMA	Stress-induced Magnetic Anisotropy parameter derived from the rotation sensor of the MAPS probe.	mV
H	Applied magnetic field strength	Am ⁻¹

H_c	Coercive force	$A m^{-1}$
M	Magnetisation	T
M_s	Saturation magnetisation	T
B	Magnetic induction	T
B_r	Residual induction	T
μ_{max}	Maximum permeability	
μ_{Δ}	Incremental Permeability	
MBN	Magnetic Barkhausen Noise	
MBE	Magnetic Barkhausen Emission	
ABE	Acoustic Barkhausen Emission	
f_{ex}	Excitation frequency of external magnetic field	Hz
Δf_a	Analysing frequency range of the magnetic Barkhausen noise signal	
RMS	Root mean square	

3 Introduction

Ferromagnetic materials consist of magnetic domains in each of which all the atomic magnetic moment vectors are aligned in parallel (Figure 1). In ferromagnetic steels, 90° and 180° domain walls separate adjacent magnetic domains (Figure 2). When a demagnetised ferromagnetic material (where all the domains are oriented randomly) is subjected to an external varying magnetic field, the magnetisation (total magnetic moment per unit volume) in the material increases in the direction of the applied magnetic field (Chikazumi [1], Jiles[2]). It is well known that the cyclic magnetisation process (alternatively sweeping the material from a maximum magnetic field in one direction to the maximum field in opposite direction) leads to magnetic domain nucleation, magnetic domain wall movement and domain rotation (Craik and Tebble [3]). A major portion of this magnetisation process involves the irreversible movement of magnetic domain walls overcoming various obstacles such as grain boundaries, second phase precipitates and dislocations. However, the irreversible movement of domain walls is considered as the major contribution to the hysteresis process (Figure 3). Since the presence of applied or residual stresses alters the preferential orientation of the domain structure, it also strongly influences the magnetisation process.

The magnetisation process is also strongly influenced by microstructural features such as dislocations, grain size, second phase precipitates, non-ferromagnetic phases as well as the internal stresses. The grain boundaries in polycrystalline material are regions of magnetic discontinuity due to the different crystallographic orientation (and easy magnetisation direction) of adjacent grains. The magnetic free poles at the boundaries generate a demagnetising field and hence would act as obstacle to domain wall movement. Generally, it is considered that the grain size and its distribution would affect the mean free path of the domain wall displacement and hence the magnetisation process. Similarly, the presence of any non-ferromagnetic inclusions and/or second phase precipitates like carbides in steels can pin the domain walls and act as obstacle to their movement. The size and distribution of second phase particles would influence the magnetisation process.

Joule [2,3] first observed the phenomenon of magnetostriction, which is the dimensional change during magnetisation of a ferromagnetic material. The mechanism of magnetostriction is complex, but on a macroscopic level it can be attributed to the re-orientation of magnetic domains in response to the magnetisation, and this results in internal mechanical stresses. Later, Villari [2,3] showed the inverse phenomenon, i.e. the magnetic state of a ferromagnetic material changes when it is subjected to external mechanical stress, and depending on the material characteristics there may be very different responses. In positive magnetostriction materials like iron and ferritic steels, a tensile stress tends to align the magnetic domain along the stress direction and hence it is easy to magnetise the material along the stress direction, but compressive stresses tend to align the domains perpendicular to the stress direction and it then becomes more difficult to magnetise the material along a compressive stress direction. The effect of applied stress is reversed in a negative magnetostriction material such as Nickel. The extent of changes in magnetic domain structure and the magnetisation process in response to the changes in microstructure and stresses are widely different in different materials and are quite complicated, particularly when there is synergistic variation in both microstructure and stresses. However, in many ferromagnetic steels, the magnetic response to variations in material properties is quite sensitive and can be easily detected and measured

accurately. The magnetic techniques generally involve the measurement of a range of different magnetic properties and their correlation to the different microstructural features and material properties like hardness and residual stresses.

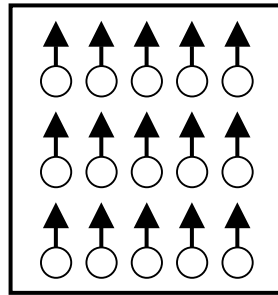


Figure 1. A magnetic domain with all magnetic moment vectors pointing in the same direction.

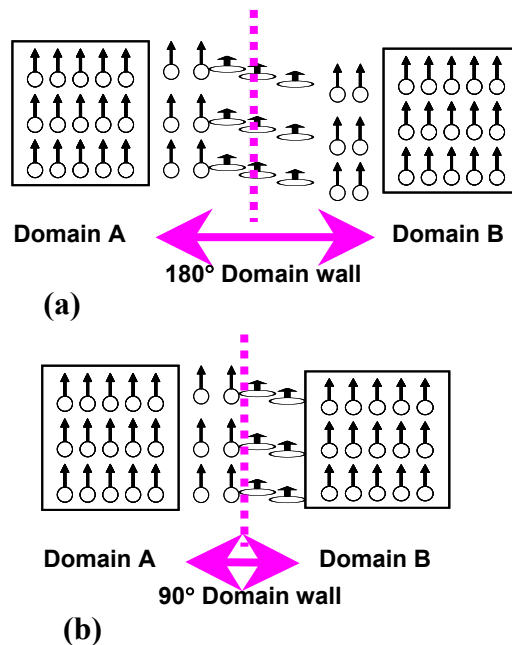


Figure 2. (a) 180° and (b) 90° Domain walls.

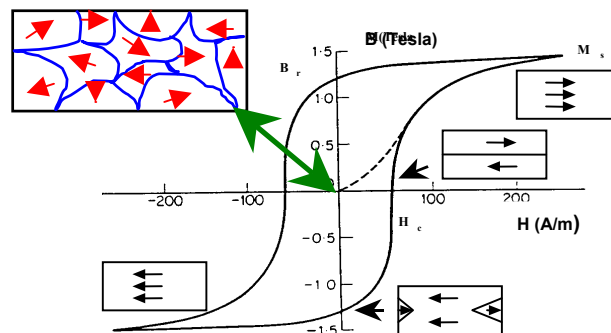


Figure 3. Magnetic domain alignment during magnetisation.

A large number of magnetic and electromagnetic methods are used to characterise materials, material degradation processes and internal stresses (Jiles [4]), and these may be loosely classified into methods that use *macroscopic* magnetic properties, such as hysteresis loop and related parameters, where ‘macroscopic’ refers to properties averaged over longer times and involve the movement of domain walls in many grains; and those that use *micro-magnetic* properties such as Magnetic Barkhausen Emission (MBE) and Acoustic Barkhausen Emission (ABE), where the signals are sensed from individual or few magnetic domain wall movements over a shorter time during the magnetisation cycle. There are also many different methods used to *monitor* these magnetic properties, the term ‘monitor’ being used as practical approaches often *sense* signals that depend indirectly upon the magnetic property or properties of interest. As mentioned previously it is not the purpose of this guide to review all these approaches, particularly as currently very few have matured to a sufficient degree for general field application and are also in widespread use. So this guide is limited to just two techniques, the multi-parameter MAPS method and the MBE method, one from each of the groupings referred to above.

Prior to measurement, several practical aspects should be considered. Firstly it is helpful to understand how the data is to be used and what stress distributions may be expected in the component - for example, are absolute stresses required or only bending moments or load assessments? This information will influence the requirements for an optimum calibration. It will also influence where the measurements should be taken, the choice of suitable probes, what measurement characteristics should be selected and what *reference* measurements should be used. Also, depending upon the surface condition or if a surface treatment exists on the test component, a careful choice of penetration depth for the measurements needs to be made and a decision whether to use a stress profiling option during data collection. The thickness of the specimen may also influence the measurements made. In many cases it will be necessary to perform some surface preparation before measurement, and it is important to avoid any methods that may introduce additional high surface stresses into the material.

The number and locations of the measurements will depend primarily on the requirements of the test programme and on the component geometry, location of welds, features etc., and may be limited in some cases by the need for access and the shape of the component surface and proximity of edges and abutments. The probe manipulation procedure (static non-rotating, manual rotate by hand, motor automatic rotation, automatic translation etc) should be planned carefully depending upon access and geometry and an appropriate method used to accurately place the probe orthogonal to each measurement position. More information and guidance is given in subsequent Sections of the Guide.

4 Magnetic Methods

It has long been known that the magnetic properties of ferromagnetic materials are sensitive to internal stress. Interactions between the atomic moments in the lattice cause alignment into magnetic domains (ferromagnetism), which in turn generates a small strain in the lattice (magnetostriction). With internal stress, it becomes energetically favourable for the orientation of atomic magnetic moment vectors to change, so that in steel (positive magnetostriction) for example, the magnetisation vectors point towards the tensile stress direction and they point perpendicular to compressive stress direction to reduce the

magnetoelastic energy. This results in gradual enhancement of the reorientation of magnetic domains along the tensile stress direction and perpendicular to the compressive stress direction with increasing magnitude of stress as schematically shown in Figure 4. However, this redistribution of domains tends to increase the magnetostatic energy. As a consequence equilibrium arises with these energy terms in balance. The changes in magnetic domain distribution mean that magnetic hysteresis, permeability and remanence are all functions of the stress tensor and, as a result, changes in the magnetic signature can therefore be used to deduce the underlying state of stress (Buttle & Scruby [5]).

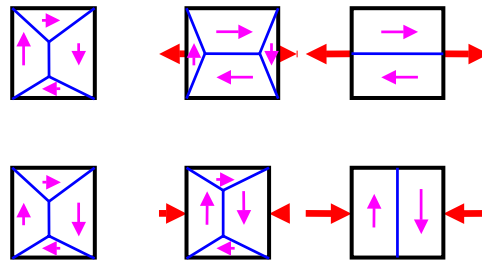


Figure 4. Magnetic domain alignment due to tensile and compressive stresses.

Magnetoelastic methods have the advantage over some of the other residual stress measurement techniques of being rapid, non-destructive and applicable for in-situ measurement on industrial plant and components. Nevertheless their high sensitivity to the internal stress is complicated and historically poorly understood. They are also sensitive to other factors such as material microstructure often making it difficult to interpret data unambiguously. However over the last ten years significant advances have been made in understanding the physical principles making this approach for practical measurement increasingly desirable. Today there are several portable systems in the market place that have taken advantage of developments in the field and this trend is likely to increase in future (Schneider [6], Buttle [7], Buttle et al [8]).

4.1 Hysteresis Loop and Related Parameters

The magnetic hysteresis is represented as a plot of magnetic flux density or induction (B) vs. applied magnetic field (H) in a magnetisation cycle (Figure 5), and the shape of the hysteresis varies with:

- (i) Magnetising field
- (ii) Magnetising frequency
- (iii) Temperature
- (iv) Composition of the material
- (v) Microstructural conditions
- (vi) Applied and/or residual stresses

The area enclosed by the hysteresis loop represents the energy loss. A number of properties can be derived from the B-H loop including *coercivity*, *remanence*, *maximum permeability*, *differential permeability* etc. The *coercivity* is defined as the reverse magnetic field at which the magnetic induction comes down from saturation (B_s) to zero. The *remanence* is defined as the retained magnetic induction when the magnetic field is reduced from saturation (H_s) value to zero. The *maximum permeability* ($\mu_{\max}$) is the maximum value of B/H in a cycle and the *differential permeability* is the derivative of B (dB/dH) at a given value of H in a magnetisation cycle. Since, in practice achieving ideal

saturation (B_s) requires very high magnetic field, normally, these parameters are defined for a given maximum magnetic field ($H_{\max}$) namely, the maximum induction ($B_{\max}$) at $H_{\max}$, coercive force (H_c) and residual induction (B_r).

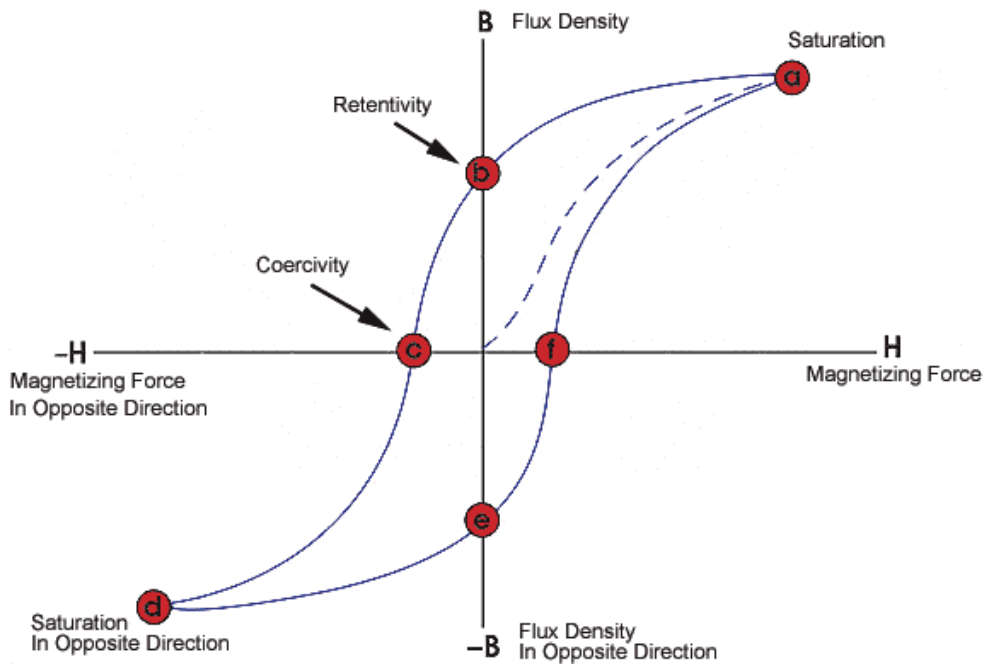


Figure 5. Typical B-H curve.

It follows from the above that the magnetic hysteresis loop is distorted as a consequence of stress so that there will be changes in the coercivity ($H_{B=0}$ or H_c), remanence ($B_{H=0}$ or B_r) and permeability (dB/dH). However full loop measurement on plant components is usually not practical because it is not possible to generate uniform fields; neither is it possible to achieve saturation levels due to the presence of demagnetising fields. Nevertheless, practical approaches have been developed using low field magnetic susceptibility measurement for determining the magnitude and direction of the uniaxial stress.

Coercive force values can also be deduced from practical components because at zero magnetic flux there is no flux leakage, and such measurements can be made largely independent of demagnetisation effects. However the sensitivity of the coercive force measurement to stress is much lower than to microstructure, such as grain size or carbon distribution. Coercive force is also strongly linked with irreversible wall movements caused by pinning points. Other related parameters such as the measurement of incremental permeability, (μ_{Δ}), can also be measured by superimposing a small amplitude modulation upon a low frequency drive field. The frequency of the secondary field must be high compared to the primary field, but still low enough to maximise penetration.

Another simplified method known as, *Directional Effective Permeability*, (DEP), has been developed for use in the field (Allen et al [9]). This uses a fixed amplitude AC field electromagnet with equipment for sensitive impedance measurement. The voltage induced across the sensor is amplified and multiplied by fixed amplitude sine and cosine voltages separately. The two signals are then separately low-pass filtered to remove remaining AC components and digitised to provide the measured in-phase and quadrature signal amplitudes,

$V_X^{Linkage}$ and $V_Y^{Linkage}$, the whole process commonly known as synchronous quadrature demodulation. Sensitivity to probe lift-off is minimised by using some initial measurements, which are plotted on an in-phase – quadrature signal plane while moving the probe away from the steel surface so as to obtain a lift-off line locus. The tangent angle (lift-off angle θ_{LO}) is then determined at a position on the lift-off line close to the minimum lift-off position. For all subsequent measurements the DEP signal parameter is then defined as the orthogonal distance from the lift-off line: i.e:

$$DEP = V_X^{Linkage} \cos \theta_{LO} + V_Y^{Linkage} \sin \theta_{LO} \quad (1)$$

The derived DEP value is sensitive to the average permeability along the measuring direction, $\mu_{material}$, and can be evaluated using simple magnetic circuit theory. Magnetic field strengths much less than saturation are used so that the permeability is assumed to be independent of the applied field. $\mu_{material}$ and can then be replaced by a suitable triaxial stress formulation to give the predicted stress sensitivity of the DEP method.

By rotating the probe the DEP measured, as a function of probe angle, will be constant so that no magnetic anisotropy is measured in a stress free state in the absence of material texture. In a biaxial stress field, DEP will change sinusoidally as a function of the measuring angle, with the maximum and minimum DEP along the maximum and minimum stress axes respectively. This enables a measure of the two principal surface stress values and directions to be attempted. Figure 6 shows a comparison between the experimental and theoretically derived biaxial response for DEP measured with the magnetic field parallel to the longitudinal axis (DEP 1) in a mild steel plate. A similar result is obtained for the transverse field orientation (DEP 2). Some workers prefer to use non-linear harmonic analysis (NLHA) rather than a direct measure of the impedance or induced signal voltage.

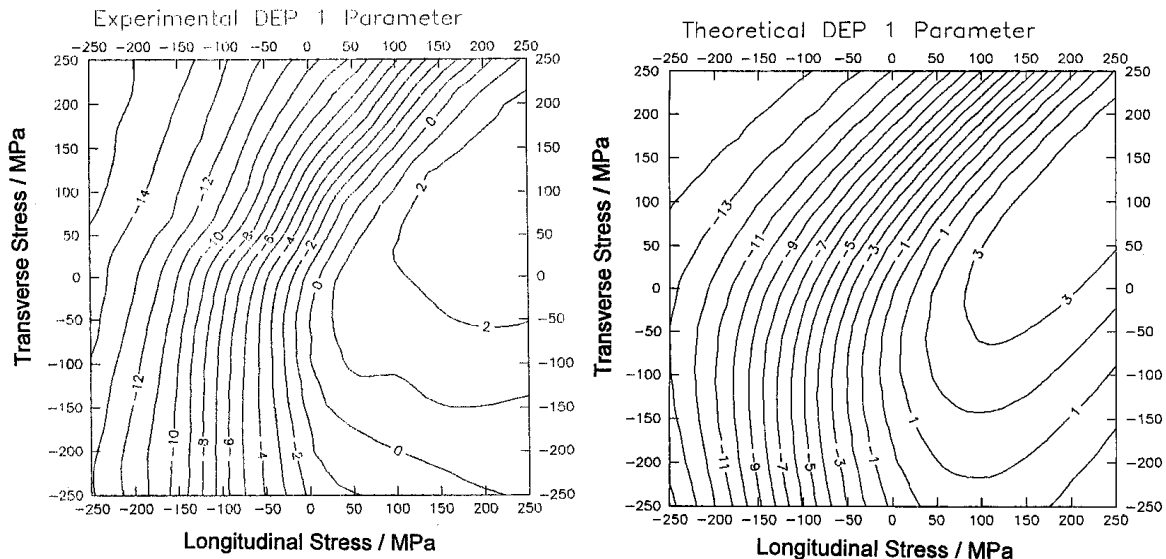


Figure 6. (a) Experimental and (b) theoretical DEP 1 shown as a contour level for applied biaxial stress for 30 mm rolled mild steel plate. (DEP 2 similar with stress axes reversed).

4.2 MAPS Measurement Method

The MAPS multi-parameter magnetic system was developed for making biaxial measurements on industrial plant and components. It incorporates several techniques into a single unit enabling absolute biaxial stress levels to be determined in a wide range of industrial materials by providing sufficient information to discriminate partially microstructural changes and to allow full correction for poor surface quality and geometric influences.

With the MAPS technique practical measurements on components are carried out using a specific experimental arrangement, involving an electromagnet to apply a magnetic field and coils to measure the electromagnetic signals for flux linkage, flux leakage and flux rotation (Figure 7). The induced voltage across the sensor coils is monitored while rotating the probe through 360°. As discussed previously, the measured voltage signal is indirectly related to the material magnetic properties such as permeability and coercivity. Measurements are made using a very stable constant current amplifier driving the electromagnet at a specified frequency. The absolute amplitude of the flux density is not considered critical except that it must be much lower than M_s to ensure good stress sensitivity, and much higher than the coercive field in order to minimise sensitivity to the magnetic and mechanical history.

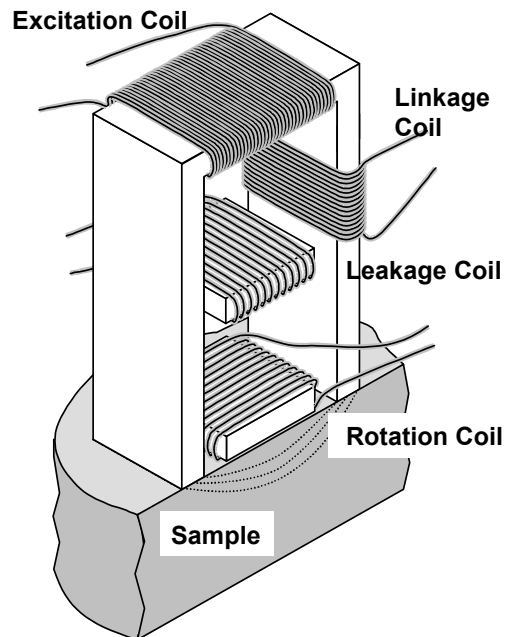


Figure 7. Schematic of a specific probe arrangement (MAPS) used to measure local magnetic properties.

Over 20 parameters are measured during the MAPS measurement, each giving their own principal values and axes at either one or more applied field frequencies including:

- Directional Effective Permeability (DEP)
- Material Delta Value for linkage sensor (PMD)
- Material Delta Value derived from the flux leakage (FMD)
- Stress-induced Magnetic Anisotropy (SMA)

And these are described in more detail below.

First consider the linkage sensor. The voltage induced across the sensor electronically is processed in a manner similar to the DEP method described above. The readings are then stored together with the accurately measured electronic gains of the system. However there are several weaknesses to the DEP method, namely:

- (i) The lift-off line is not straight and so the lift-off correction is effective only over a limited range
- (ii) The lift-off angle is also a function of stress
- (iii) Zero DEP is arbitrarily based on the lift-off line measurement (preferably based on an unstressed sample of the steel)
- (iv) The absolute sensitivity will depend upon the selected lift-off angle and the relative sensitivity will be partially distorted as the true angle changes with stress.

Recent developments have enabled the weaknesses of the DEP method to be overcome and the effects of lift-off variation to be almost completely removed from the measurement of stress for a large range of probe standoff. The derived parameter, known as PMD, is otherwise similar to DEP in its response to stress, except that measurements made with different probes on the same material will yield more consistent PMD values due to the PMD parameter's insensitivity to impedance contributions from the probe.

When making measurements the probe is rotated on its axis and data collected every α° from $-\alpha^\circ$ to $+360+\alpha^\circ$, and each point is processed as described above to yield a $\cos 2\theta$ variation (Figure 8). The principal magnetic parameter amplitudes are then given by the PMD extremes and the principal axes by the angles of the extremes.

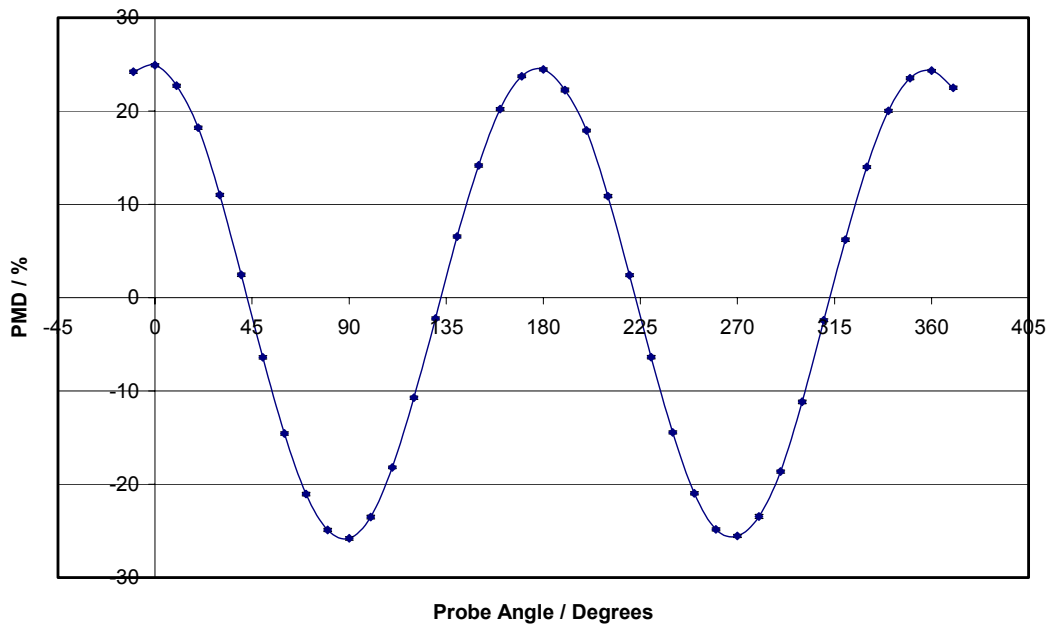


Figure 8. MAPS PMD measurements as a function of applied field direction (probe angle) for a tensile stress of 267 ± 1 MPa applied at $0 \pm 2^\circ$ in a rail steel

In addition to the linkage coil signal, measurements can also be made of the flux leaking between the poles of the electromagnet (Figure 9), and in this case the stress response of the derived FMD parameter is similar to that of the PMD parameter but with the sign reversed.

The partial alignment of magnetic domains towards the maximum positive stress axis will increase the magnetic permeability because a smaller applied magnetic field is then required to fully align the domains. Conversely the magnetic permeability measured along the minimum or most negative stress axis will be reduced. This induced magnetic anisotropy can

be accurately measured, and hence the stress parameter, $\sigma_1 - \sigma_2$, (or shear for biaxial stress) determined in the plane of the material surface. The measurement is made using a simple air coil known as the flux rotation coil (Figure 7).

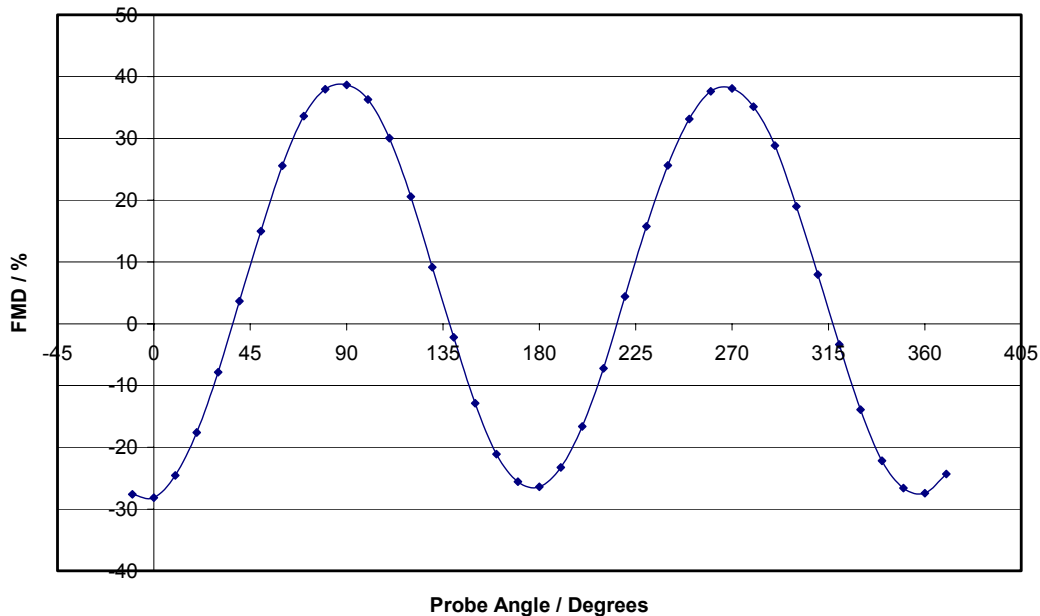


Figure 9. MAPS FMD measurements as a function of applied field direction (probe angle) for a tensile stress of 267 ± 1 MPa applied at $0 \pm 2^\circ$ in a rail steel

Magnetic anisotropy induced by stress results in the rotation of an induced magnetic field away from the direction in which it was applied. For example if a magnetic field is applied at some angle other than parallel or orthogonal to a uniaxial tensile stress in steel, the induced field will rotate towards the tensile axis. The sensor alignment will link any flux in the direction perpendicular to the applied field in the plane of the component surface. Thus as the probe assembly is rotated through 360° on the material surface, the induced voltage will vary periodically because the rotation of flux will depend upon the angular relationship between the applied field and principal axes (Figure 10). The principal stress directions can be determined from angles where there is a null signal. The signal peak-to-peak amplitude is approximately proportional to the difference between the two principal biaxial stresses, and theoretical development has yielded an exact relationship between the signal and the stress anisotropy so that the technique can be used for quantitative stress evaluation.

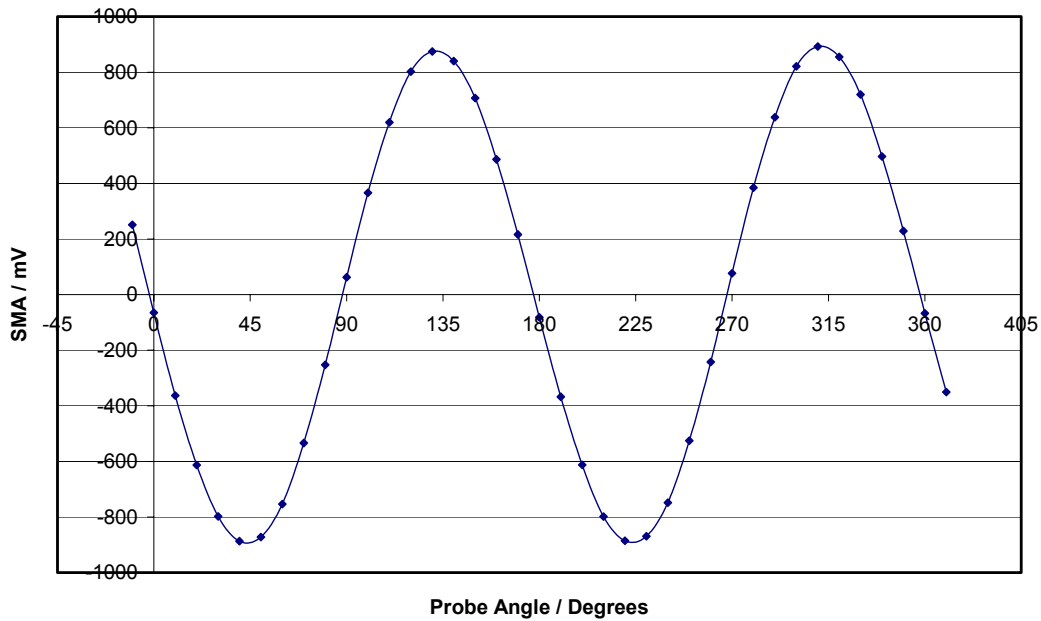


Figure 10. MAPS SMA measurements as a function of applied field direction (probe angle) for a tensile stress of 267 ± 1 MPa applied at $0 \pm 2^\circ$ in a rail steel

Magnetic anisotropy techniques are very sensitive to stress and have only weak sensitivity to texture. The experimental and theoretical response to an applied biaxial stress (*calibration maps*) for a 30 mm rolled mild steel plate is shown in Figure 11. Note that the rolling texture results in only a small ‘offset’ of the zero SMA contour away from the $\sigma_1 - \sigma_2 = 0$ line on the biaxial plane.

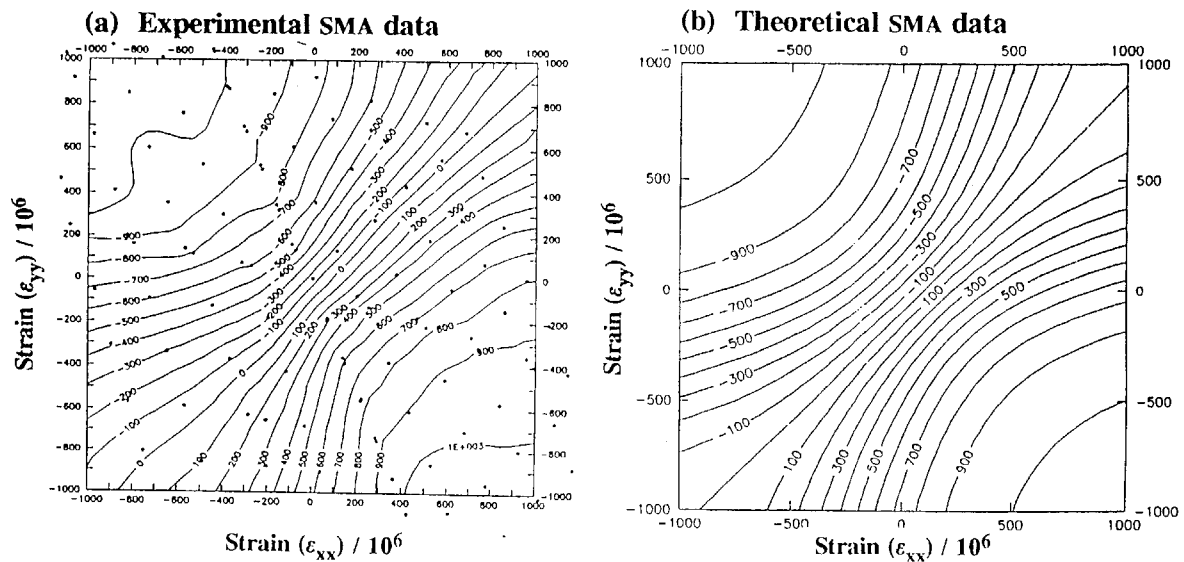


Figure 11. (a) Experimental and (b) theoretical SMA shown as a contour level for applied biaxial stress (plotted in terms of elastic strain) for 30 mm rolled mild steel plate.

4.3 Magnetic Barkhausen Noise (MBN)

When a ferromagnetic material is subjected to a varying magnetic field, the magnetic induction during magnetisation varies in discrete steps, as the magnetic domain walls have to overcome various types of obstacle during their movement. These discrete changes in magnetisation, known as “Barkhausen jumps”, can be seen as steps in the hysteresis curve when it is magnified by $\sim 10^5$ times, and induce noise-like voltage pulses comparable to the time derivative of the actual magnetic flux changes into a pickup coil placed on the surface of the material. During a magnetic hysteresis cycle, the changes in magnetisation level in the ferromagnetic material occur in discrete steps, as the magnetic domain walls have to overcome various types of obstacles during their movement in order to increase the magnetisation in the direction of external magnetic field. The discrete changes in magnetisation induce electric voltage pulses in a pick-up coil placed near the surface of ferromagnetic material. These “noise like” voltage pulses (Figure 12) were first observed by Barkhausen [10], and this phenomenon is known as Magnetic Barkhausen Noise (MBN) or Magnetic Barkhausen Emission (MBE). The MBN signal has been found to be very sensitive to variations in material properties such as chemical composition, microstructure, applied and residual stresses (Tiitto [11], Pasley, [12]).

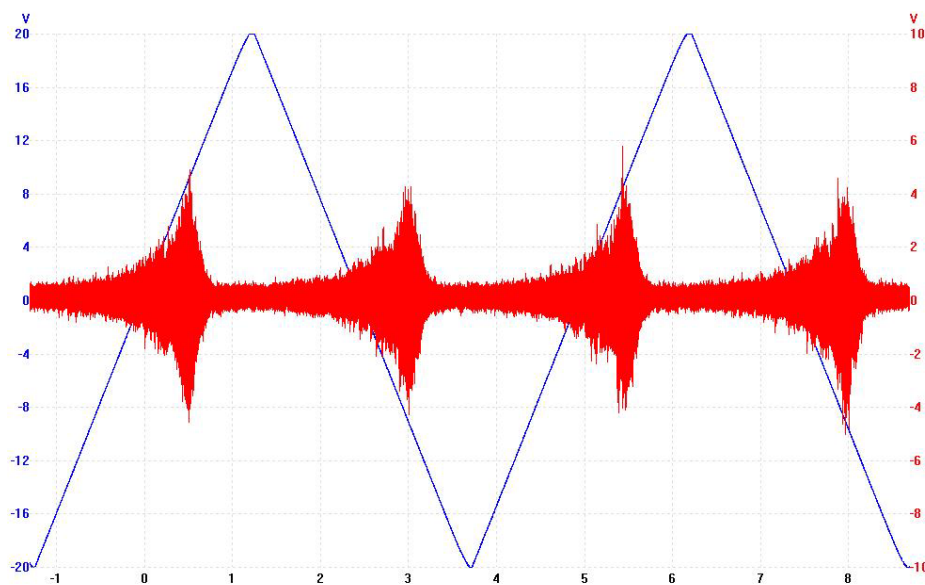


Figure 12. Typical voltage pulses of the MBN signal (Red) shown with voltage applied to the electromagnet (Blue) as a function of time over two hysteresis cycles.

The variation in ferromagnetic material properties can be correlated to different parameters derived from the MBN signal generated during the magnetisation cycle. The MBN profile is a plot of the RMS voltage of the MBN voltage pulses as a function of applied magnetic field or the voltage or current applied to the electromagnet. The variations in the shape of the MBN profile such as changes in the number of peaks, peak height, peak position, area under the peak etc., indicate the changes in material properties. Other MBN parameters like the RMS value of the overall MBN signal generated over a number of cycles, the pulse-height

distribution of the MBN signal, the total MBN energy (which is the time integration of the squared MBN voltage signal over a cycle) are also used for correlation with material properties.

Review of the literature shows that MBE measurements are generally made either through use of a low magnetic excitation frequency (0.1Hz to 1Hz) with analysis of the MBE signal in the frequency range of 0.5 to 100kHz or using a high magnetic excitation frequency (10 to 125Hz) with signal analysis in the range of 10 to 1000kHz. Typical commercial systems may be based on a high frequency excitation at 125Hz and analysis in the range of 70-200kHz. A low frequency MBE system is capable of generating a high magnetic excitation field giving a relatively high MBE signal skin depth. On the other hand, a high frequency MBE system can generate only low magnetic field strengths giving correspondingly low MBE signal skin depths of perhaps less than 20 μ m. Hence, the choice of the MBE system depends on the application requirements. Normally, in a high frequency MBE system, a single parameter such as total RMS value or MBE energy is used for analysis. In a low frequency MBE system, additional information can be gained by analysing the plot of RMS voltage of the MBE signal as a function of the voltage applied to the electromagnetic yoke. The detail in the MBE profile can show variations in the magnetisation process caused by microstructure and stresses as it traces the entire range of magnetisation. Variations across a component can also be identified by scanning the material surface with an MBE pick-up probe.

Changes in material parameters, even at the microscopic level, are often reflected in the MBE profile. The changes in magnetic properties associated with changes in material parameters (such as alloying elements; grain size; density and arrangement of dislocations; size and volume fraction of secondary phases; applied and residual stresses, creep damage, fatigue damage etc.) and in-turn the mechanical properties, can be measured and a correlation obtained for future evaluation of components. Typically, a microstructure with a high dislocation density, such as that of a quenched steel, will give a low level of MBN due to a restricted movement of magnetic domain walls during magnetisation. Further tempering of steel after quenching will reduce the dislocation density and hence, result in an increased MBE level. Other microstructural changes such as grain size, precipitation of second phases etc. will also affect the magnetisation process due to their strong influence on domain nucleation and domain wall movement. For example, the grain size affects the mean free path of the domain wall displacement and the size distribution affects the number of domain walls moving at a given instant. The size of second phase precipitates determines the pinning strength of domain walls since the energy of a domain wall is reduced by the intersection at precipitates. The volume fraction of precipitates influences domain wall displacement. During heat treatment, the formation of paramagnetic austenite phases will reduce MBE whereas the formation of martensite will relatively increase the MBE level.

4.4 Acoustic Barkhausen Emission (ABE)

When non-180° domain walls move irreversibly during magnetisation, the magnetostriction causes strain redistribution and in the process generates elastic stress waves known as Acoustic Barkhausen Emission (ABE) or Acoustic Barkhausen Noise (ABN), which can be detected by a piezoelectric transducer bonded to the surface of the ferromagnetic material. It is well known that only non-180° domain wall movement can induce ABE and the 180° wall movements do not cause ABE because there is no net change in strain when the total angular displacement of magnetic moment vectors across the domain wall is 180°. Hence, ABE is most sensitive to 90° domain wall motion whereas MBE is most sensitive to 180° domain wall

motion. During cyclic magnetisation particularly in ferritic steels, since the majority of the magnetic flux reversal occurs by the movement of 180° domain walls, the ABE signal is considerably weaker than the MBN signal. Hence, the ABE measurement requires larger amplification level and is also relatively difficult to detect in hard materials like case-hardened steels. Similar to the MBE signal processing, different set of parameters can be derived from the ABE signal and can be correlated to material properties.

5 Measurement Depth and Spatial Resolution

5.1 MAPS Measurement

Practical measurements are usually limited to the surface of a component because the magnetic field penetration into the bulk is limited by eddy current screening. For MAPS, if the probe active diameter is large compared with the field penetration, then a simple exponential formula can be used for the sampling sensitivity, $s(z)$, as a function of depth z , which defines a skin depth δ thus:

$$s(z) = s_0 e^{-z \sqrt{\pi \mu_0 \mu_r f_{ex} / \rho}} = s_0 e^{-z/\delta} \quad (2)$$

where ρ is the electrical resistivity and μ_r is the relative low field permeability, here assumed constant. Thus, **by varying the drive and detected frequency, f_{ex} , the measurement penetration can be adjusted.** This proves to be a useful tool for investigating stress depth profiles. For single frequency measurements, if possible, a depth should be chosen which is large compared to any surface abuse. Figure 13 gives a guide to typical measurement penetration for MAPS for a range of materials, assuming the probe dimension is appropriate.

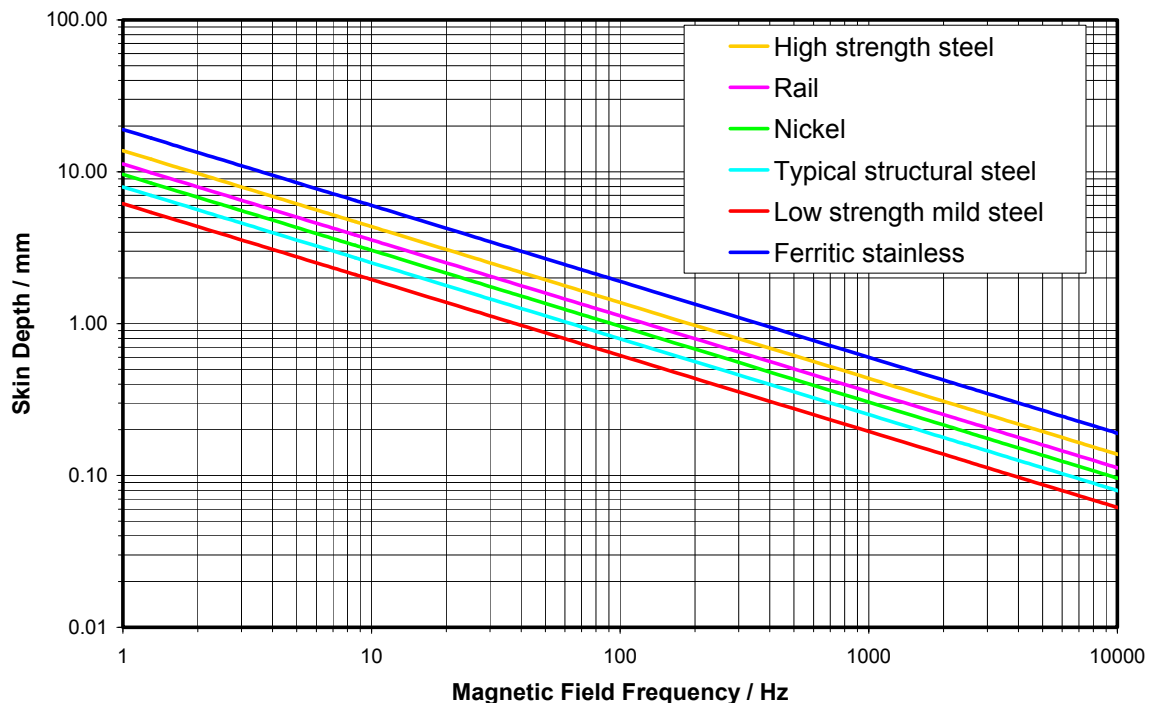


Figure 13. Skin depths (measurement penetration) as a function of magnetic field frequency for a range of ferromagnetic materials.

When measurements are made on a thin sample **the maximum penetration depth should not exceed half of the component thickness** unless a correction is made for the flux distortion due to the lower surface.

The measurement resolution in the plane of the surface is linearly related, for a linkage sensor, to the size of the electromagnet core, and for a leakage sensor, the size of the sensor. Specifically for a probe whose core has a footprint of $a \times b$ which contains a leakage sensor with dimension $c \times d$ the spatial resolutions (full width half max.) are approximately:

$$r_{linkage} \approx 2\delta + 3\sqrt{a^2 + b^2}/8 \quad (3)$$

and

$$r_{leakage} \approx \sqrt{c^2 + d^2}/2 \quad (4)$$

where it is assumed that the probe is rotated from 360° for measurement. For the leakage coil a secondary influence from the size of the core has been neglected. For typical MAPS probes, linkage sensor resolutions from 2 mm to 30 mm are available. For a linkage sensor measurement the penetration must always be smaller than the spatial resolution whereas, because the leakage sensor is decoupled from the energising electromagnet, this limit is weakened.

5.2 MBN Measurement

The general practice for MBN measurements can be broadly classified into two categories: high frequency MBN and low frequency MBN (Moorthy et al [13,14]). The high frequency MBN measurement typically involves the use of higher external magnetic field excitation frequencies (f_{ex}) >10 Hz and analysis of the MBN signal in the frequency range (Δf_a) of 2-1000 kHz, and the lower cut-off frequency for MBN signal analysis is selected to avoid interference from the upper harmonics of the excitation frequency. The low frequency MBN measurement is typically performed at magnetic excitation frequencies (f_{ex}) <1 Hz and the MBN signal is typically analysed in the frequency range (Δf_a) of 0.5 - 100 kHz.

The spatial resolution of the MBN measurements is determined by the size of the measuring device, which consists of an electromagnetic yoke and a pick-up coil. The high frequency MBN measurement involves lower applied magnetic field strength and hence the measuring device can be made smaller, with the electromagnetic yoke typically 10 mm x 8 mm. With such an arrangement it should be possible to make measurements from about ~ 6 mm from the edges of the testpiece or component. The spatial resolution for the high frequency MBN measurement is decided by the size of ferrite core in the pick-up coil which is typically ~1mm, and hence the spatial resolution can be considered as ~ 1mm.

The low frequency MBN measurement involves higher applied magnetic field strengths and hence the device will have a larger electromagnet yoke typically covering an area of ~50 mm (length) x 25 mm (width) with a pole gap of 20 mm. In this case it is possible to make low frequency MBE measurements from about ~ 20 mm from the edges of the testpiece without any distortion in the magnetic field distribution due to field divergence at the edges. If it is possible to magnetise from the end faces of the specimen, then the MBN measurement may

be made close to the edges. However, it is always better to avoid MBN measurements very close to the pole face because of non-uniform field distributions and interference from the leakage of magnetisation of the core material. It is always better to make measurement at least 5 mm from the pole face end. The spatial resolution for low frequency MBN measurements can also be considered to be $\sim 1\text{mm}$ which is normally the ferrite core diameter of the pick-up coil.

The maximum depth from which the MBE signal can be detected on the surface (skin-depth) poses a limitation for evaluating the variation in material property in the depth direction. Generally, the skin-depth of the MBE signal is calculated from equation 2 based on the standard electromagnetic theory of attenuation depending on the low field permeability, electrical resistivity of the test material and frequency of the MBN signal. Since the MBN signal is generated over a range of frequencies, it is difficult however to determine the skin-depth based on equation 2. Also, since the actual maximum magnetic field strength decreases with depth inside the test material, the extent of magnetic hysteresis loop and hence the level of MBN signal generation varies with the depth of origin. Studies have also revealed that the MBN signal is also strongly affected by a variety of other factors such as excitation frequency of external applied magnetic field, size and geometry of the material, type and geometry of the electromagnetic yoke, sensitivity of the MBE pick-up coil, the selection of analysing frequency range of the MBE signal etc. At present therefore there is no proven method to determine the actual skin depth of the acquired MBE signal in a given measurement. However, the skin-depth is considered to be much lower in measurements made with high frequency MBE due to the effects of lower magnetic field penetration and higher attenuation of the high frequency MBE signal compared to the low frequency MBE measurement.

The experience from different applications indicates that the detection depth for high frequency MBN measurement is limited to the near surface (typically $<10\text{ }\mu\text{m}$ depth, for measurements made with $f_{ex} = 125\text{ Hz}$ and $\Delta f_a = 70\text{-}200\text{ kHz}$) while that for low frequency MBN measurement is about $600\text{ }\mu\text{m}$ (for measurements made with $f_{ex} = 0.2\text{ Hz}$ and $\Delta f_a = 1\text{-}50\text{ kHz}$). Both sets of data are specific to the particular probe/device used, and the observations were made on rectangular bar specimens with $(l/w) > 10$. Similar results have been observed in case-carburised gear steels, but the values are likely to be much lower in soft steels due to their higher permeability.

It has also been found that the skin-depth is strongly affected by the geometry of the testpiece or component, particularly when its size is smaller than the electromagnet used to magnetise the test component. The actual skin-depth could vary depending on the selected measurement parameters and device/probes. The skin-depth is an area which needs careful consideration while correlating the MBE measurement. To achieve better understanding, it is important and essential to calibrate and standardize the MBN measurement parameters.

6 Surface Condition and Preparation

6.1 MAPS Measurement

Since the measurement penetration is relatively high, the MAPS method is less surface-critical than any other surface stress measurement technique. Nevertheless **care must be taken to avoid surface waviness or high near-surface stresses generated by use of hand grinders**

and machining. It is generally advisable not to prepare the surface with any hand tools unless it has been abused.

6.2 MBN Measurement

As mentioned previously, since the skin-depth of the high frequency MBN signal is relatively shallow, the surface properties will have a strong effect on the MBN signal. For example, any oxide layer on the surface, significant surface roughness, and variation in microstructure and residual stresses near the subsurface and in the bulk will influence the high frequency MBN measurement. Manufacturing processes such as machining, grinding, shot-peening etc. can result in severe thermal damage and changes in the residual stress state at the surface, which can strongly affect the MBN signal. Such effects should be taken into account when correlating the MBN data. **Hence, for high frequency MBN measurement, surface preparation using chemical and/or electro-chemical methods is preferred over mechanical methods.**

For low frequency MBN measurements, since the skin-depth of the MBN signal is significantly higher, the variation in surface properties alone does not have such a large effect on the MBN signal generation. However, when there is a sharp gradient in the properties near the surface, this can also be reflected in the low frequency MBN signal level. Again, it is always better to use chemical or soft mechanical surface preparation methods and avoid methods that would cause severe deformation of the surface. Generally, low frequency MBN measurements would be preferred in cases where the variations in surface properties can be ignored and the subsurface properties are considered important.

6.3 Recommended Surface Preparation Guide

Where some level of surface preparation cannot be avoided the following sections give advice and recommendations for achieving optimum results. This is an important issue as proper and consistent surface preparation is a vital part of obtaining reliable stress results, and the surface preparation method should be carefully selected and controlled as recommended below.

6.3.1 Hand Preparation of Components

The key to avoiding the introduction of surface stresses during preparation, whilst maintaining the specimen geometry, relies on the removal of thin layers of material over a large area. This may be achieved using a high-speed rotary or orbital sander fitted with a flexible pressure pad. Note that using a flexible pad on the sanding device is essential, as it will allow the pad to conform to the overall shape of curved testpieces and components, though extra care is needed when preparing flat surfaces by hand.

Use the sander over the area to be inspected, first using a coarse grade emery- or sand-paper (#60 or #80 grit), to remove surface defects and stresses, then using progressively finer grits (#120 or #180) to remove material affected by the coarser grade, finishing with a very light sanding that effectively leaves the surface with a moderate polish. While carrying out the sanding, it is important to maintain a low angle between the pressure pad and the surface being prepared. This will preserve the general form of the surface and will better avoid deep or violent abrasion of the surface.

On completion of the preparation, a visual inspection of the surface will show any irregularities that may influence results. Note that it can be counter-productive to try to remove any small irregularities detected in this inspection, as any additional effort to remove a small, local irregularity are likely to degrade the finish of other regions nearby, with the result that the overall surface is not as good as the original. If there is any doubt about the suitability of a local area for measurement, then it may be better to identify an adjacent area with an acceptable finish and make additional measurements there.

6.3.2 Preparation using Machine Tools

The principles to use here are the same as those for hand preparation: remove material as gently as possible and remove progressively finer layers of material.

Turning and milling must be carried out at as high a speed as possible using a sharp tool while taking care that excessive heat is not generated in the specimen. The pattern of cuts should be scheduled so that the required dimension is reached after at least three of the finest cuts possible with a final sanding with 200 grit emery paper or finer. For example, the final mm of material may be removed by the sequence of cuts: 0.5mm, 0.2mm, 0.1mm, 0.1mm, 0.1mm, with completion using emery paper to remove all machining marks.

Surface grinding should be carried out so that a fine grade wheel is used and, if necessary, repeated passes are made taking fine cuts. Again completion should be used with a fine emery paper.

6.3.3 Rust and Loose Scale

Loose scale should be removed before measurement by lightly sanding the surface. During the measurement the probe should be kept away from loose magnetic oxides as these may stick resulting in distorted readings. Strongly bound rust may be left in place provided that the MAPS frequency range is set for a reasonably large penetration (1 mm or more) and some degradation of the ultimate accuracy is acceptable.

With regard to the chemical composition of the scale, the outer layer of Magnetite (Fe_3O_4) is ferromagnetic and so should be removed before measurement. Both Hematite (Fe_2O_3) and Wustite (FeO) have a magnetic susceptibility of less than 1 and do not interfere with the signals. They can, however, cause “lifted off” of the probe from the specimen surface, but a scale thickness up to 50 microns would be well within the operational range of probes with spatial resolutions ≥ 7 mm.

6.3.4 Roughness and Pitting

The rough surfaces encountered on plant may still need some preparation. The main problem encountered is flux distortion due to small bumps and edges on the surface. As a rule the surface roughness should be $<0.5x$ mm Ra where x is determined according to the accuracy requirement (Section 13).

6.3.5 Cast Surfaces

Castings often present good surfaces because the surface has not seen any machining or other working that would result in localised stresses. However poor quality castings can have quite rough and pitted surfaces. This presents the operator with the dilemma of whether to spend time preparing the surface thereby introducing surface stresses or whether to measure on the rough surface with some level of signal distortion likely. The choice will depend upon the measurement depth and the material’s sensitivity to stress, as well as the time available, likely stress levels expected and degree of surface roughness.

6.3.6 Machined Surfaces

Machined surfaces are deceptive because they may appear smooth and flat, but the machining process could have introduced very high and variable stress levels (up to yield) in the surface layers of the material. Generally some additional surface preparation is necessary, and both the MAPS and MBN measurements will give an indication of these high levels over the underlying bulk stress levels and distributions.

6.3.7 Hand Grinders

When inspecting welded structures it is quite common to find localised spots where the surface is heavily scratched and gouged. This is where hand angle grinders have been used to remove spattered weld metal from the surface, and **measurements at these positions should be avoided.**

6.4 Demagnetisation

For techniques that use applied magnetic fields well below saturation, remanent fields are likely to influence the measurements. In this case it may be necessary to use a procedure to demagnetise the material or at least remove the magnetic history by randomising the domains at the measurement positions. For high frequency MBN measurements, since the applied magnetic field is low, if there is any residual magnetism left in the test component due to mechanical processes such as grinding etc., this will result in an asymmetrical hysteresis in the magnetisation cycle. **It is particularly important therefore to demagnetise the test component in order to achieve symmetrical magnetisation and a corresponding symmetrical MBN signal on both sides of the magnetisation cycle.**

6.5 Coatings and Cladding

MAPS measurements can be made through coatings such as paint or conductive cladding such as non-magnetic stainless, but the accuracy will be reduced depending upon the coating thickness. High frequency MBN measurements are very sensitive to near surface properties, and the coating will strongly affect the field penetration and hence the MBN signal detection in this case. If the coating needs to be removed the normal procedures for surface preparation should be used. For the low frequency MBN measurement, a thin coating would not significantly affect the MBN signal level.

Thick cladding will strongly affect the field penetration in all magnetic measurements.

7 Access to the Measurement Area

7.1 Space

There must be sufficient access to the area of interest on the component to get the probe onto the surface and make any necessary adjustments. In practice this means that the operator must be able to get the probe and their hand into position while being able to see that the probe is placed and operating properly and, if appropriate, that the probe can be held in position firmly and securely. If the surface area is flat or uniformly curved over a region smaller than the motor assembly footprint, then consideration should be made for taking the

measurements by hand using a small non-metallic guide block. If this is the case, all measurements should be carried out in this manner to maintain consistency.

7.2 Edges and Abutments

Both edges and abutments will cause signal distortion if they are close to the probe. For a probe with core dimension a by b the closest approach, d , to an edge is given by:

$$d = \alpha\delta + 0.5\sqrt{a^2 + b^2} \quad (5)$$

where the factor α is set depending upon the desired final measurement accuracy, a value of 2 being typical, and 3 reducing the distortion to a negligible level. A nearby electrical artefact or instrument can be more of a problem than an edge because of the possibility of inducing eddy currents in it directly from the probe energising magnet, resulting in some sensor signal distortion. However its influence declines rapidly with multiples of the $\sqrt{a^2 + b^2}$ dimension.

7.3 Weld Caps

Measurements can be difficult to make below a weld cap because of the highly uneven surface, and this can affect the proper positioning of the probes. If it is acceptable to *dress* the weld cap flush then the normal procedures for surface preparation described previously should be used.

8 Measurement Probes and Positioning

8.1 MAPS Measurement

A suitable measurement probe should be chosen based on the requirements of the spatial resolution, measurement depth, typical lift-off levels to be encountered and the required stress accuracy. There is a trade off between these factors, where larger probes are less influenced by lift-off and yield more accurate results when operating at low frequencies (high penetration). **Therefore the largest probe compliant with the required spatial resolution should always be selected.**

Figure 14 (foreground) shows a selection of probes with spatial resolutions from 2 mm up to 17 mm. The drive current should be set to provide a flux density in line with that discussed in Section 4, and MAPS probes are designed so that this is only a function of the measurement frequency. During the measurement, the probe may be rotated either manually or mounted in a motor-drive unit controlled from the computer. Figure 14 shows examples of the motorised units. The probe is first inserted into a small collar, which is twisted tight, allowing it to be located into the motor unit. Most measurements will be made using the motorized option, where the angular positioning of the probe is automatically controlled from within the data collection program using a prescribed increment. However, there are instances where using the motor drive may not be appropriate or possible. For example, the physical size and shape of the work-piece or the available access to it may be too small, but it may be adequate to position and manipulate the probe manually. In that case the probe must be held in a suitable guide block.

Whether doing measurements using the motor assembly or by hand, a non-metallic plate or guide block respectively (usually made from Perspex) is used. In both cases this allows the

probe to be easily aligned so that its face is orthogonal to the surface even when working on components that are shaped. Figure 15 shows examples of these. It is easier to machine a new plate for a new application than to design a new motor assembly. The plates are fitted to the base of the motor assembly as shown in two cases in Figure 14.



Figure 14. Examples of MAPS probes and motorised units of various sizes together with collars for assembly of the probe into a motor unit or for hand rotation using an angle calibrated guide block (not shown). Ruler length is 150 mm.



Figure 15. Examples of MAPS guide blocks (right) for manual probe rotation and face plates (left) for motorised measurement. These are shaped to match the geometry of the application.

The be angular increment should be set according to the accuracy required for defining the principal stress axes. The accuracy achieved depends on the in-plane shear stress and the measurement accuracy. For routine use with motorised control of the probe, an increment of 10° is usually adequate. If manual control of the probe is used, an increment of 15° or 22.5° is normally used.



The probe must also be positioned to be accurately orthogonal to the surface. An error of 0.1° can result in a change in the measured stress of typically 1 to 2 MPa, the value depending upon the stress sensitivity of the material and the size and standoff of the probe. Typically the acceptable working alignment accuracy can be taken as the probe being normal to the sample surface within 0.5° , with a corresponding error or uncertainty of ± 5 MPa when measuring to a depth of 1 mm in a typical mild steel.

The desired spatial resolution, measurement penetration, measurement time and accuracy must all be considered when designing probes. The requirements are interrelated so that it is necessary to derive a compromise between them. Small probes having high spatial resolution, obviously cannot measure deep below the surface but they are also much more sensitive to small variations in lift-off.

For some of the most important applications on components and pipework, it is necessary to measure on curved surfaces. Here some of the issues in probe design are more acute. Smaller probes may be necessary for restricted space, or alternatively shaping the probes for the geometry is possible. However shaped probes cannot be rotated to determine the stress axes. Electromagnetic Finite Element software has been used to design probes in some cases. All of the above considerations apply whether the programme of work requires single- or multiple-frequency measurements.

8.2 MBN Measurement

The MBN measurement probe consists of an electromagnetic yoke for excitation and a pick-up coil for sensing the MBN signal (Moorthy et al [15, 16]). The electromagnetic yoke has a core material, which is a soft ferromagnetic material with low hysteresis loss in order to enhance the magnetic flux generation. The magnetic pole face of the core material should be made such that it has good area contact with the surface of the testpiece. This is to minimise the air gap, which is the main source of demagnetisation, and hence maximise the magnetic field penetration. Such requirements generally mean that a unique probe design, with a suitable core with pole faces in an electromagnetic yoke, must be designed for a given geometry and component.

The number of turns of the coil and the current applied in the electromagnetic yoke can be selected depending on the requirements for the maximum magnetic field strength, and optimising the number of turns and current is essential for producing smaller electromagnetic yokes suitable for practical application. A larger number of turns and higher current will give a higher applied magnetic field strength and maximise the extent of the hysteresis loop that is close to the saturation level, but they do result in a larger back emf, which will oppose the applied magnetic field, particularly at higher excitation frequencies. Higher magnetic field strengths and deeper field penetration can be achieved only at lower excitation frequencies. Also, at higher currents $> 1.5\text{A}$ (depending on the coil wire diameter), the heating of the yoke will prevent its use for long-term continuous measurement. By keeping the current to a minimum level ($\sim 1\text{A}$), the number of turns in the coil can be increased to achieve the desired magnetic field strength.

The selection of a suitable soft-core material with a higher magnetic flux density such as Pure Iron, Fe-Si steel, permundar etc. will help to enhance the applied field strength in low frequency measurements, an effect that can be achieved using ferrites in high frequency measurements. Since the high frequency MBE measurement normally involves lower applied

magnetic field strength, the electromagnetic yoke can be made with a smaller number of turns wound on a ferrite core shaped to suit a particular application. For low frequency MBN measurements that normally involve higher applied magnetic field strengths, the requirement for a large number of turns in the coil makes the size of the electromagnetic yoke relatively large. In some applications this can be an important issue, as the geometry of the component and the accessibility of the measurement location pose limitations on the size and design of the electromagnetic yoke. Figure 16 shows typical high frequency MBN devices and Figure 17 shows typical low frequency MBN devices for different applications.

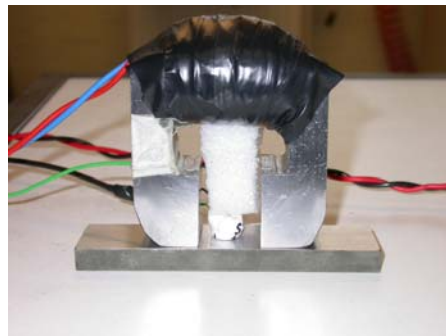


(a)

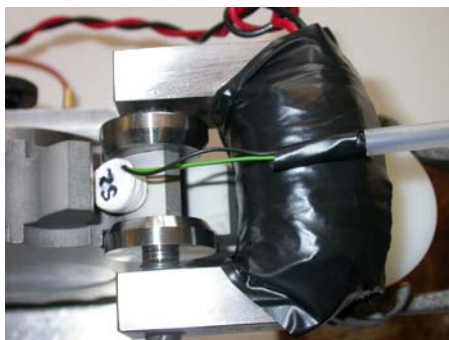


(b)

Figure 16. High frequency MBN devices for measurement on (a) Flat surface and (b) Gear flanks (Courtesy Stresstech, Finland).



(a)



(b)



(c)

Figure 17. Low frequency MBN devices for measurement on (a) Flat surface and (b) Smaller tooth-width Gear flanks and (c) larger tooth-width Gear flanks (Courtesy Design Unit, University of Newcastle, UK).

The number of turns in the MBN pick-up coil determines the sensitivity and the frequency response. Figure 18 shows the typical low frequency MBN profile for three pick-up coils with different number of turns (represented as coil resistance). It can be observed that increasing the number of turns in the pick-up coil increases its sensitivity (higher MBN peak). With a lower number of turns in the pick-up, it may not be possible to detect the MBN signal originating from the deeper subsurface layers (disappearance of the MBN peak at lower applied voltage in Figure 18).

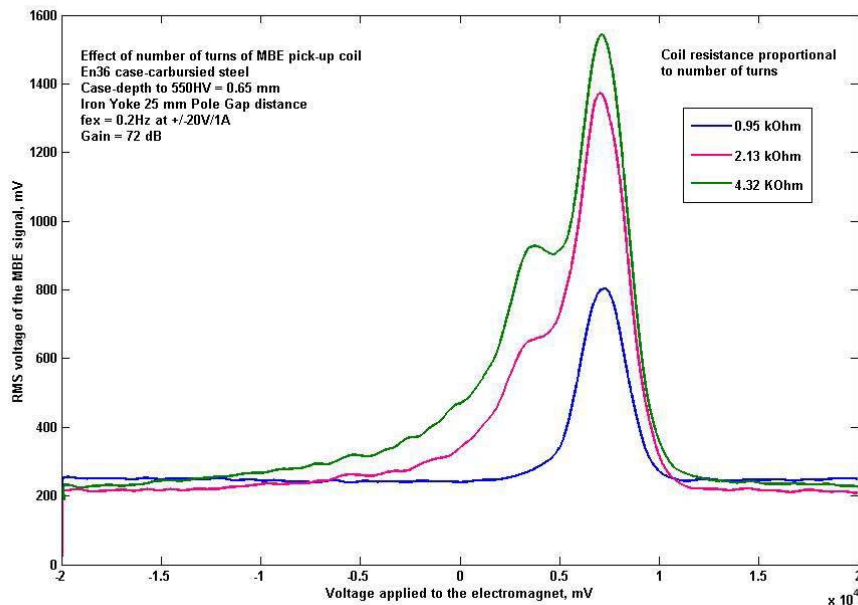


Figure 18. Typical low frequency MBN profiles for three pick-up coils having different number of turns (represented as coil resistance).

The high frequency MBN measurement is performed at a higher magnetic excitation frequency ($f_{ex} > 10$ Hz), and this results in a higher rate of change of magnetisation and hence higher induced MBN voltage level in the pick-up coil. Also, the frequency range of the MBN signal generation will be quite high in direct relation to the f_{ex} . And hence the MBN signal in the high frequency measurement can be easily detected with pick-up coil with a smaller number of turns. For the low frequency MBN measurements, since the f_{ex} is low (< 1 Hz), the rate of magnetisation is lower and hence the induced MBN voltage level in the pick-up coil is also low. The majority of the MBN signal will be generated in the low frequency range (well below 50 kHz), so it is essential to have more turns in the pick-up coil for the low frequency MBN measurement. This is also necessary for detecting the MBN signal generated from the deeper subsurface region. As a consequence, the pick-up coil for the low frequency MBN measurement will generally be bigger than that for high frequency MBN measurement.

However, it is possible to make smaller size pick-ups with large number of turns using thin copper wire to achieve higher sensitivity. The MBN pick-up can be used as an encircling coil (for measurements on long round or square bars) or as ferrite-cored surface coil (for measurements on localised spots in large components). In many applications, the geometry of the component and the accessibility of the measurement locations pose limitation on the size and design of the MBN pick-up, and in some cases, it may be necessary to have an extended ferrite core of the pick-up for better access to measurement location.

9 Measurement Procedures

9.1 MAPS Measurement

The MAPS analogue measurement system is shown in Figure 19. This consists of a PC unit containing digital electronics and hosting the proprietary control and analysis software, together with a remote unit containing the probe driver and analogue electronics for the sensor head (also shown). The remote unit is attached to the PC via a long umbilical (30 m) so, if necessary, one operator can manipulate the probe whilst monitoring the remote screen and a second operator can operate the PC (Figure 20).



Figure 19. MAPS analogue biaxial stress system; showing PC, remote unit and motorised probe head.

The MAPS remote unit contains a highly linear constant current amplifier used to drive the probe electromagnet (Figure 7) with a sinusoidal current at a frequency between 3 Hz and 2500 Hz and suitable current amplitude (Section 4). Signals from each of the three sensors, linkage, leakage and flux rotation, are amplified ensuring no phase distortion before being demodulated into in-phase and quadrature components with respect to the drive current phase. These are digitised at 16 bits in the PC unit before being stored to file, together with the sensor gain levels. The sensor readings are processed using software analysis algorithms to extract the different magnetic parameters. For each measurement, data are collected using between 1 and 40 sequentially applied magnetic field frequencies with the probe rotated sequentially from $-\alpha^\circ$ to $360+\alpha^\circ$ in α° intervals (Figures 8-10). The principal axes and magnetic parameters along these axes are then determined as described previously in Section 4.



Figure 20. Examples where MAPS PC unit is remote from the probe unit using the umbilical.

There is a wide range of parameters that can be evaluated from the three sensors, each being determined for each applied field frequency. Additionally a dc sweeping field is used to measure the magnetic coercive force using the flux linkage sensor. The choice of parameters is under the control of the operator and will depend upon the application. Also advanced analysis methods are being added to the MAPS system on a regular basis as new developments are made in the theoretical understanding of the relationship between sensor signals, magnetic properties and tensor stress. It is beyond the scope of this document to describe how each magnetic parameter is derived but below is a summary of their application, together with some developments:

- The original parameters were made relatively insensitive to lift-off variation by resolving changes perpendicular to a lift-off direction on the impedance plane (similar to eddy current method). For flux linkage *DEP 1*, *DEP 2*, for flux leakage *ADC 1* and *ADC 2*, for flux rotation *SMA Q* and *SMA I* all with their principal axes, *PA σ1* and *PA σ2*. Different probes and MAPS systems require the data to be scaled due to changes in sensitivity. Also when working on curved surfaces (e.g. pipes) flux distortion factors can be derived to enable data to be compared with say plate material of the same steel.
- By resolving measurements on the impedance plane perpendicular to stress changes, it is possible to extract parameters to monitor and better correct for lift-off variation.
- The parameter list was extended to include stress angle parameters (directions on the impedance plane which when resolving the measurement nulls the variation with probe angle, for flux linkage, *DSA*, for leakage, *RSA*, for rotation, *SSA*. *SSA* is insensitive to stress, and depends upon the material type.

- New parameters have been developed that enable complete separation of material / stress and lift-off. This has enabled practical measurement on variable curved surfaces, with the response being identical to that on flat plate. For flux linkage, *PSV 1*, *PSV 2* and true stress angles *PSA 1*, *PSA 2* (i.e. stress angles are also a function of stress), also so called gamma angles, the angles between lines of constant stress and lines of constant lift-off on the impedance plane, *PGAI*, *PGA 2*. These three parameter pairs have true principal axes (i.e. not distorted towards geometry axis like *DEP* on curved surfaces). Additionally *PLV 1*, *PLV 2* are true lift-off parameters in microns along the evaluated geometry axes, *GA 1* and *GA 2*. Similarly for the flux leakage coil the three parameter pairs, *FSV 1*, *FSV 2*, and *FSA 1*, *FSA 2*, and *FGA 1*, *FGA 2*, are available with their principal axes together with the geometry parameters *FLV 1*, *FLV 2* and their axes. The lift-off geometry parameters can be used for coating thickness measurement or surface radius measurement. Ratios of linkage to leakage parameters have special uses in material monitoring. Different probes and MAPS systems require the data to be scaled due to changes in sensitivity.
- More recently theoretical developments have enabled generalization of the stress / material and geometry separation so that in parameter space lift-off and material are orthogonal, and also invariant to the probe sensitivity and measurement frequency. These are the delta parameters discussed in Section 4. For the linkage coil the parameter pairs are *PMD 1* and *PMD 2*, for the leakage coil *FMD 1* and *FMD 2* each with their principal axes. This method is not applicable to measurements made with the rotation sensor.

To convert all measurements into stress it is necessary to have a suitable calibration for the basic material grade. Both the magnetic properties corresponding to zero stress (either single parameter values for homogeneous materials or pairs of parameters and axes for sufficiently textured materials), and the variation of magnetic properties with stress (sensitivity) must be measured. There is a range of approaches to determine both of these aspects depending upon the level of accuracy desired and the effort and the available material.

The main approaches for establishing the sensitivity (relationship between magnetic properties and stress) of the MAPS parameters are:

- (1) **Experimental biaxial method.** This approach is the most elaborate, requiring a special cruciform sample to be manufactured, strain gauged and tested in a suitable four-axis testing machine. A range of biaxial loads (generating elastic strains over the biaxial plane as complete as possible) are applied and the various MAPS parameters measured. Figures 6 and 11 show the biaxial calibration maps obtained for the parameters *DEP 1* and *SMA Q* for a mild steel grade. This method was historically the most accurate approach.
- (2) **Theoretical (thermodynamic) method.** Thermodynamic models (neglecting hysteresis) are used together with the MAPS measurements at a few known stress levels (at least 6) to evaluate theoretical biaxial maps. Typically a uniaxial test may be performed to establish the known stress data.
- (3) **Experimental bi-uniaxial method with complex scaling.** If a biaxial calibration for a similar material is already available then this data can be compared to uniaxial data made on the test material to generate a modified biaxial calibration.

Typically if the material is textured a uniaxial test is carried out using samples cut along the two orthogonal material axes. The existing biaxial data is then scaled in two dimensions (hence complex scaled) to fit the uniaxial test data.

- (4) **Mixed map method.** As biaxial calibrations for a range of materials now exist it is possible to generate all intermediate variants by combining combinations of the existing maps such that the resulting mixed map agrees with data measured on the test material at a few known stresses.

9.1.1 Stress Inversion

At each measurement location a number of magnetic parameters and their axes are determined. Together with the calibration data, each measured parameter defines a contour line on the biaxial plane with a width equal to the standard error of the measurement. The region where all parameter lines cross then defines the unique biaxial stress state together with the standard error (Figure 21).

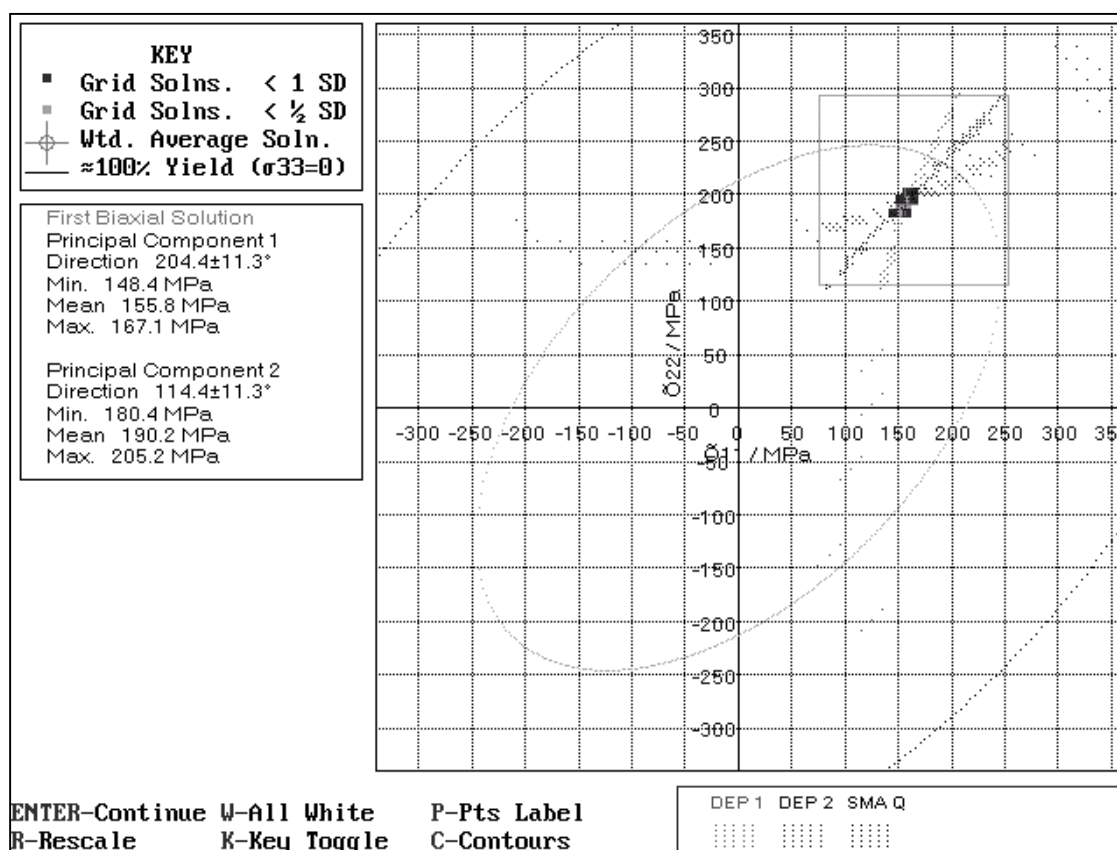


Figure 21. Example of stress inversion using parameter contours from the calibration. This example shows evaluation of a biaxial tensile state (156, 190) MPa.

9.2. MBN Measurement

The basic measurement system consists of a function generator output that is connected to a bi-polar power amplifier, which generates the required power and drives the electromagnet. The MBN pick-up coil is connected to a filter/ amplifier to process the MBN signal to the desired frequency range and amplification. The processed MBN signal can be acquired using

PC-based data acquisition and different MBN parameters such as the *MBN profile*, *total RMS voltage*, and others can be calculated.

The experimental set-up for MBN measurements is shown in Figure 22. The basic system of a function generator, bi-polar power amplifier, MBN Signal Filter/Amplifier and Data acquisition and analysis can be common to both types of MBN measurement. However, the measuring device with the electromagnetic yoke and MBN pick-up coil is different for the high and low frequency MBN measurements. Also, the selection of (signal filtering range) frequency range of the MBN signal and the amplification level would be different for these two types of measurement. The low frequency MBN measurement would require higher signal amplification.

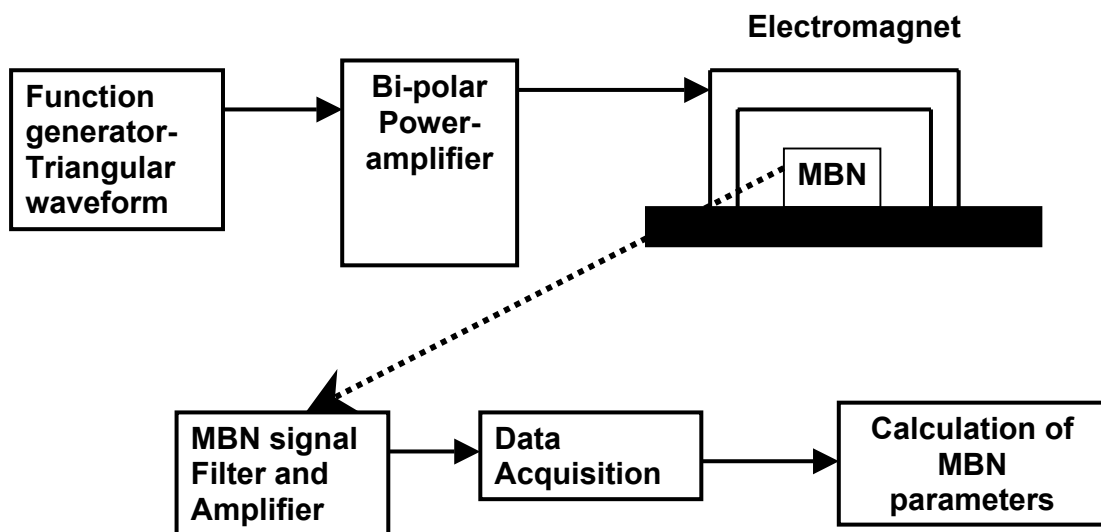


Figure 22. Typical Experimental set-up for MBN measurement.

For example, a typical low frequency MBE measurement can be made using a set-up in which a continuously varying bi-polar symmetrical triangular waveform at a frequency $f_{ex} = 0.2$ Hz is fed from a function generator to a bi-polar power amplifier, which amplifies the waveform signal and drives a suitably designed electromagnetic yoke, made with a commercially pure Iron core, at a given current of ± 1 A, which generates a maximum applied magnetic field strength $H_{max} = \pm 20$ kA/m at the centre of the poles of the electromagnet with a pole gap distance of 25 mm. A ferrite-cored pick-up coil can be used to detect the MBN signal. In order to achieve the highest detection sensitivity, it is important that the ferrite core of the pick-up is in good contact with the surface of the test component. Typical low frequency MBN profiles for different tempered case-carburised specimens are shown in Figure 23.

The acquired MBN signal would then require frequency filtering using a 1 kHz high-pass filter to eliminate any interference from the upper harmonics of the excitation frequencies and amplification with a gain of typically ~ 60 dB for soft steels and ~ 72 dB for hard steels. The frequency filtering and amplification need to be adjusted according to the characteristics of the generated MBN signal. Data such as the MBN signal and voltage/current applied to the electromagnet, tangential magnetic field etc. can be acquired using a multi-channel data acquisition with ADC and suitable DAQ software. To achieve better reliability and repeatability of the MBN signal characteristics, the average of MBN signals generated in at least 2-4 magnetisation cycles should be used. The various MBN parameters such as RMS voltage profile of the average MBE signal plotted as a function of the voltage applied to the

electromagnet, total RMS value of the signal, energy, etc. can then be calculated for analysis and correlation.

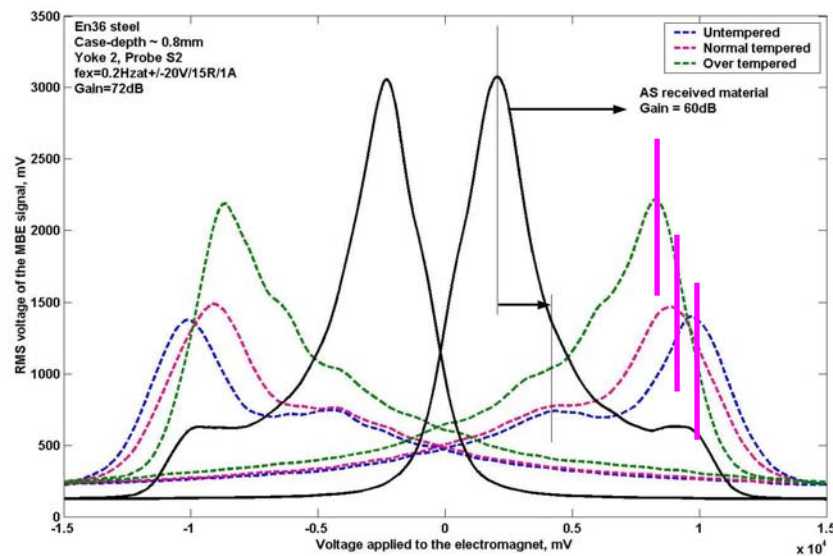


Figure 23. Typical low frequency MBN profile for different tempered En36 steel case-carburised specimens ($f_{ex} = 0.2\text{Hz}$, $\Delta f_a = 1\text{-}20\text{ kHz}$).

The high frequency MBE measurements can be made using a ferrite-cored electromagnetic yoke and a ferrite-cored MBE pick-up fixed at the centre of the pole gap. The f_{ex} can be selected to a desired frequency, (typically $f_{ex} > 10\text{ Hz}$) for easy detection of the MBN signal. The maximum magnetic field strength depending on the number of turns in the yoke and the current capability of the coil can be selected, and in turn this decides the external magnetic excitation level. The detected MBN signal is then processed with suitable frequency filtering (normally in the range of $10\text{ kHz} - 1000\text{ kHz}$) to avoid interference from harmonics of excitation frequencies and amplified with a typical gain of $\sim 20\text{dB}$ for soft steels and $\sim 40\text{dB}$ for hard steels. Again, averaging of the MBN signal generated over many cycles (> 10 cycles) is required for better repeatability due to a faster rate of magnetic excitation, which results in non-steady state magnetisation. Different MBN parameters can be calculated for analysis and correlation with material properties. Typical high frequency MBN profiles for different tempered case-carburised specimens are shown in Figure 24.

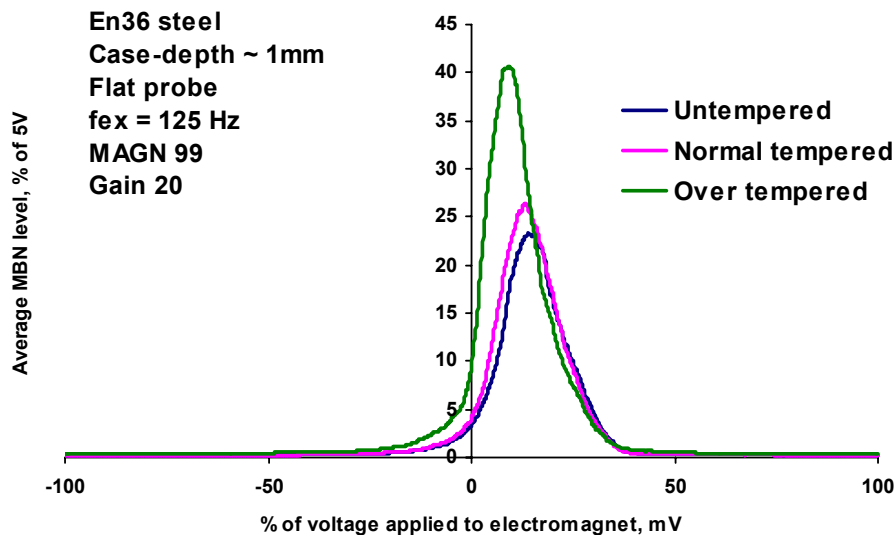


Figure 24. Typical high frequency MBN profiles for different tempered En36 steel case-carburised specimens ($f_{ex} = 125$ Hz, $\Delta f_a = 70$ -200 kHz).

10 Issues of Calibration

10.1 MAPS Measurement

The microstructural sensitivity of the magnetic parameters makes it important to carry out calibration. For some methods, such as those based on anisotropy, one calibration will serve over a significant range of material conditions. Other methods may be highly sensitive to variations in microstructure, so that it may not be possible to obtain a unique calibration for an application. Calibration is usually carried out by applying known stresses to test samples, but it is important to ensure that the initial stress state of the test samples is known. Since magnetic techniques exhibit a tensor relationship to stress, a uniaxial test is usually not sufficient to characterise the material response.

10.2 MBN Measurement

It is well known that the magnetic properties and their variation in response to changes in material properties are unique to a given material. Since each material can have a different magnetic response to stress variation, it is inappropriate to correlate the MBN signal, in particular quantitatively, without proper calibration for the specific material of interest. Also, since the MBN signal is influenced by both microstructure and stress, it is essential to calibrate the effect of variations in these properties independently to achieve reliable correlation during the actual measurement. For example, the effect of variations in the microstructural features can be determined by measuring test specimens subjected to different tempering or thermal aging conditions. The effect of stresses can be determined for a given

microstructural condition by measuring MBN on specimens subjected to known applied tensile and compressive stresses in a cantilever bending beam set-up. In some cases, the synergistic nature of variations in material properties poses limitations in obtaining a set of calibration data, but in many cases calibration of the individual material properties will always help to evaluate the material quantitatively and give a better understanding of the MBN behaviour.

As mentioned earlier, the effective magnetic field strength in the test component and hence the magnetisation and MBN signal strongly depend on the measurement parameters such as electromagnetic yoke, applied field strength etc. In addition, the geometry of the test component has a strong influence on the magnetisation level and hence on the MBN signal. The demagnetisation effect of the component, which reduces the effective field strength inside the material and distorts the hysteresis loop, depends on the aspect ratio (length/width) of the component. Also, the surface area of the component in relation to the area coverage of the electromagnetic yoke will affect the magnetic flux concentration and hence the effective field strength. A larger surface area of the component will dilute the flux concentration due to wider spreading over a large area and hence decrease the magnetic field penetration depth. For example, the MBN measurements on a flat bar specimen and gear tooth flank made with the same material and having the same properties will be different due to their different geometry and measurement set-up. **The influence of these factors strongly advise that, it is essential to make calibration for each test geometry, material and measurement parameters combination for quantitative evaluation.**

Generally, since the magnetic response to variations in material properties is difficult to predict in any new material, it is best to first examine the magnetic response to different property variations in that material. It is known that the maximum extent of the magnetisation process is revealed only when the magnetisation cycle involves a major hysteresis loop, and this requires maximum applied magnetic field strength to take the material to the near-saturation level. During this major hysteresis cycle, it is possible to obtain maximum possible MBN signal and hence the material information and response. The applied field can then be gradually reduced to an optimum level where sufficient MBN signal can be measured and correlated with a particular material property. This helps the operator to decide whether a low frequency MBN or high MBN measurement is required to evaluate the material property reliably.

11 Materials and Microstructure

The magnetic properties of materials are affected by the material composition and structure. It is important to understand these effects when using magnetic methods to measure stress, since to ignore them is to risk misinterpreting results. At a fundamental level the alloy content will affect whether the material is ferromagnetic, and the magnitude of the permeability. Thus alloys which are close to 100% iron or nickel with unpaired d-electrons are strongly ferromagnetic, but alloys with intermediate concentrations of iron or nickel with other elements may be either ferromagnetic or not, depending on the filling on the d-band. The alloy composition also determines whether the structure is f.c.c. or b.c.c., which in turn affects the magnetic properties. In steels, the carbon content is important mainly for determining magnetic softness or hardness because the carbon tends to influence the domain wall movement whether in solution (causing crystal lattice strain) or precipitate form (pinning the

domain walls). Thus the sensitivity of a magnetic parameter to stress varies with alloy composition.

The crystal structure can also have an important effect on the magnetic properties via crystallographic texture. If a grain of the material has high crystal anisotropy then it will also have a high magnetic anisotropy. If stress measurement is attempted in a region of strongly preferred orientation, for example in a rolled material that has not fully recrystallised, then the texture must be compensated for to avoid errors.

Domain walls are pinned by various microstructural features introduced during fabrication, including grain boundaries, phase boundaries, precipitates, inclusions and dislocations. In the first case if the grain size decreases there will be more pinning points for the domain walls. In the second case, it will depend upon the nature of the phases present. If only one of the phases is magnetic, or if there is a large difference in properties, then the phase boundary will strongly pin the walls, raise the coercivity and cause the hysteresis loop to broaden and the material to harden magnetically, e.g. in pearlite with alternating ferrite and cementite (iron carbide) laths compared to ferrite grain structure. In the case of precipitates or inclusions, it depends on their magnetic properties. If they are non-magnetic, as is often the case in steels, then they pin the domain walls strongly, raising the coercivity and hardening the structure magnetically (Buttle et al [20], Moorthy et al [17]). Thus the sensitivity of a particular magnetic measurement to stress can change during heat treatments such as annealing and ageing, and may vary from specimen to specimen of nominally the same material. An important example arises near welds where the heat-affected zone will contain significant variations in microstructure just where knowledge of residual stress levels may be desirable. Care must be taken to ensure that material effects such as these are compensated for when using that measurement to deduce the stress state.

Thermomechanical treatment and in-service creep and/or fatigue loading may mean the material has been plastically deformed, in which case it will contain networks of dislocations and different substructures. These too may pin the magnetic domain walls, although the effect may not be great unless there has been heavy deformation (Maker and Tanner [19], Moorthy et al [18]).

For most magnetic techniques it is not possible to fully separate the microstructural and stress effects. One example is during the case hardening of steel to produce a martensitic surface layer. Martensite has a fine lath structure with dissolved carbon, and this structure strongly pins domain walls. However, because of its different crystal structure, martensite is heavily strained, so that there is an internally generated residual stress that will change the local permeability. It is impossible to separate these two effects with a simple measurement. A second example is in the bending of a bar. This generates an intrinsic depth dependent combination of plastic and elastic strains, which will remain unless the bar is annealed. A simple magnetic measurement will be sensitive to both simultaneously.

The materials with the best stress-sensitivity characteristics are normalised mild steels that contain reasonably large grains of ferrite (nickel alloys and superalloys can be better but are not considered here). Cast iron and low alloy steels have lower sensitivities but are usually acceptable in this regard as are high-strength bearing steels. Higher carbon steels and partially magnetic stainless steels can also give acceptable results provided other factors, such as geometry are favourable. Weakly magnetic stainless materials can be inspected but the risk of a poor result is high.

Material variations can also give problems due to calibration difficulties. The materials in which this can be particularly problematic are: cast iron (property variations), duplex steel, weakly magnetic stainless steels (ferritic content variations) and the heat affected zones in welded components (strong microstructural variations).

12 Temperature

Temperature influences the measurement in three ways:

- The stability of the electronic hardware
- Changes in ferromagnetic properties approaching the Curie temperature
- Changes in the electrical resistivity of the test material

It is good practice to leave equipment turned on for a period prior to measurement (the time depending upon the equipment) to allow the electronics to be in thermal equilibrium. Furthermore, in order to compensate for potential changes in the system hardware during a long measurement sequence, reference samples should be used. In this case it is important to ensure that these samples are at the same temperature as the test component ($\pm 3^\circ\text{C}$). The use of reference samples will also largely remove the influence of the arising thermally induced physical property changes on the measurements.

The ferromagnetic magnetisation initially drops only very slowly with absolute temperature until the Curie temperature is approached (770°C in iron), when the decline becomes much more rapid. The magnetic permeability initially increases with temperature before reaching a peak and dropping dramatically to zero at the Curie temperature. Thus for a constant current probe and a fixed standoff, the flux density in the surface of the steel should increase with temperature for ambient temperatures.

The electrical resistivity, ρ , has a linear temperature coefficient, k , expressed as:

$$\rho(T) = \rho(0)[k(T - T_0) + 1] \quad (6)$$

The energy loss from induced eddy currents in the steel volume interrogated by the applied magnetic field is given by the integral:

$$E_{ec} = \int \rho |J|^2 dV \quad (7)$$

so as the temperature changes, both the magnetic field penetration (eqn.2) and the induced eddy currents (eqn.7) in the surface of the steel will change. Some typical values are:

Material	Resistivity ($\Omega\cdot\text{m}$)	k ($^\circ\text{C}^{-1}$)
Pure iron	10×10^{-8}	6.5×10^{-3}
Wrought iron	14×10^{-8}	6.0×10^{-3}
Mild steel	15×10^{-8}	5.0×10^{-3}

For measurement, as the resistivity increases with temperature the measurement penetration will also increase causing a slight drop in the magnetic flux density in the steel surface.

Thus the different factors influence the measurements in opposing directions making accurate prediction difficult. For mild steel, comparisons of the changes in experimental measurements with the typical stress sensitivity indicate, that at low stresses, a 1°C difference in temperature between the reference samples and the test component will equate to a typical equi-biaxial error in stress of 0.7 MPa. Therefore provided temperature differences are kept to a few degrees, these sources of error should be small.

13 Issues on Accuracy

13.1 MAPS Measurement

The most important factors affecting the ultimate accuracy of magnetic stress measurement techniques are:

- 1) The ultimate precision and stability of the equipment
- 2) Ferromagnetic issues such as material magnetic and loading history
- 3) Calibration issues such as the intrinsic magneto-elastic response of the material and the method and procedures employed to determine it
- 4) Operational factors such as probe design, measurement frequency and probe lift-off.

The precision and stability of the equipment is beyond the scope of this guide. For MAPS the hardware must be considered both in terms of the ability to deliver an accurate and stable current to the probe drive coil and in the measurement of both the amplitude and phase (with respect to the current) of each sensor signal with minimal drift and sufficient resolution. The performance of the hardware contributes to the minimum random error for stress measurement.

The influence of magnetic and loading history of the test component arises from the magnetic hysteresis properties of the material grade. As the MAPS probes apply magnetic fields significantly below saturation, the measured response will depend upon where on the hysteresis loop the interrogated material previously lay. **For relatively soft magnetic materials such as low carbon steels this problem should be very small, typically causing uncertainties of the order of 1 MPa. For harder materials such as fully pearlitic or martensitic steels the arising uncertainties become large, typically a few tens of MPa. In these cases a local demagnetisation procedure should be used prior to each measurement.**

Different steel (and other ferromagnetic materials) types exhibit different relationships between the stress tensor and the magnetic measurements (Section 5). Low permeability steels exhibit a weaker sensitivity to stress leading to lower overall stress accuracy for the measurement. In industrial applications the difference between a low strength mild steel and a high strength steel can be a factor of five or so in sensitivity, and appropriate calibration must be used to avoid serious errors in the measured stresses.

The relationship between the measurement and the stress is a non-linear tensor one, although as the measurements are made from a surface, a plane stress assumption is made. Therefore it is important that the calibration procedure establishes the full biaxial stress response and not

just a uniaxial one. Calibration is usually carried out using strain gauges bonded to suitable test samples of the selected steel grade, and applying controlled static loading in a suitable loading machine while collecting data. It is desirable to first remove residual stresses from the calibration samples by using a suitable stress relief heat treatment. This is not always possible, particularly for steels that lose their microstructural properties following such a treatment (e.g. low temperature tempered martensites). In this case the difference between the two residual principal stresses (at the calibration position) can still be determined from the calibration data and added to the loading stresses used, but it will be necessary to determine the absolute levels of residual stress using some other approach. Unknown residual stresses in the calibration will result in a corresponding systematic error for stress measurement.

The operational factors, probe size, measurement frequency and probe lift-off, together with the underlying accuracy of the hardware, set the size of the random error for stress measurement. As an example, Figure 25 shows that, although the MAPS measurement result does not change with the probe standoff, the predicted standard error increases rapidly from 0.5% to 13% when moving the probe from a standoff of 280 μm to 2.8 mm respectively for a typical probe. This is despite the ability to completely remove the influence of lift-off from the measured data and is simply a consequence of the decreasing signal to noise ratio.

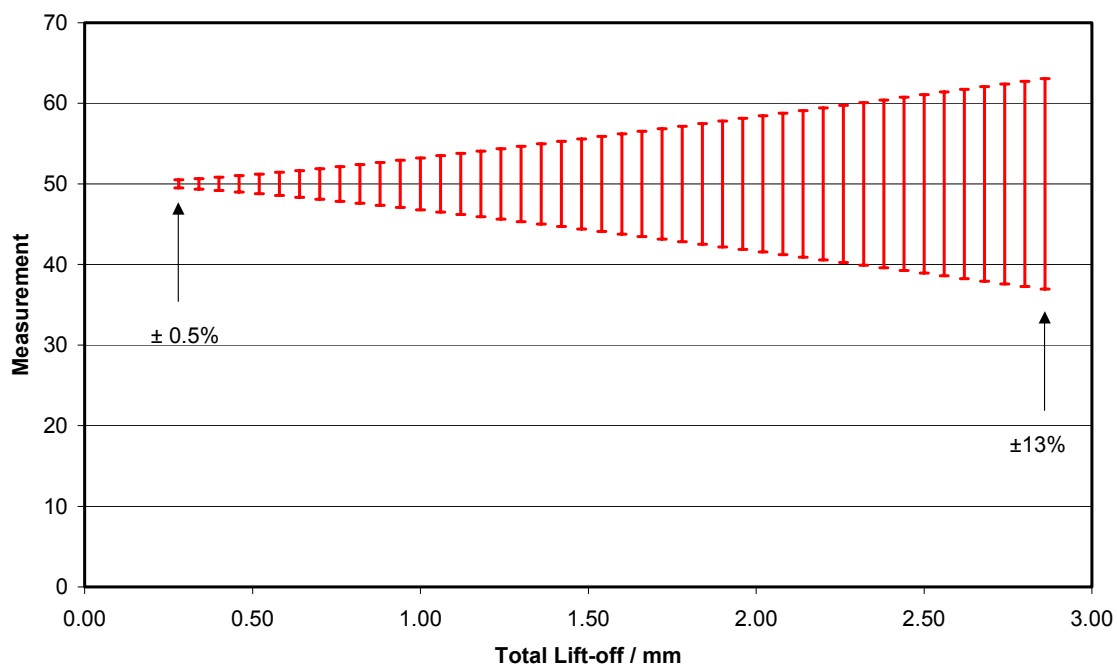


Figure 25. Graph demonstrating how the MAPS measurement value is invariant but the standard error increases with lift-off.

To give a better feel for these data it would be useful to convert performance into a MPa accuracy. This is not possible in principle because of the non-linear tensor relationship between the magnetic properties and the stress state. However a guide can be given for steel with typical mid-range sensitivity and assuming an underlying system stability corresponding to the MAPS 2 analogue unit.

Figures 26 to 28 show theoretical results for a range of probe sizes for drive frequencies of 10 Hz, 100 Hz and 1000 Hz. From these we note:

- Accuracy degrades rapidly with standoff
- For a particular standoff, larger probes deliver better accuracy
- Higher drive frequencies yield higher relative accuracies.

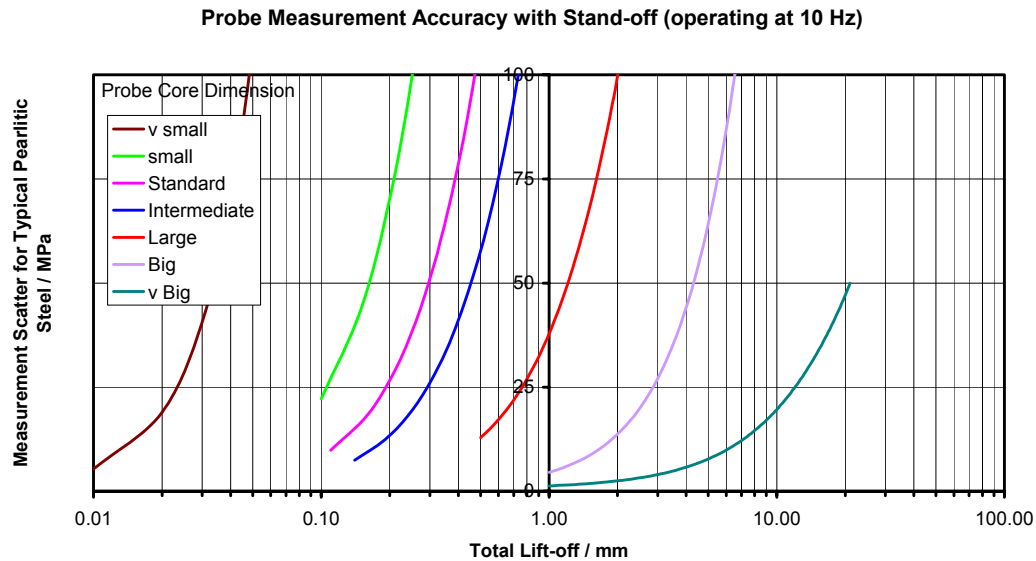


Figure 26. Theoretical measurement accuracy in a typical steel for probes of different sizes operating at 10 Hz ($\delta \approx 3$ mm). MAPS 2 analogue system.

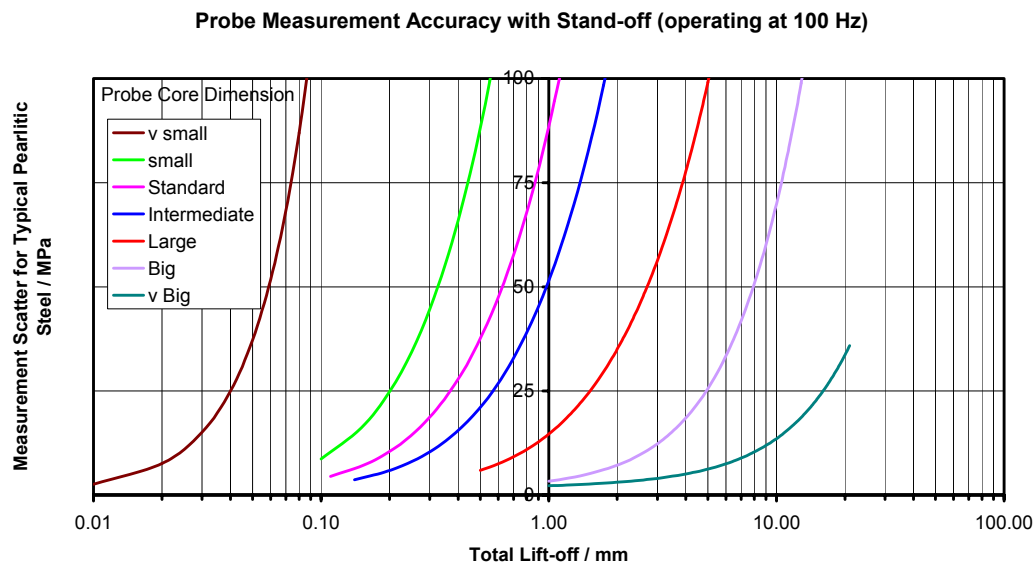


Figure 27. Theoretical measurement accuracy in a typical steel for probes of different sizes operating at 100 Hz ($\delta \approx 1$ mm). MAPS 2 analogue system.

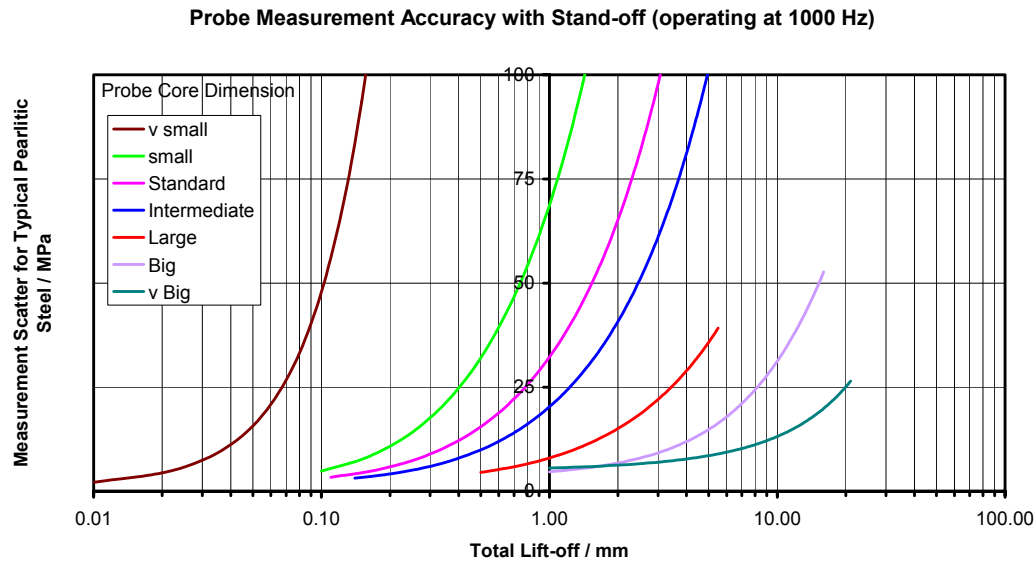


Figure 28. Theoretical measurement accuracy in a typical steel for probes of different sizes operating at 1000 Hz ($\delta \approx 0.3$ mm). MAPS 2 analogue system.

Different steel grades will result in a change in the numbers on the stress axis. Similarly the new digital hardware MAPS platform yields much lower measurement scatter giving increased accuracy, but in both cases the trends remain the same as they depend upon the principles of the method.

These trends are important to allow an optimum selection of the probe for any particular application. For example, a small probe should never be used where the lift-off variations cannot be controlled within an acceptable margin suggested by the appropriate curve. In practical measurements it is often possible to improve on this predicted theoretical scatter simply by averaging several measurements. However systematic errors from calibration and, if relevant, random errors from variable magnetic history, cannot be dealt with in that way.

13.2 MBN Measurement

The MBN measurement is repeatable to a large extent provided the measurement parameters and method remain unchanged. Hence any correlation made with MBN measurement can be reliably considered as accurate. Normally, unexpected variations in background noise (mostly industrial environment) and malfunctioning of the electronics in the measurement system would result in variations in the MBN measurements. However, these can be easily identified using measurements on previously measured test specimen blocks and by looking at the actual signal pattern. Sometimes, an error in the placement of the electromagnet and pick-up sensor on the test component would cause an air gap (lift-off) and that would result in variations in the MBN signal level. With experience, it is relatively straightforward to ensure accurate MBN measurement and hence the material property evaluation.

More certainly, the issues on accuracy of determining a particular material property with MBN parameter will arise due to the combined influence of variations in more than one material property on the MBN signal. This would limit the ultimate accuracy. In some cases,

the use of two or more MBN parameters might help in isolating the individual effect and thereby improving the accuracy.

14 Summary and Conclusions

The magnetic techniques offer a practical approach to stress measurement on industrial components and structures that are not accessible by conventional methods. This guide considers just two of these techniques: the multi-parameter MAPS (Magnetic Anisotropy and Permeability System) method and the MBE (Magnetic Barkhausen Emission) method. In the past these methods relied on expert operators skilled in all aspects of the technology in order to obtain reliable results. This guide sets out to remedy that, in providing an account of all aspects critical to accurate measurement so enabling the technology to be systematically used by a wider spectrum of operators, still skilled in inspection procedures but not necessarily academics in magnetism.

For magnetic stress measurement, the basic areas to consider are:

(1) The component to be inspected. Avoid surface waviness or high near-surface stresses generated by use of hand grinders and machining. Remove loose rust. For high frequency MBE measurement consider preparing the surface using chemical and/or electro-chemical methods. For MAPS always use the largest probe compliant with the required spatial resolution. If the material is magnetically hard it is particularly important to demagnetise it. Curved surfaces will require a suitable support to hold the probe accurately upright on the surface while scanning.

(2) The material. The material grade will need to be calibrated for MAPS; for MBE it is essential to make calibration for each test geometry, material and measurement parameter combination for a quantitative evaluation.

(3) The information desired. Are absolute stresses required or only bending moments or load assessments? This will influence the measurement regime. For MAPS if the surface is damaged or treated in some way and bulk stresses are wanted, use multiple frequency measurement. Try and avoid spot measurements just at the critical points, scans always provide more information if few frequencies are being used (data using many frequencies take longer to collect).

The MBN technique is a sensitive NDT method for assessing the residual stress variation in components. This MBN measurement technique is basically classified as two types: 1) High frequency and 2) Low frequency MBN measurements. The high frequency measurement involves applying lower excitation magnetic field at higher frequencies (> 10 Hz) and acquiring and analysing the MBN signal in high frequency ranges (> 2 kHz). This type of MBN measurements can be made using smaller devices with faster measurement. However, this is more suitable for near-surface measurement due to its lower skin-depth of the MBN signal. The low frequency measurement involves applying higher excitation magnetic field at lower frequencies (< 1 Hz) and acquiring and analysing the MBN signal in high frequency ranges (> 0.5 kHz). This type of MBN measurements requires larger device and is also slower. However, this is more suitable for near-surface and subsurface measurements due to

its larger skin-depth of the MBN signal. In both cases, the MBN signal indicates the average changes with the skin-depth or detection depth of the signal.

In both types of measurement, the MBN signal level strongly depends on the measurement device and parameters used. The MBN measurement device suitable for a given application can be designed and various measurement parameters can be optimised for achieving maximum sensitivity. Since the MBN generation and its stress sensitivity are strongly material characteristics, it is essential to have to calibration for each types of ferromagnetic steel. In most applications, the MBN measurements can be reliably used for qualitative assessment of residual stress variation with minimum calibration work. But, for quantitative determination of residual stress, this technique requires greater understanding of the MBN behaviour and extensive calibration for each type of application

15 Acknowledgements

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17 MAPS Stress measurement examples

Magnetic measurements are relatively fast to collect making it possible to make detailed maps of the stress distribution over the surface of components and structures. Each measurement yields principal biaxial stress levels and axes in the plane of the surface with a sampling depth depending upon the applied magnetic field frequency. The stress orthogonal to the surface plane is assumed to be zero, whereas boundary conditions dictate this only at the very surface.

17.1 Rail Cross Sections

As an example of the biaxial information which can be studied with MAPS consider the complex stress environment within a rail. Stresses in new unstraightened rail are comparatively small and arise from phase transformation combining with differential cooling through the section. Roller straightening introduces much higher (100 to 300 MPa) variation and magnitude stresses; these usually are tensile in the crown and foot, and compressive in the web. The stress distribution in the crown evolves rapidly once the rail experiences traffic. A thin layer (5 to 10 mm in unhardened rail) on the running surface becomes highly compressive, and is balanced by tensile stresses below. This layer may be important for limiting defect growth rates. Note that the plastically damaged layer is much thinner than this. Figure 29 illustrates the residual stresses in the crown of an un-cracked service rail (the arrows represent orientation of the principal stresses with inward pointing arrows representing compression, and the arrow size relates to the magnitude of the stress). Measurements were made to a depth of 0.5 mm on cut sections of rail using a probe with 4 mm spatial resolution operating at a single frequency of 252 Hz.

Figure 29 also shows a transverse serviced rail section cut to include some cracking. Note the disruption of the usual surface compressive layer with significant tensile. Information on the subsurface stress levels can also be obtained non-destructively by measuring on the railhead using multiple frequencies and deconvolving the data to obtain results at discrete depths, an example of this approach is shown later. Each biaxial measurement is represented by a pair of orthogonal arrows aligned with the principal stress axes with a length proportional to the principal stress magnitude (refer to scale bar). Red arrows pointing outwards are used to show tensile and green arrows pointing inwards compressive stress levels. The second example shows how gauge corner cracking disrupts the compressive stress layer.

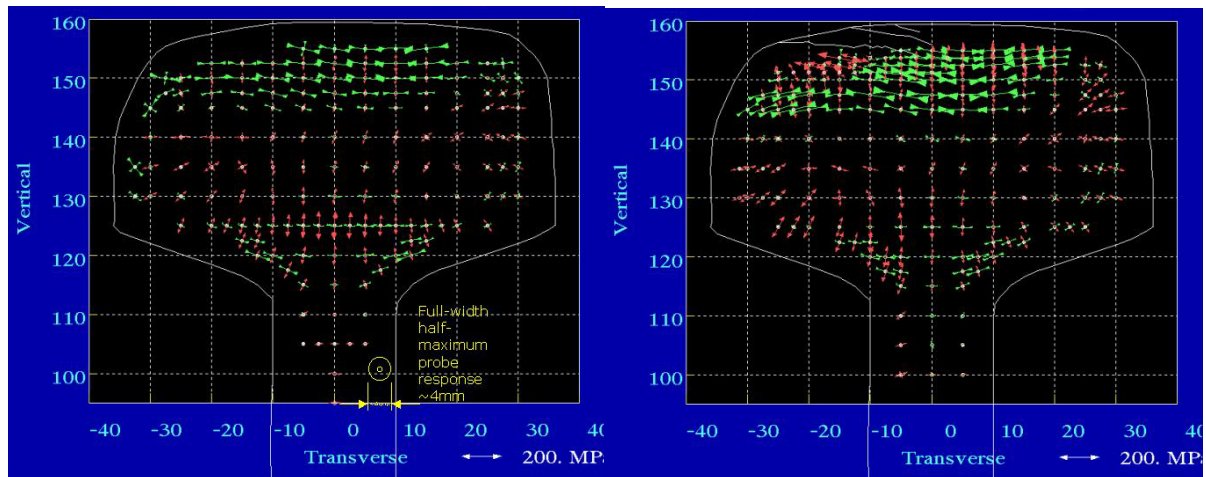


Figure 29. Biaxial stress levels measured over the cut face of worn steel rails showing a ~10 mm deep compressive layer introduced by traffic.

17.2 Aerospace Bearing Raceway Inspection

The rapid measurement makes it possible to automate inspection as shown in Figure 30. This equipment will inspect aerospace bearing raceways using an XYZ robotic arm to manipulate the probe over the raceway track while the bearing is rotated on a turntable. As the probe is held statically (not rotated) it is necessary to carry out the measurements twice, using alternatively a magnetic field oriented in the hoop and the orthogonal ‘cross-track’ or axial axes, the stress levels being determined in only these two ‘geometry axes’ directions. The inspection replaces conventional X-ray diffraction measurement, many thousands of biaxial stresses being measured in just two hours in place of a single x-ray measurement. Figure 30 also shows an example of one of the stress components (‘cross-track’) mapped as a false colour contour plot over part of the raceway surface, measurements sampling to ~250 μm depth. Also shown is the position where conventional eddy-current inspection identified grinding damage.

Surface and near sub-surface residual stresses, caused by the manufacturing process, should be highly compressive in order to prevent surface and near sub-surface cracks from initiating and growing, thereby extending the fatigue life of the bearing. Figure 31 shows an example of measurements made with the scanning system using a frequency of 150,000 Hz to obtain a skin depth of only 26 μm , comparable to x-ray penetration depths. Note the high and uniformly compressive values observed over the complete raceway surface.

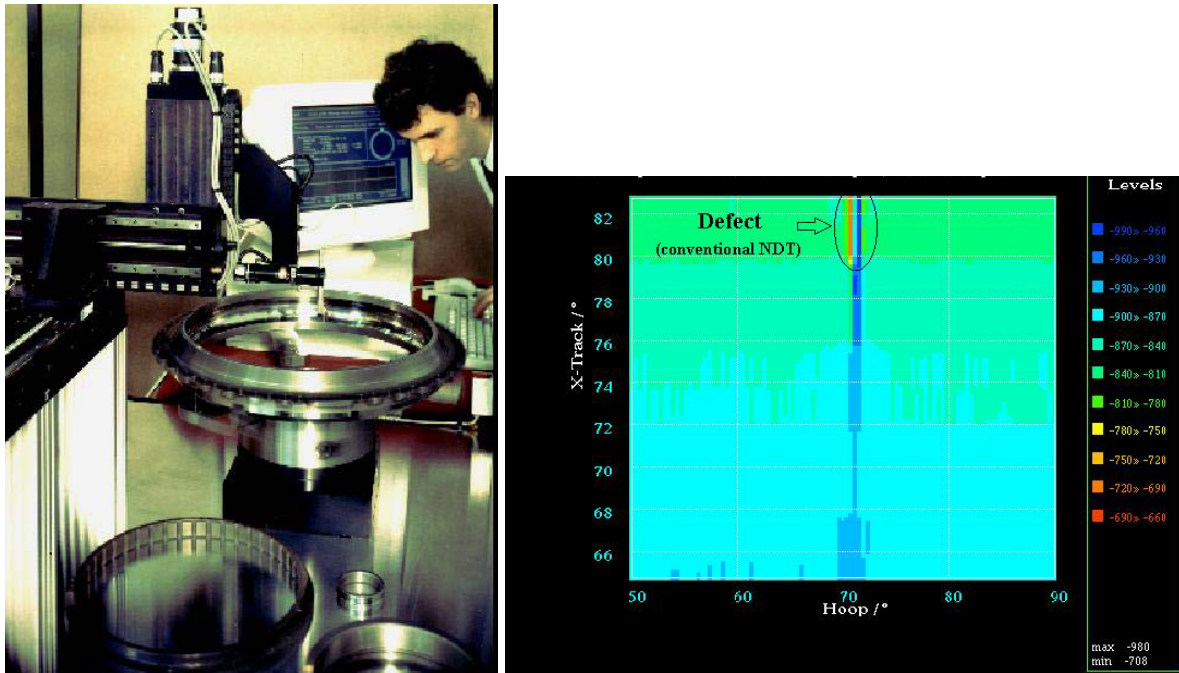


Figure 30. Automated bearing inspection system based on early MAPS techniques. Example of contour mapping of the ‘cross-track’ stress component measured at 2 mm spatial resolution over part of an aerospace raceway (hoop component not shown). A grinding burn defect detected by conventional eddy-current technology is highlighted. Note the stress pattern associated with the defect.

17.3 Ring and Plug Test Sample

In order to measure how the stresses vary with depth, MAPS can make measurements at multiple frequencies and deconvolve the magnetic field attenuation function to establish the properties, and hence the stress at discrete depths. As an example a ring and plug sample was manufactured from mild steel grade D (0.2% σ_{yield} 280 MPa) for testing. This comprises a 50 mm diameter circular plug inserted into a 100 mm diameter ring with a 50 mm hole. The plug is cooled and the ring heated during the insertion to produce a specified residual stress field once the two pieces reach room temperature. Figure 32 shows the expected stress levels for a 50 μm tolerance fitting. In the plug the predicted stress is equi-biaxial at -150 MPa, whereas in the ring the radial stress decreases towards zero and the theta stress is immediately tensile at 250 MPa but decays with distance from the plug. The surface of the sample was subsequently shot peened so as to introduce a varying stress with depth below the surface.

Measurements were made using the same probe resolution as for the rail sections, but with 17 frequencies between 35 and 2300 Hz to establish a depth range, following deconvolution, of 60 μm to 2 mm. Note that this depth range is slightly greater than would be indicated from the skin depths at each individual frequency. Figure 33 shows the radial and theta stress components again plotted as false colour contour maps, but this time as a function of the radial position and depth into the surface. Both stress components are found to be compressive at approximately -200 MPa in a first 0.5 mm from the surface, this being consistent with expectations from the peening process. Not until a depth of 2 mm do the two stress components begin to follow the predicted stress variations of Figure 32. At this depth the average stresses in the plug from MAPS were -100 MPa in the radial and -70 MPa in the

theta axis. In the ring the radial stress is still compressive but drops to very small values towards to outer edge. The theta stress becomes tensile at 90 MPa but drops to around 50 MPa towards the outer edge. It may be that the stresses are generally higher in magnitude at deeper depths; otherwise these values are more consistent with a tolerance of only 27 μm when fitting the plug (Figure 32).

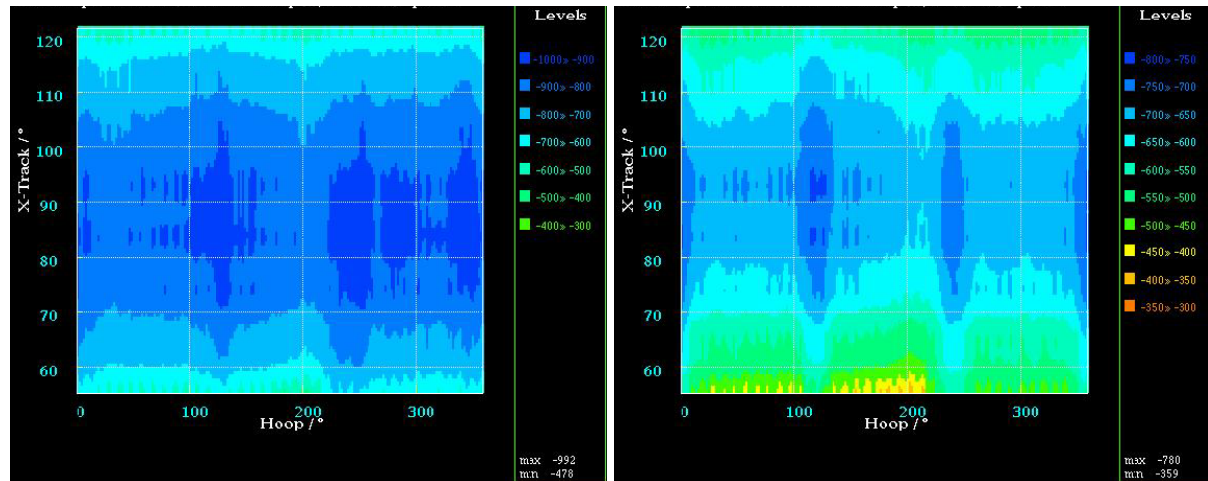


Figure 31. Example of contour mapping of the hoop and ‘cross-track’ stress components measured at 2 mm spatial resolution over the raceway surface, the values confirming expected compressive stress levels. Measurement penetration 26 μm , many thousands of biaxial stress readings collected within an hour of inspection.

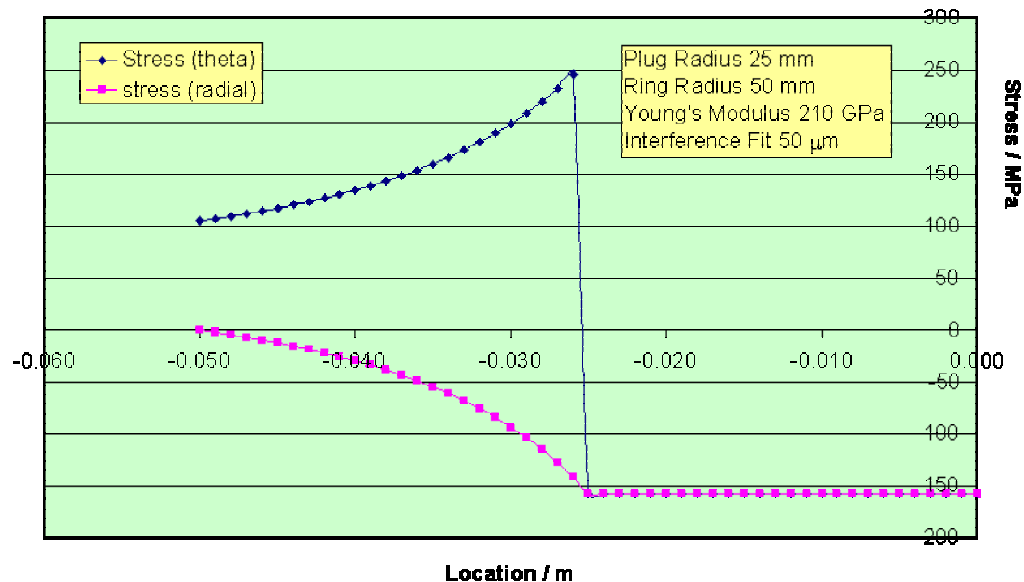


Figure 32. Predicted radial and theta stress levels within the ring and plug sample for an interference fit of 50 μm .

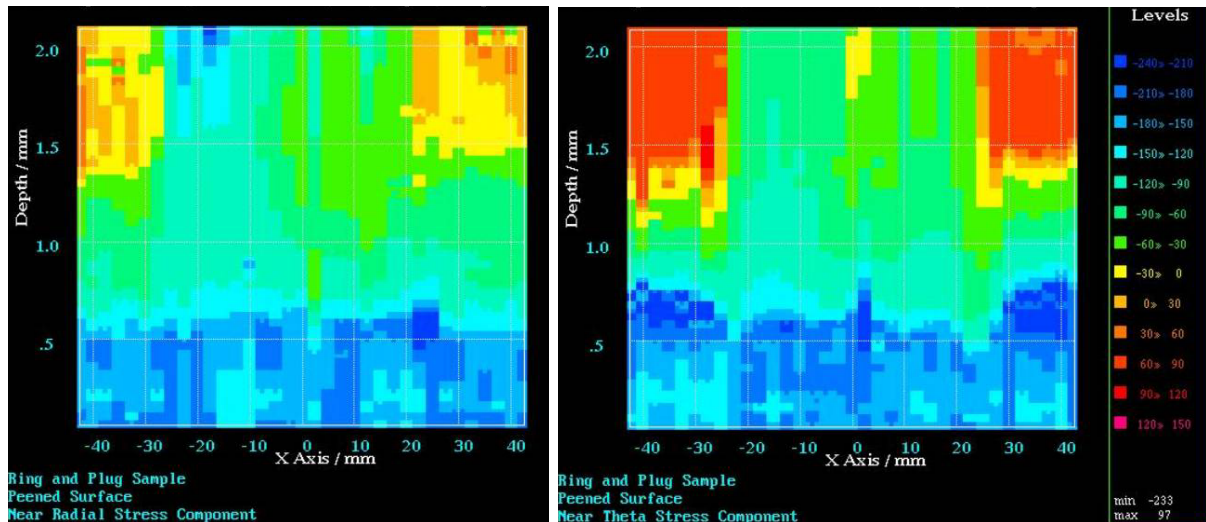


Figure 33. Radial and theta stress components ‘depth deconvolved’ from multi-frequency MAPS measurements on the shot peened ring and plug sample.

18 MBN Stress measurement examples

The MBN stress measurement can be made relatively quickly compared to X-Ray diffraction measurements. However, as mentioned earlier in section 9.2, since the MBN signal depends on the steel type, its microstructural condition and the measurement parameters, it is essential to calibrate the MBN measurement for a each type of application.

18.1 MBN stress calibration using cantilever bending tests

For stress measurements on simple geometries, the MBN calibration can be carried out using cantilever beam bending tests to measure the MBN level at each stress level on the tensile and compressive sides. Figure 34(a-b) shows the typical low frequency MBN profiles at different applied tensile and compressive stress levels for a case-carburised specimen. The low frequency MBN shows two peaks due to the microstructural variation within the case-depth [15]. It can be observed that, in the low frequency MBN measurement, both the MBN peaks increase with the applied tensile stress level and decrease with applied compressive stress. However, the extent of variation in the two peaks differs with increasing stress level due to the changing stress gradient in the depth. Figure 35(a-b) shows typical high frequency MBN profiles at different applied tensile and compressive stress levels in the same case-carburised specimen. In this case the high frequency MBN shows the same stress effect, but it shows only a single peak to its shallow skin-depth. Such MBN calibration can be used to measure residual stress level in simple geometries provided the magnetic hysteresis is not affected by the demagnetisation effect.

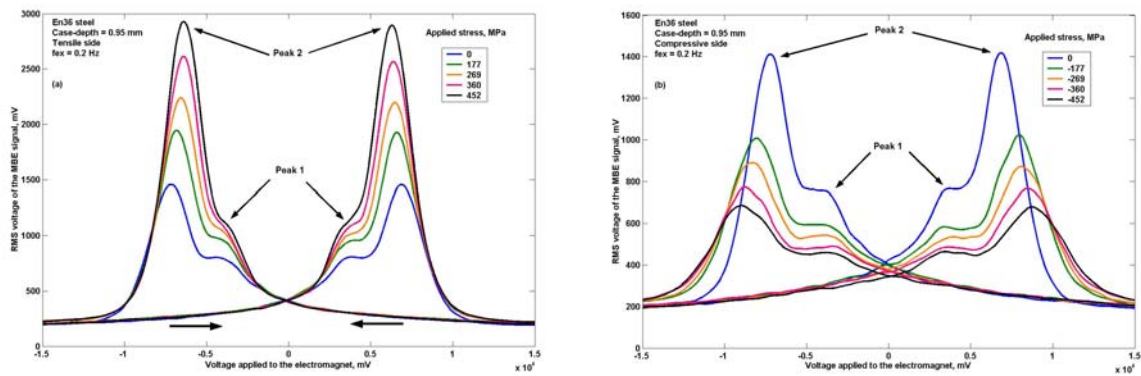


Figure 34. Typical low frequency MBN profiles showing the effect of (a) tensile and (b) compressive applied stresses in a En36 steel case-carburised specimen ($f_{ex} = 0.2\text{ Hz}$, $\Delta f_a = 1\text{--}20\text{ kHz}$).

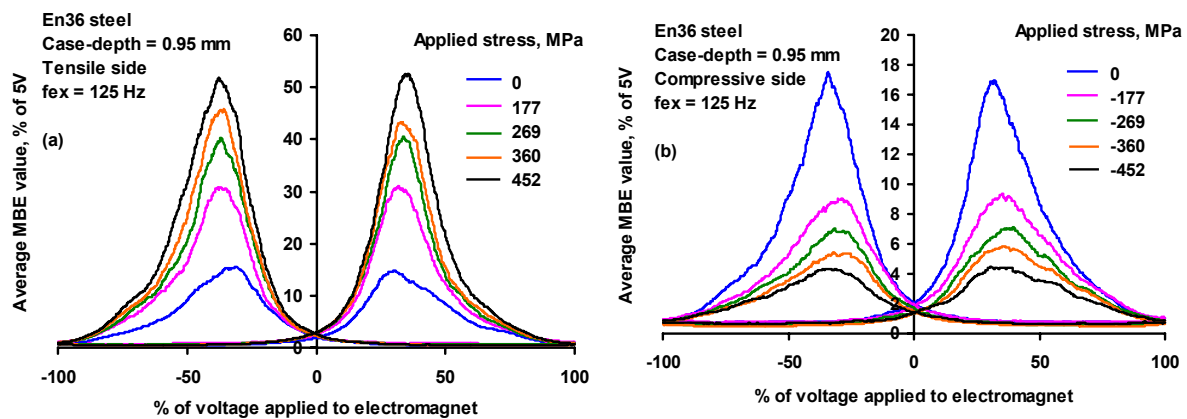


Figure 35. Typical high frequency MBN profiles showing the effect of (a) tensile and (b) compressive applied stresses in a En36 steel case-carburised specimen ($f_{ex} = 125\text{ Hz}$, $\Delta f_a = 70\text{--}200\text{ kHz}$).

18.2 MBN measurement for assessing grinding damage induced residual stress variations

MBN has been successfully used to evaluate the residual stress variation induced by grinding, and Figures 36 and 37 show the high and low frequency MBN profiles in four case-carburised bar specimens having varying level of grinding damages. The grinding damage results in thermal damage and/or changes to the residual stress distribution. Because any introduction of tensile stress is detrimental, the MBN measurement can be used to easily identify the grinding damage. Figure 38 shows the residual stress distribution through the near surface layers measured by X-ray diffraction method in these four specimens. The high frequency MBN clearly indicates the variation in the surface residual stress level. Specimen D3B shows the highest MBN level corresponding to a high tensile residual stress on the surface and the specimen D3T shows the lowest MBN level corresponding to the largest compressive residual

stress on the surface. The specimens D2T and D2B show more or less the same MBN level due to similar surface residual stress.

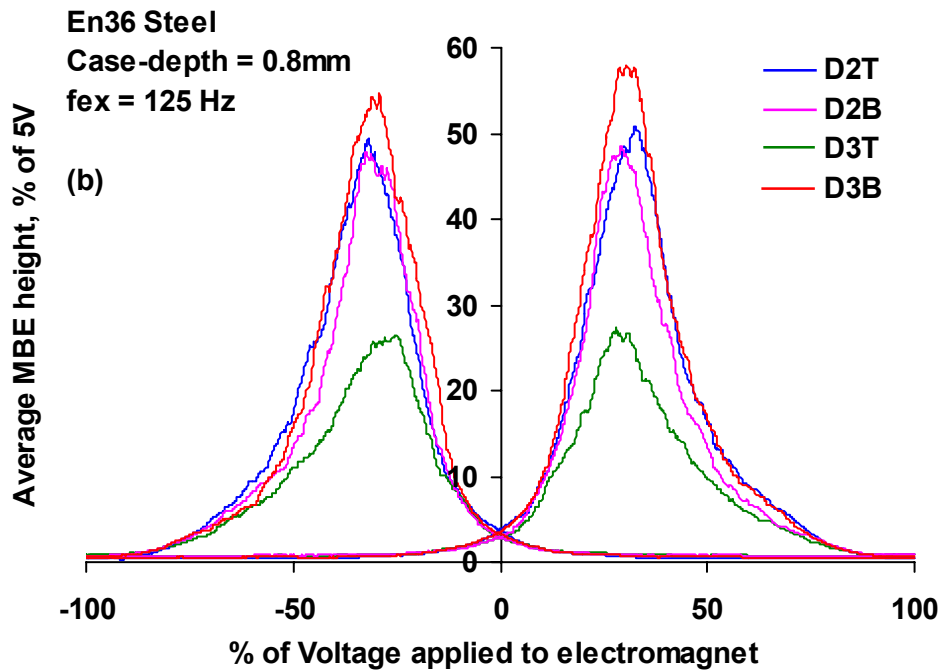


Figure 36. High frequency MBN profiles in four case-carburised bar specimens having varying level of grinding damages.

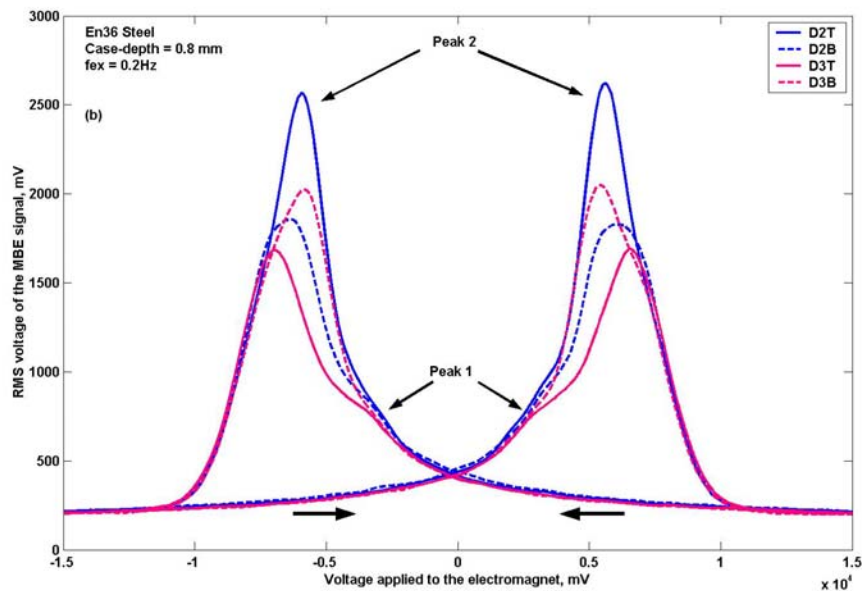


Figure 37. Low frequency MBN profiles in four case-carburised bar specimens having varying level of grinding damages.

It would be interesting to note the difference between the high frequency MBN and low frequency MBN profiles. It can be observed from Fig.37 that the specimen D2T shows the highest MBN peak corresponding to highest level of tensile residual stresses below the

surface (Fig.38), but this is not revealed by the high frequency MBN, due to the larger detection depth of the low frequency MBN signal.

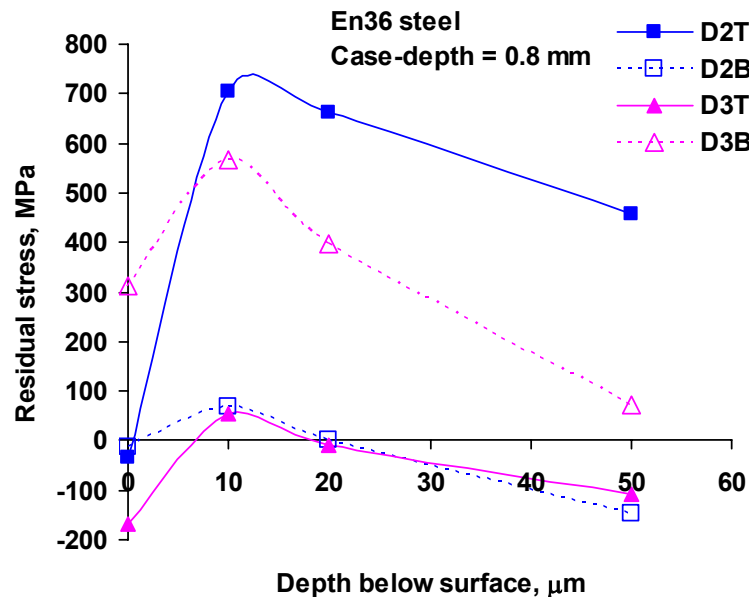


Figure 38. Residual stress – Depth variation in four case-carburised bar specimens having varying level of grinding damages.

The high frequency MBN can be used easily to assess any significant variations in the near-surface residual stress levels. It is also possible to scan the entire component surface quickly to evaluate the residual stress variations. Figure 39 shows the variation in the high frequency MBN level at different locations in a gear. The high MBN level indicates the location having high tensile residual stresses caused by severe grinding damage.

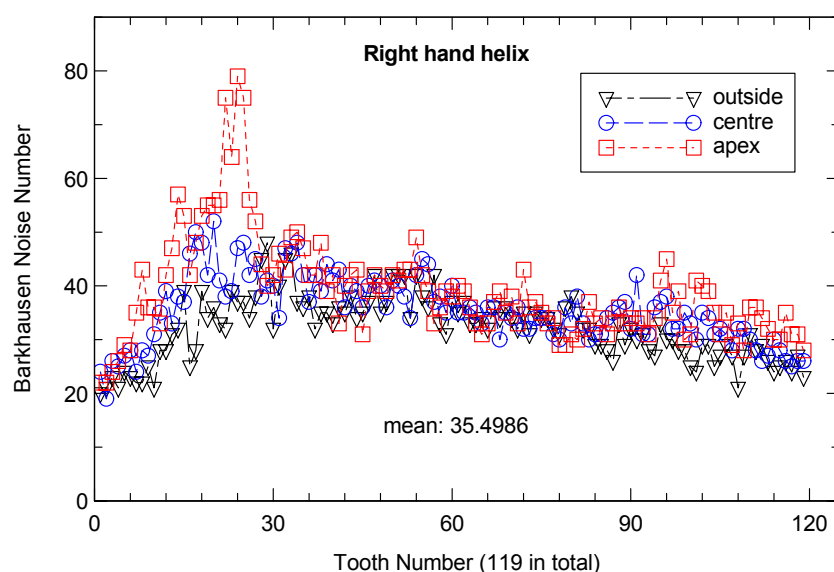


Figure 39. Variation in high frequency MBN level at different locations in a gear.

