Sensor fusion for electromagnetic stress measurement and material characterisation

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Abstract

Detrimental residual stresses and microstructure changes are the two major precursors for future sites of failure in ferrous steel engineering components and structures. Although numerous Non-Destructive Evaluation (NDE) techniques can be used for microstructure and stress assessment, currently there is no single technique which would have the capability to provide a comprehensive picture of these material changes. Therefore the fusion of data from a number of different sensors is required for early failure prediction Electromagnetic (EM) NDE is a prime candidate for this type of inspection, since the response to Electromagnetic excitation can be quantified in several different ways: e.g. eddy currents, Barkhausen emission, flux leakage, and a few others.

This chapter reviews the strengths of different electromagnetic NDE methods, provides an analysis of the different sensor fusion techniques such as sensor physical system fusion through different principles and detecting devices, and/or feature selection and fusion, and/or information fusion. Two sensor fusion case studies are presented: pulsed eddy current thermography at sensor level and integrative electromagnetic methods for stress and material characterisation at feature (parameters) level.

1. Introduction

In recent years, non-destructive testing and evaluation (NDT&E) techniques have been developed which allow quantitative analysis of the stresses acting on a material; either through direct measurement of displacement (strain measurement)[(1)] or measurement of material properties which interact with stress and can therefore be used to indicate the material stress state. The second category includes magnetic[(2)] and electromagnetic (induction) NDT&E inspection techniques which allow the quantification of material stresses through magnetic and electrical properties, including magnetic permeability μ, electrical conductivity σ and domain wall motion. Although magnetic and electromagnetic techniques are promising candidates for stress measurement, the fact that the stress measurement is performed indirectly, means the relationship between the measured signal and stress is complex and heavily dependent on material microstructure, thus material-specific calibration is almost always required.

Because of the complex nature of the mechanisms which contribute to cracking, degradation and material stresses, the use of more than one NDE methods is often required for comprehensive assessment of a given component. The development of fusion techniques to integrate signals from different sources has the potential to lead to a decrease in inspection time and also a reduction in cost. Gathering of data from multiple systems coupled with efficient processing of information can provide great advantages in terms of decision making, reduced signal uncertainty and increased overall performance. Depending on the different physical properties measured, fusion techniques have the benefit that each NDE modality reveals different aspects of the material under inspection. Therefore professional processing and integration of defect information is essential, in order to obtain a comprehensive diagnosis of structural health.

With research and development in NDE through a wide range of applications for engineering and medical sciences, conventional NDT&E techniques have illustrated different limitations, e.g. ultrasonic NDT&E needs media coupling, eddy current NDT&E can only be used to inspect surface or near surface defects in metallic or conductive objects, etc. As industrial applications require inspection and monitoring for large, complex safety critical components and subsystems, traditional off-line NDT and quantitative NDE for defect detection cannot meet these needs. On-line monitoring e.g. structural health monitoring (SHM) for defects, as well as precursors e.g. material abnormal status for life cycle assessment and intelligent health monitoring is required. Recent integrative NDE techniques and fusion methods have been developed to meet these requirements [(3)].

Information fusion can be achieved at any level of signal information representation. As a sensor system includes the sensing device itself, signal conditioning circuitry and feature extraction and characterisation algorithms for decision making, sensor fusion should include: sensor physical system fusion through different excitation and detecting devices [(4, 5)]; sensor data or image pixel-level fusion through arithmetic fusion algorithms e.g. adding, subtraction, multiplication etc[(6, 7)]; feature selection and combination from sensor data features[(8, 9, 10)]; information fusion through case studies[(10, 11)]. Signal level data fusion, represents fusion at the lowest level, where a number of raw input data signals are combined to produce a single fused signal. Feature level fusion, fuses feature and object labels and property descriptor information that have already been extracted from individual input sensors. Finally, the highest level, decision level fusion refers to the combination of decisions already taken by individual systems. The choice of the fusion level depends mainly upon the application and complexity of the system.

In this chapter, three different applications of electromagnetic NDE sensor fusion are discussed and the benefits of the amalgamation of different electromagnetic NDE techniques are examined. In section 2, three kinds of sensor fusion are reported: Section 2.1. introduces PEC thermography using integrative different modality NDE methods; Section 2.2 looks at

Magnetic Barkhausen Emission (MBE) and Magneto-Acoustic Emission (MAE) for microstructural determination using different sensing devices for material characterisation, and in section 2.3, the theoretical links between electromagnetic properties, stress and microstructural changes using features or parameters from PEC and MBE for the quantification of stresses and microstructure are examined. In section 3 a summary of sensor fusion in ENDE is given.

2. Integrative electromagnetic NDE techniques

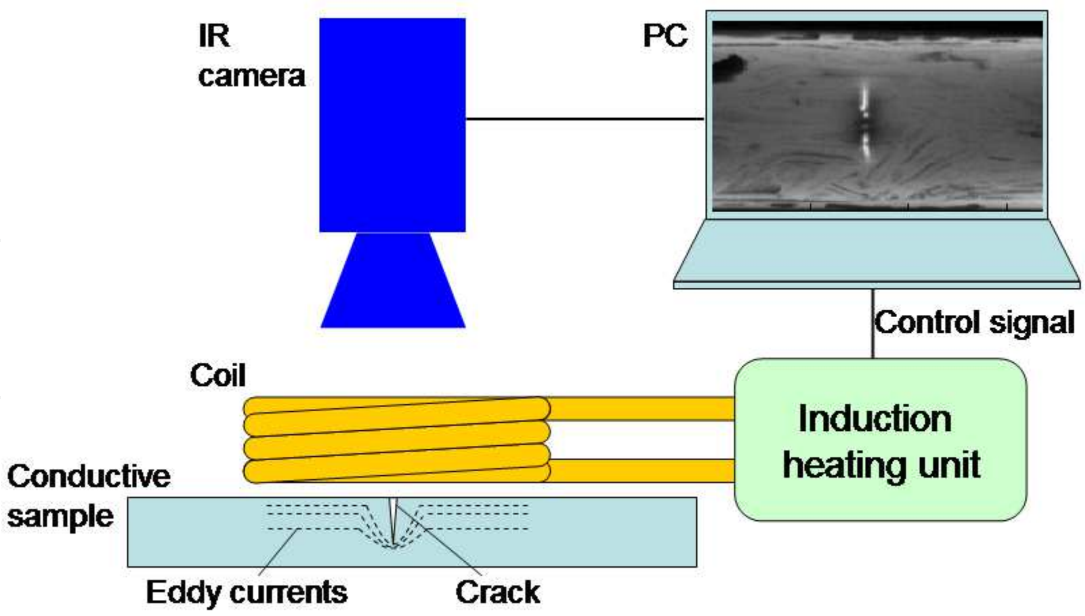
In this section, experimental results are presented for three different integrative NDE techniques, offering potential solutions to the problems associated with the attempt to gain a full understanding of material status from the application of a single technique. Sensor electromagnetic NDE fusion at the sensor system level, feature extraction, modality features and information are discussed.

2.1 Pulsed eddy current thermography

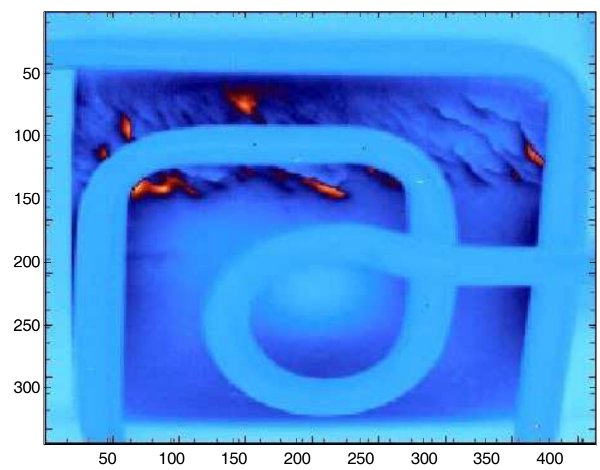
Pulsed eddy current (PEC) thermography[4, 5] is a new technique which uses thermal camera technology to image the eddy current distribution in a component under inspection. In pulsed eddy current (a.k.a. induction) thermography, a short burst of electromagnetic excitation is applied to the material under inspection, inducing eddy currents to flow in the material. Where these eddy currents encounter a discontinuity, they are forced to divert, leading to areas of increased and decreased eddy current density. Areas where eddy current density is increased experience higher levels of Joule (Ohmic) heating, thus the defect can be identified from the IR image sequence, both during the heating period and during cooling. In contrast to flash lamp heating, in PEC thermography there is a direct interaction between the heating mechanism and the defect. This can result in a much greater change in heating around defects, especially for vertical, surface breaking defects. However, as with traditional eddy current inspection, the orientation of a particular defect with respect to induced currents has a strong impact; sensitivity decreases with defect depth under the surface and the technique is only applicable to materials with a considerable level of conductivity (ferrous and non-ferrous metals and some conductive non-metals, such as carbon fibre).

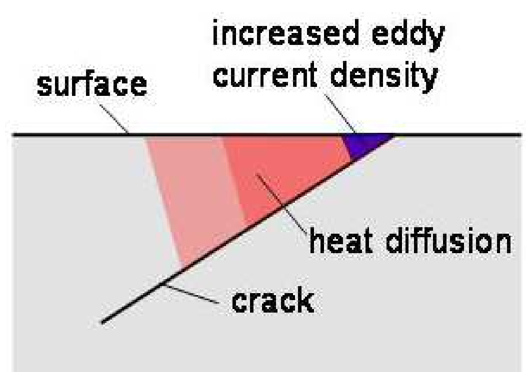
Figure 1a shows a typical PEC thermography test system. A copper coil is supplied with a current of several hundred amps at a frequency of 50kHz – 1MHz from an induction heating system for a period of 20ms – 1s. This induces eddy currents in the sample, which are diverted when they encounter a discontinuity leading to areas of increased or decreased heating. The resultant heating is measured using an IR camera and displayed on a PC.

Figure 1b shows a PEC thermography image of a section of railtrack, shown from above. It can be seen that the technique has the ability to provide a “snapshot” of the complex network of cracking, due to wear and rolling contact fatigue (RCF) in the part. It is well known that in the initial stages, RCF creates short cracks that grow at a shallow angle, but these can sometimes grow to a steep angle. This creates a characteristic surface heat distribution, with the majority of the heating on one side of the crack only. This is due to two factors, shown in figure 1c; a high eddy current density in the corner of the area bounded by the crack and an increase in heating, due to the small area available for diffusion.



(a)





(b) (c)

Fig. 1. a) PEC thermography system diagram, b) PEC thermography image of gauge corner cracking on a section of railtrack, c) Eddy current distribution and heat diffusion around angular crack

This ability to provide an instantaneous image of the test area and any defects which may be present is an obvious attraction of this technique, but further information can be gained through the transient analysis of the change in temperature in the material. The sample shown in figures 2a and 2b is made from titanium 6424 and contains a 9.25mm long semicircular (half-penny) defect with a maximum depth of around 4.62mm. The crack is formed by three point bending technique and the sample contains a 4mm deep indentation on the opposite side to the crack, to facilitate this process. Figure 2d shows the transient temperature change in five positions in the defect area, defined in figure 2c. It can be seen from the plot that different areas of the crack experience a very different transient response, corresponding to the combined effects of differing eddy current distributions around the crack and differing heat diffusion characteristics. This shows that the technique has the potential to offer both near-instantaneous qualitative defect images and quantitative information through transient analysis.

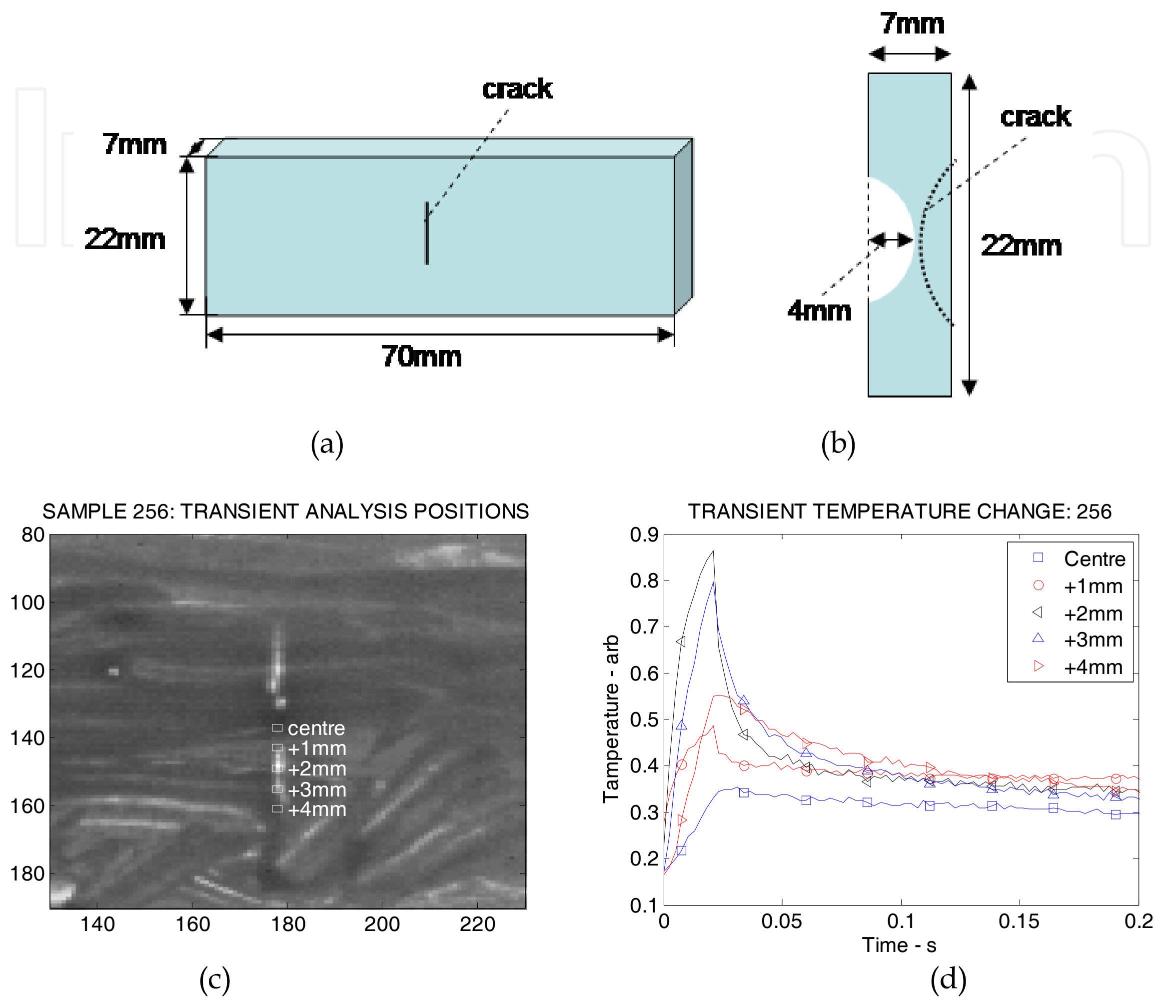


Fig. 2. Inspection of Ti 6424 sample; a) Front view, b) Cross section, c) Positions for transient analysis, d) Transient temperature change in different positions on the sample surface

2.2. Potential for fusion of MBE and MAE for microstructural characterisation

Although MBE and MAE are both based on the sensing of domain wall motion in ferromagnetic materials in response to a time varying applied magnetic field, the two techniques have important differences when applied to stress measurement and microstructural evaluation. Due to the skin effect, MBE is a surface measurement technique with a maximum measurement depth below 1mm and a strong reduction in sensitivity with increased depth. As MAE is essentially an acoustic signal, it does not suffer from the same restrictions as MBE and can be considered to be a bulk measurement technique. The interpretation of MAE can however, be complex, thus the implementation of a combination of the two techniques is advisable.

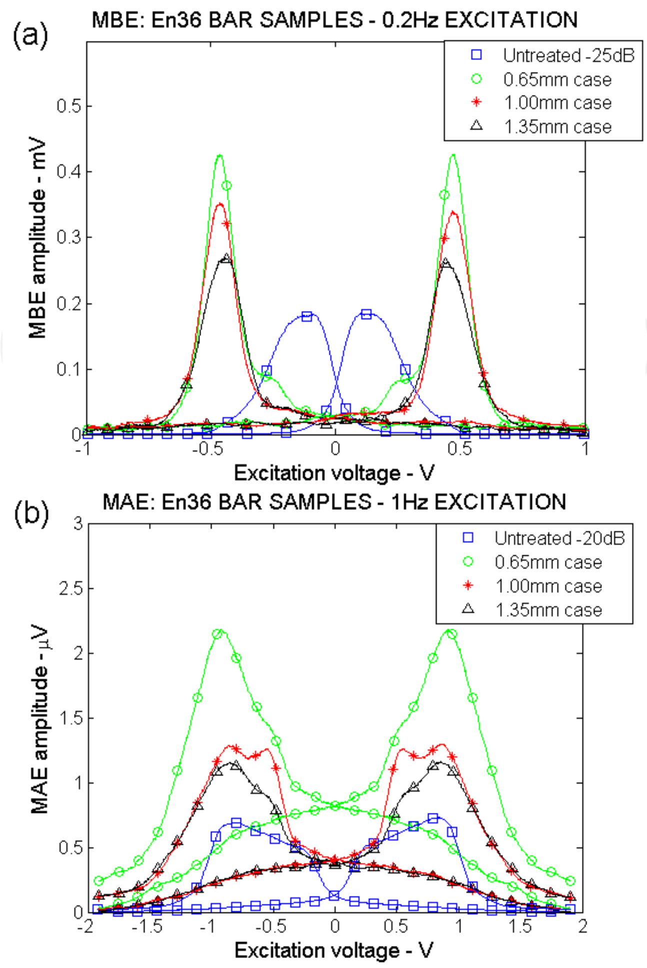


Fig. 3. MBE (a) and MAE (b) profiles measured on En36 gear steel samples of varying case depths

Figure 3 shows the results from a set of tests to quantify the case hardening depth in En36 gear steel. It can be seen from the plot that for case depths >0.64mm, the shape of the MBE profile remains the same, indicating that the case depth has exceeded the measurement depth, whereas for MAE, the profile shape continues to change up to the maximum depth of 1.35mm, indicating a greater measurement depth for this technique.

2.3. Complementary features of PEC and MBE for stress measurement

In this section selected results from a series of tests to quantify tensile stresses in mild steel are reported. Figures 4b and 5a show the change in the non-normalised PEC maximum ΔB_Z and the MBE_{ENERGY} respectively. Both results exhibit the greatest change within the first 100MPa of applied elastic tensile stress. This is due to a large initial change in permeability for the initial application of tensile stress. This is confirmed by examination of Figure 5c, where an initial shift in the peak 1 position towards a lower voltage and a corresponding increase in peak 1 amplitude indicates maximum domain activity at an earlier point in the applied field cycle, though this trend is reversed as stresses are increased. As the material under inspection is an anisotropic rolled steel this large initial permeability change is thought to be due to the rotation of the magnetic easy axis towards the applied load direction in the early stages of the test. The two peak activity which is observable in Figure

5c indicates that two different mechanisms are responsible for the change in MBE with stress. The peaks exhibit opposite behaviour; peak 1 increases with stress, whereas peak 2 decreases with stress. This indicates that each peak is associated with a different microstructural phase and / or domain configuration, active at a different point in the excitation cycle.

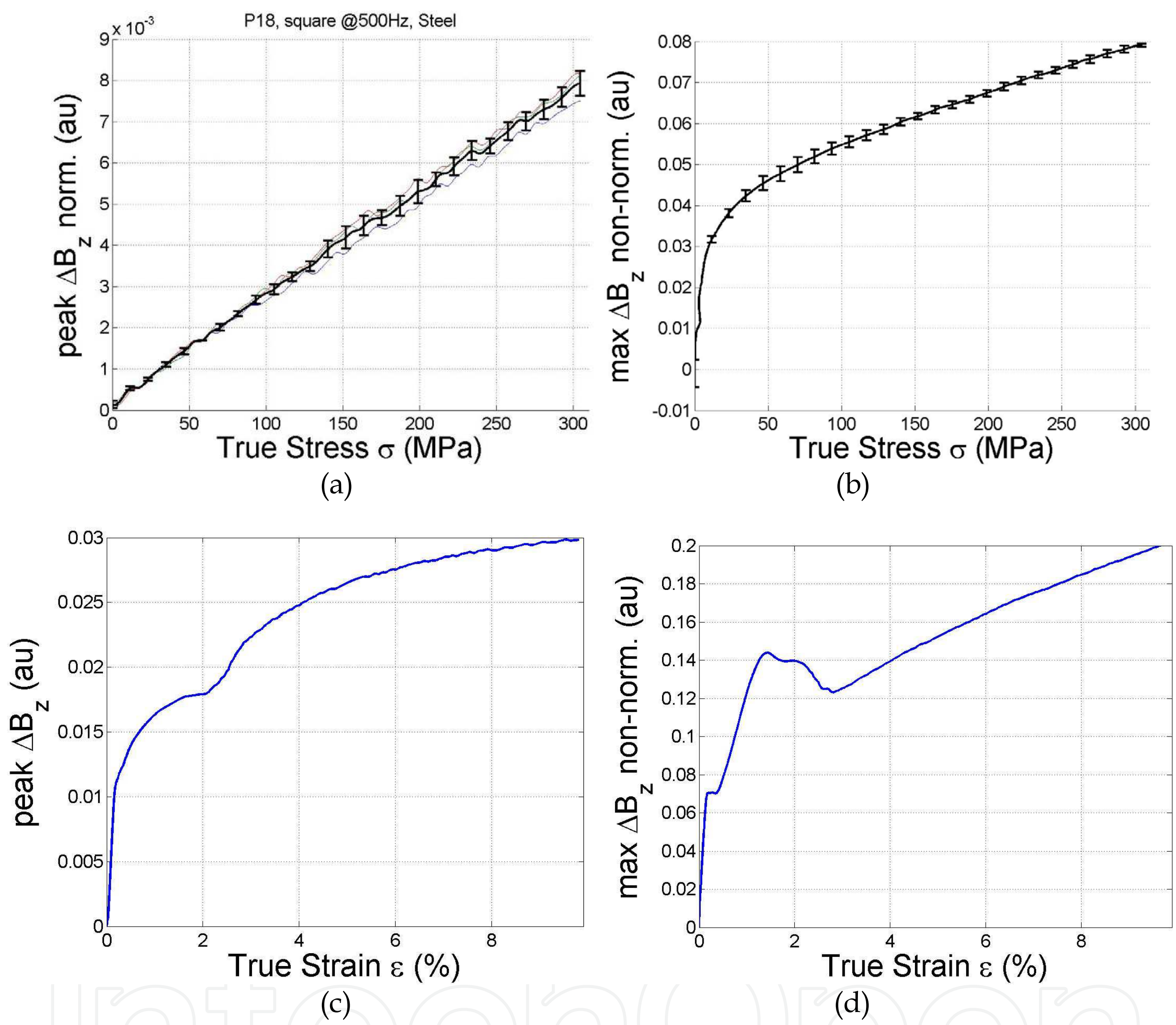


Fig. 4. Results of PEC measurements on steel under elastic and plastic deformation; a) Normalised PEC response *peak*(ΔB^{NORM}),under elastic stress; (b) Non-normalised PEC response *max*($\Delta B^{NON\text{-}NORM}$) under elastic stress, a) Normalised PEC response *peak*(ΔB^{NORM}) under plastic strain (b) Non-normalised PEC response *max*($\Delta B^{NON\text{-}NORM}$) under plastic strain

Figure 5b shows the change in MBE_{ENERGY} for plastic stress. The MBE_{ENERGY} exhibits a large increase in the early stages of plastic deformation indicating a change in the domain structure due to the development of domain wall pinning sites, followed by a slower increase in MBE_{ENERGY} as applied strain increases. Figure 5d shows the development of the MBE profile for an increase in plastic stress. It can be seen from the plot that as plastic deformation increases, the overall amplitude of the MBE profile increases, corresponding to the increase in MBE_{ENERGY}. It can also be seen that the increase in overall amplitude is coupled with a shift in peak position with respect to the excitation voltage. This change in the MBE profile is due to the development of material dislocations increasing domain wall pinning sites, leading to higher energy MBE activity later in the excitation cycle. Examination of this in peak position has shown that it has a strong correlation to the stress/strain curve in the plastic region.

The dependence of the MBE peak position qualitatively agrees with the dependence of *max*($\Delta B^{NON\text{-}NORM}$) as a function of strain shown in Figure 4d. These dependencies decrease according to the tensile characteristics in the yielding region and therefore it has the same value for two different strains, which makes it difficult to quantify the PD. However the dependence of *peak*(ΔB^{NORM}) as function of strain, shown in Figure 4c, increases in the same region which provides complimentary information and enables PD characterisation using two features proportional to the magnetic permeability and electrical conductivity respectively.

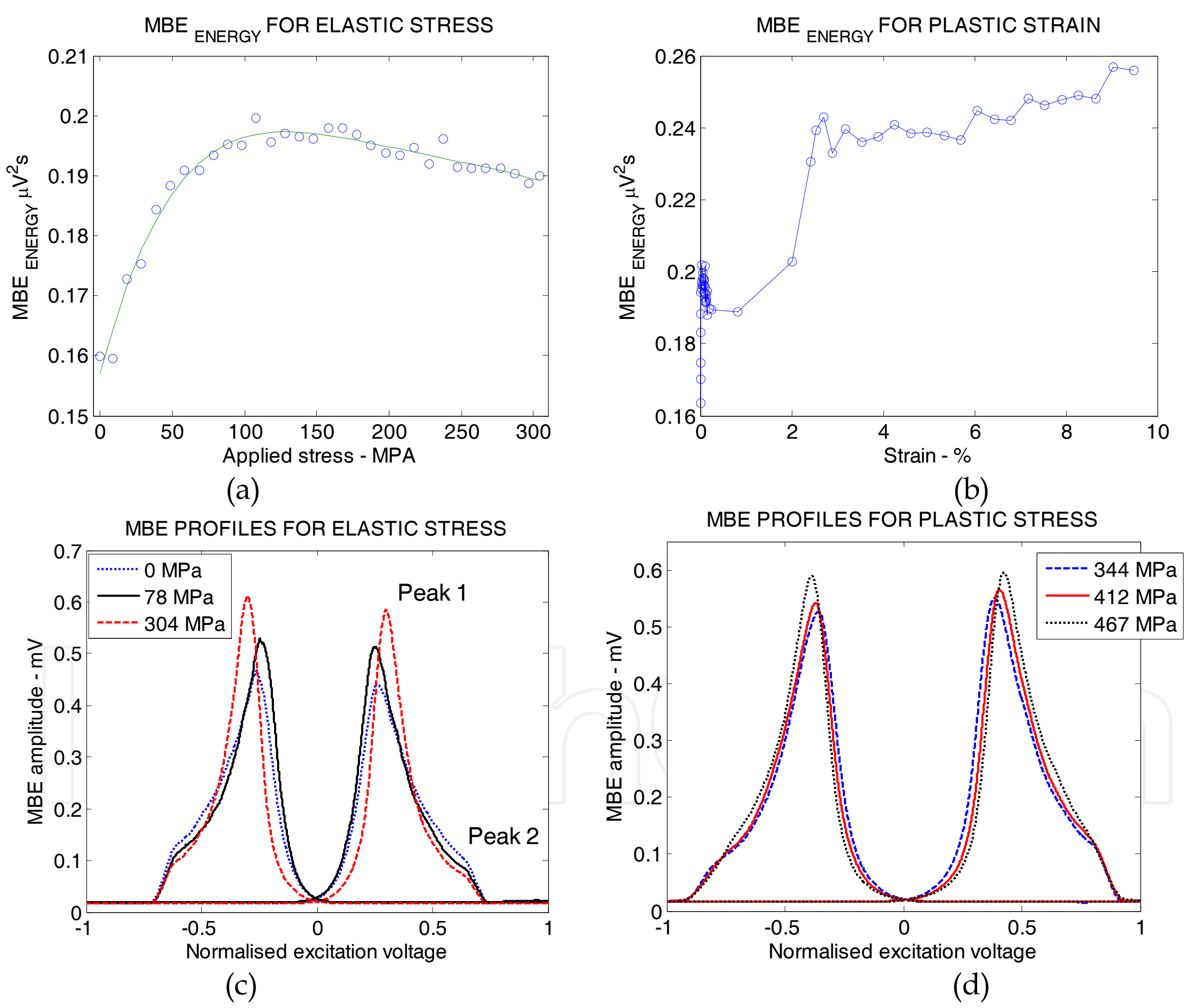


Fig. 5. Results of MBE measurements on steel under elastic and plastic deformation; a) MBE_{ENERGY} for elastic stress, b) MBE_{ENERGY} for plastic strain, c) MBE profiles for elastic stress, c) MBE profiles for plastic stress

These results illustrate the complementary nature of these two electromagnetic NDE techniques. PEC can be used for simple stress measurement, but to gain a full picture of the microstructural changes in the material, MBE profile analysis should be employed. Thus, fusion of PEC and MBE in a single system, with a common excitation device and a combined MBE/PEC pickup coil has the potential to provide comprehensive material assessment. This fusion technique has been used for the second Round Robin test organised by UNMNDE (*Universal Network for Magnetic Non-Destructive Evaluation*) for the characterisation of material degradation and ageing

3. Sensor fusion for electromagnetic NDE

Many attempts have been made at sensor and data fusion for NDE applications, with varying levels of success. Previous work[9] reports the development of a dual probe system containing an electromagnetic acoustic transducer (EMAT) and a pulsed eddy current (PEC) transducer. EMATs have excellent bulk inspection capabilities, but surface and near surface cracks can be problematic, whereas the PEC system can accurately characterise surface breaking cracks (as well as deep subsurface ones), thus PEC data was used to characterise near surface defects and EMAT data was used to characterise deep defects. The nature of PEC means that it also lends itself to the extraction of different features from the same signal. Hilbert transform and analytic representation are used to extract a variety of features from the PEC signal in order to characterise metal loss and subsurface defects in aluminium samples. Paper [12] reports the influence of duty cycle on the ability to detect holes and EDM notches beneath rivet heads in subsurface layers of stratified samples. The works highlight the gains that can be made from feature fusion if clear correlations are established between material / defect properties and signal features prior to fusion.

MBE has the capability to provide stress and microstructure information, but has a low measurement depth (up to 1 mm), a weak correlation with defects and the determination of exact correlations between signal features and material properties can be difficult without a full range of calibration samples; consequently the combination of MBE with other inspection techniques has received some attention in recent years. Quality Network, Inc. (QNET), the marketing and services affiliate of the Fraunhofer Institute for Non-Destructive Testing (IZFP) has introduced the multi-parameter micro-magnetic microstructure testing system (3MA)[13]. The 3MA system is optimised to measure surface and subsurface hardness, residual stress, case depth and machining defects through simultaneous measurement of MBE, incremental permeability, tangential magnetic field strength and eddy current impedance. As 3MA is a commercial system, exact details of the 3MA operational parameters are not available, but it is implied in the literature that variations in excitation field strength and frequency is used to control measurement depth and the measured parameters are combined using a multiple regression technique.

Chady et al. have assessed the comparative strengths of MBE, ECT, flux leakage and Hysteresis loop measurement for the characterisation of fatigue failure through cyclic dynamic loading of S355J2G3 structural steel [14]. Pixel level fusion of the scan results from the different inspection techniques was performed and it was found that fusion of all the signals creates opportunity to detect and evaluate quantitatively a level of material degradation.

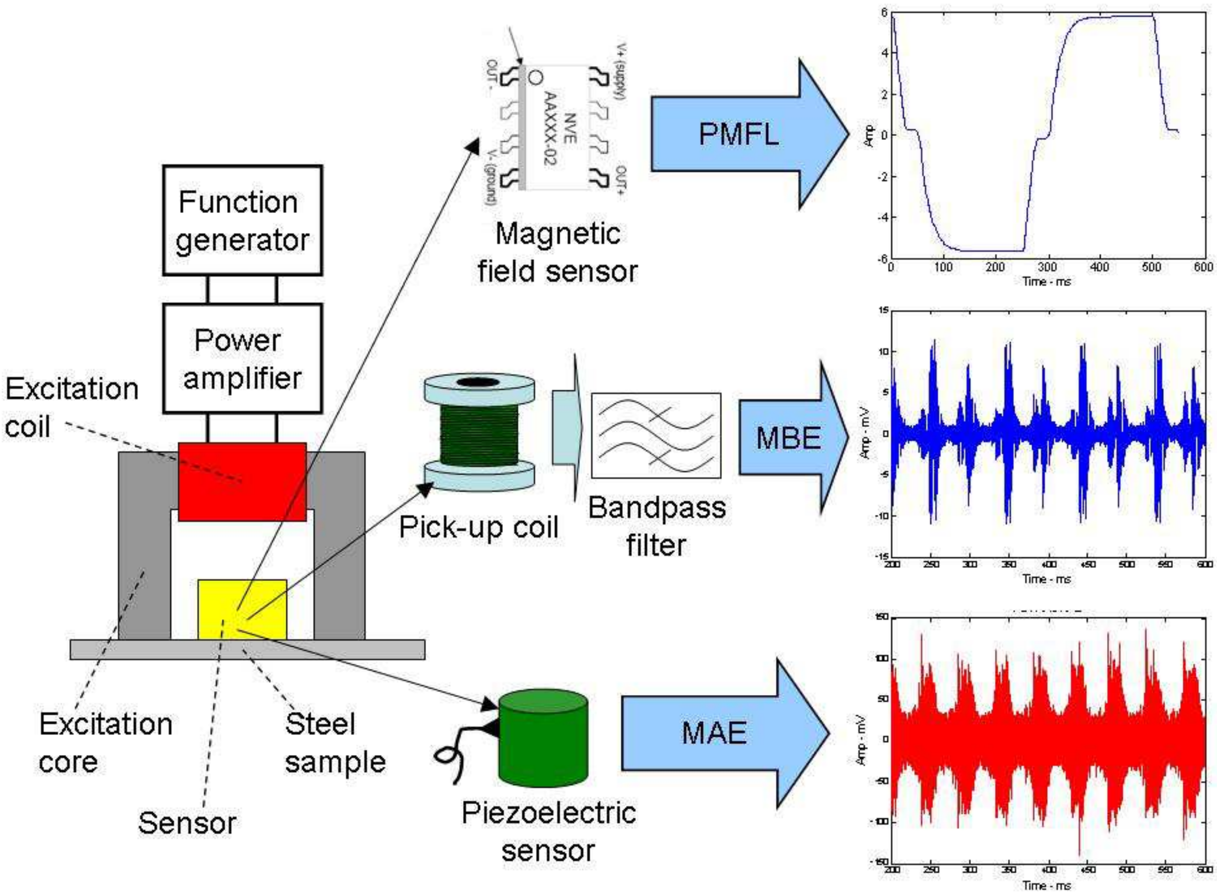


Fig. 6. Sensor fusion for comprehensive evaluation of defects and material properties

In addition to the sensor or data fusion above, Figure 6 shows an example of how sensor fusion can be used to implement a comprehensive material assessment system. A common excitation device is used to apply an electromagnetic field to the material under assessment and the response of the material is measured in several different ways. Firstly, a magnetic field sensor, operating as a pulsed magnetic flux leakage (PMFL)(15) sensing device, is used to measure the tangential magnetic field. This signal is analysed to extract information and quantify any surface, subsurface or opposite side defects which may be present. Secondly, the field at the surface of the material is measured using a coil, the measured signal is then band-pass filtered to reject the low frequency envelope and isolate the Barkhausen emission signal. This can then be used to characterise surface material changes, such as surface residual stresses and microstructural changes, i.e. degradation, corrosion, grinding burn. Using MBE, these changes can be quantified up to a depth of around 1mm. Bulk stress/microstructure changes are quantified using a piezoelectric sensor to measure magneto-acoustic emission, thus by comparing MBE and MAE measurements(16), bulk and surface changes can be separated and quantified.

The capability to simultaneously measure defects and surrounding stresses is especially useful where stress corrosion cracking (SCC) is expected. Residual stress concentrations, along with information on existing cracks and their surrounding stresses can be used to identify sites of potential future failure by identifying crack precursors.

4. Conclusions

Sensor fusion for electromagnetic NDE at different stages and levels has been discussed and three case studies for fusion at sensor and feature levels have been investigated. Instead of applying innovative mathematical techniques to utilise multiple sensors to improve the fidelity of defect and material characterisation, physics based sensor fusion is investigated. It has been shown that the three types of sensing system fusion, feature selection and integration and information combination for decision making in Quantitative NDE and material characterisation have different complementary strengths. Our future research efforts will explore the platform of features (parameters) of the signatures from the multimodal sensor data spaces using physical models and mathematic techniques for different engineering and medical challenges, including quantitative non-destructive evaluation, structural health monitoring, target detection and classification, and non-invasive diagnostics.

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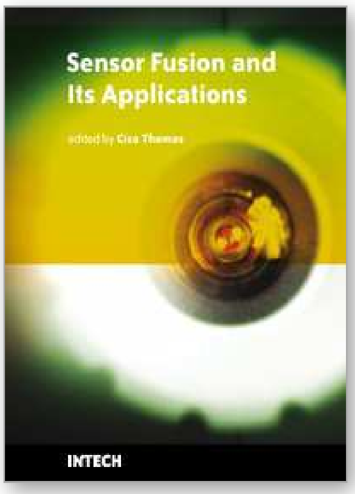

Sensor Fusion and its Applications
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This book aims to explore the latest practices and research works in the area of sensor fusion. The book intends to provide a collection of novel ideas, theories, and solutions related to the research areas in the field of sensor fusion. This book is a unique, comprehensive, and up-to-date resource for sensor fusion systems designers. This book is appropriate for use as an upper division undergraduate or graduate level text book. It should also be of interest to researchers, who need to process and interpret the sensor data in most scientific and engineering fields. The initial chapters in this book provide a general overview of sensor fusion. The later chapters focus mostly on the applications of sensor fusion. Much of this work has been published in refereed journals and conference proceedings and these papers have been modified and edited for content and style. With contributions from the world's leading fusion researchers and academicians, this book has 22 chapters covering the fundamental theory and cutting-edge developments that are driving this field.

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