Recent advances in magnetic non-destructive testing and the application of this technique to remanufacturing

Article *in* Insight - Non-Destructive Testing and Condition Monitoring · August 2018

DOI: 10.1784/insi.2018.60.8.451

2 authors:

Haihong Huang
Hefei University of Technology

Zhengchun Qian
Hefei University of Technology

DOI: 10.1784/insi.2018.60.8.451

Recent advances in magnetic non-destructive testing and the application of this technique to remanufacturing

Haihong Huang and Zhengchun Qian

As an emerging green technology, remanufacturing has received increasing attention worldwide due to its energy-saving and waste-reducing benefits in manufacturing processes. Core damage assessment and repair quality evaluation are two important issues in remanufacturing. Magnetic non-destructive testing (NDT) has positive effects on remanufacturing quality control because of its unique detection advantages. Three magnetic NDT technologies, namely the magnetic memory method (MMM) and the use of magnetic Barkhausen noise (MBN) and magnetoacoustic emission (MAE), are introduced in this study. An overview of the fundamentals and recent advances of these magnetic NDT technologies are provided based on a literature review of over 100 references published from 2000 to 2017 in various academic journals. Their present and potential applications in remanufacturing engineering are then summarised and compared and existing problems and prospects are presented.

Keywords: non-destructive testing, remanufacturing, magnetic memory method (MMM) , magnetic Barkhausen noise, magnetoacoustic emission.

1. Introduction

Global environmental pollution and resource scarcity have become increasingly serious at present. Meanwhile, many pieces of mechanical equipment have been scrapped from various industries, including the automobile, shipping, aerospace and petroleum industries. Taking China as an example, official statistical data from the China Construction Machinery Association in 2014 indicated that product ownership of engineering machinery reached as high as 7 million, 80% of which exceeded warranty. Moreover, approximately 1.2 million devices are scrapped annually. Maximising the usefulness of waste products is the key to improving the resource utilisation level against the new background. Remanufacturing, an emerging green technology, is defined as a series of processes that allows end-of-life products and parts to be recommercialised as new products with the same quality, functionality and warranty[1-2]. The main remanufacturing process consists of disassembling, cleaning, inspecting, repairing and reassembling (Figure 1). Compared with the products of the traditional manufacturing industry, remanufactured products can reduce cost by 50%, save more than 60% in energy consumption and 70% in materials and reduce emissions by 80%. Consequently, remanufacturing exhibits an affinity to the concepts of sustainable production and sustainable society and has been attracting increasing attention worldwide[2]. For example, the USA owns the largest industry scale, which exceeds US$75 billion[3], Europe enforces recycling and remanufacturing laws for waste automotive parts, Japan exports one-third of its remanufactured products, earning high profits from such practice[4], and China has exerted immense efforts in recent years to promote the sustainable and healthy development of the remanufacturing industry based on the 'Made in China 2025' plan.

As shown in Figure 1, remanufacturing cores disassembled from used products should be inspected before repairing. Cores that satisfy remanufacturability requirements will be restored to their original specifications via a series of repairing techniques, including laser cladding, plasma spraying, plasma transferred arc welding and electroplating deposit. During the repairing process, a cladding coating is prepared by these surface engineering technologies on the damaged surface of the cores so that their performance can be improved and the remanufactured parts can remain in service[5]. Therefore, quality control and evaluation of the remanufacturing process is essential because they are directly related to determining whether the reliability of remanufactured parts can meet the standard for new parts. From the perspective of remanufacturing engineering, inspection plays a key role in assessing the damage degree and repair quality of the cores, in order to ensure that the remanufacturing process proceeds smoothly.

A non-destructive testing (NDT) technique, which can detect flaws from the interior or surface of a component based on the

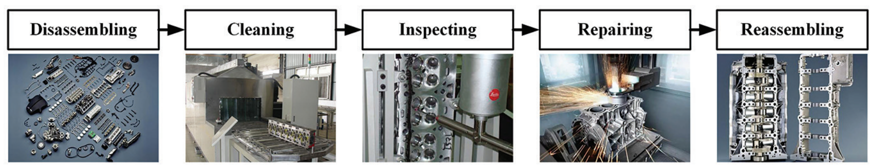


Figure 1. Typical remanufacturing process

Submitted 27.09.17 / Accepted 16.02.18

Haihong Huang and Zhengchun Qian are with the School of Mechanical Engineering, Hefei University of Technology, Hefei 230009, China.*

**Corresponding author. Email: huanghaihong@hfut.edu.cn; Tel: +86 0551 62901351.*

variations of heat, sound, light, electricity or magnetism attributed to unusual structures and defects, is essential. At present, there are several conventional NDT techniques, including penetrant, magnetic particle, radiographic, eddy current and ultrasonic testing. Each NDT technique has its own limitations when it is applied to remanufacturing. For example, penetrant and magnetic particle testing can only find the surface defects, such as macro-cracks and pores, instead of inner defects. Radiographic testing is limited by high cost, low efficiency and radiation hazards. Eddy current testing is not applicable to detect the complicated structures of remanufacturing cores and ultrasonic testing may not find the defects in the remanufacturing cladding coating with columnar crystals and dendrites, for which anisotropy affects the propagation of sound waves. Fortunately, magnetic NDT can overcome the weaknesses of the aforementioned conventional NDT techniques when applied to remanufacturing.

The remainder of this paper is organised as follows. The advantages of magnetic NDT in remanufacturing are explained in Section 2. The physical mechanisms of the three types of magnetic NDT techniques are introduced in detail in Section 3, along with their recent research advances. The present and potential applications of these techniques to remanufacturing engineering are summarised and compared in Section 4. Existing problems and prospects are discussed in Section 5. Finally, a conclusion of the study is presented in Section 6.

2. Advantages of magnetic NDT in remanufacturing

Ferromagnetic materials are widely used in mechanical structures, particularly in the nuclear, aerospace and military fields, because of their considerable strength, hardness, plasticity and other mechanical properties. Most of the remanufacturing cores are made of ferromagnetic materials, as well as the cladding coating, which is made from iron-, cobalt- and nickel-based alloys. Accurately determining the damage degree and/or the repair quality of these cores is very challenging due to the uncertainty in their service process. Therefore, remanufacturing has its own unique feature and specific demands, and it is necessary to find a type of NDT with high sensitivity, easy automation and quantitative characterisation[4]. Magnetic NDT happens to meet these inspection requirements.

During the service process of a mechanical component, it is found that the ferromagnetic materials exhibit various magnetic properties, such as coercivity, permeability and remanence; they are also sensitive to external applied loads, microstructural features and plastic deformation[6]. The magnetic signals measured from ferromagnetic materials contain a large amount of information about the change of material behaviours. These signals can be used to predict early damage zones, stress concentration degree and even residual service life, which determine where and when remanufacturing cores should be repaired. Besides, the devices used for magnetic NDT are lightweight and suited to complicated surface detection, allowing flexible detection in remanufacturing to be easily realised. Compared with conventional NDT techniques, magnetic NDT has its own unique advantages when applied to remanufacturing.

At present, the three main magnetic NDT techniques are the magnetic memory method (MMM) and the use of magnetic Barkhausen noise (MBN) and magnetoacoustic emission (MAE). Although the literature on magnetic NDT is rapidly growing in terms of material characterisation, the literature on magnetic NDT for remanufacturing remains fragmented. Hence, the time has come to delve into the current knowledge in the research field to summarise outputs and thereby provide direction and guidance for future research.

3. Recent research advances

3.1 MMM

MMM is an NDT method proposed by Russian scholar Doubov in 1997. As a passive and weak magnetic testing method, MMM can detect flaws online without the use of a specialised excitation device, unlike other magnetic NDT techniques. In addition, MMM can discover the location of stress concentration, evaluate the damage degree of components and predict residual life[7]. The detection mechanism of MMM is based on magnetomechanical and magnetoelastic effects[8]. When ferromagnetic components are subjected to machining, transportation and service, the microstructure and distribution of the magnetic domain will change under the combined actions of the load and the geomagnetic field, as shown in Figure 2(a). Meanwhile, the phenomenon of force/magnetism coupling occurs, which leads to variations in spontaneous magnetisation and permeability. Consequently, a leakage magnetic field is generated in the stress concentration zones, where tangential components reach the maximum value and normal components change polarity and have a value of zero[9], as shown in Figure 2(b). Magnetic signals are retained even if the load is removed, because of the irreversible rotation of magnetic domains caused by stress concentration; thus, the signals can apparently memorise the locations of flaws and stress concentration in ferromagnetic materials.

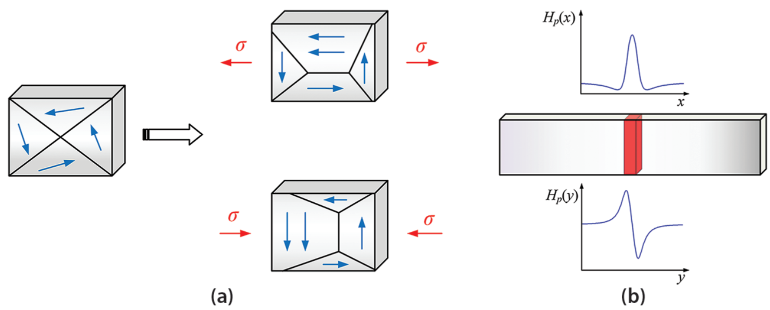


Figure 2. Schematic diagram of MMM: (a) movement of the magnetic domains; and (b) distribution of magnetic signals in the stress concentration zones

Due to the aforementioned advantages, MMM can play an important role in core damage assessment and repair quality evaluation. Experts and scholars have conducted considerable research in this area. In the fundamental experiments, five factors that can affect the variation of magnetic memory signals are discussed as follows:

- **Fatigue cycles:** During the service process, cyclic loading directly affects the residual life of ferromagnetic materials. Thus, specimens of 18CrNi4A steel[10], 45CrNiMoVA steel[11] and 45 steel[12], as common ferromagnetic materials used in the remanufacturing industry, were tested under fatigue tensile loads by a team from the Academy of Armored Forces Engineering in China. The quantitative relationship between magnetic signal characteristic values and fatigue cycle number was presented, as shown in Figure 3.

- **Crack length:** Crack initiation will occur after certain fatigue cycles and crack propagation will also influence magnetic memory signals. A research group from Hefei University of Technology in China investigated the magnetic signals induced by fatigue bending loads. The results showed that the maximum gradient of magnetic signal normal component K_{max} increased linearly with an increase in crack length in Q345 structural steel[13], whereas it increased exponentially in the welded joint of Q235 steel[14], as shown in Figure 4.
- **Plastic deformation:** The properties of ferromagnetic materials will change considerably when they enter the plastic stage. The effect of plastic deformation on magnetic behaviour was studied[15-17]. These research results indicated that MMM can detect the early stages of plastic deformation and effectively identify damage zones[18,19].

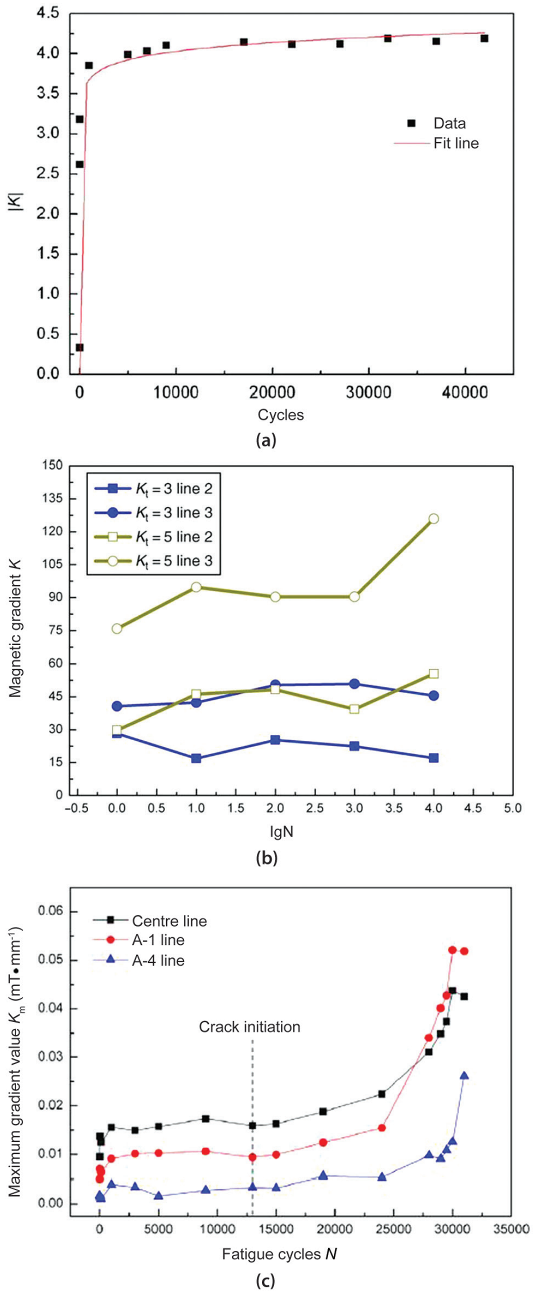


Figure 3. Relationship between magnetic memory signals and fatigue cycles: (a) 18CrNi4A steel[10]; (b) 45CrNiMoVA steel[11]; and (c) 45 steel[12]

- **Loading history:** Loading history and speed were also considered as influencing variables in MMM testing by Zhejiang University, in China[20,21]. Experimental results indicated that magnetic field variation depends not only on the existing damage state, but also on the plastic deformation caused by the loading history[20].
- **Stress state:** Roskosz *et al*[22,23] from the Silesian University of Technology in Poland, studied the distribution of residual stress using MMM. This method enabled the qualitative relationship between the residual magnetic field and residual stress to be determined.

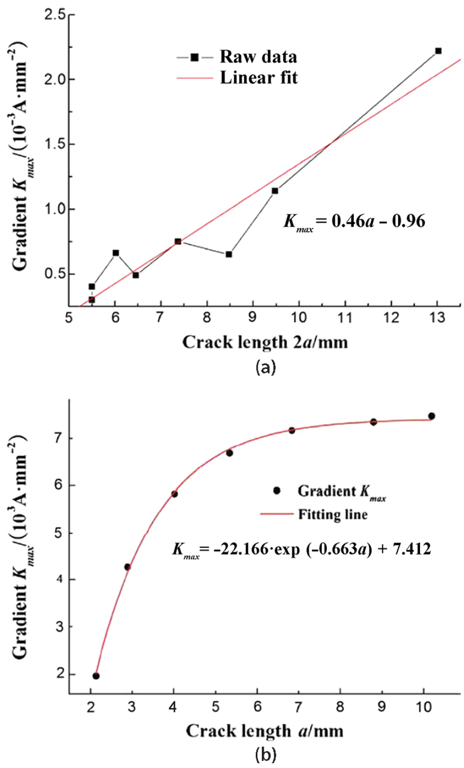


Figure 4. Relationship between magnetic memory signals and crack length: (a) Q345 structural steel[13]; and (b) Q235 weld joint[14]

Four theoretical models are studied to explain the generation mechanism of magnetic memory signals in the aforementioned fundamental experiments. Firstly, the distribution of magnetic memory signals induced by stress concentration was achieved via finite element simulation of force/magnetism coupling[24,25]. Singh *et al*[25] found that geometry and plastic deformation significantly influenced magnetic signals, as shown in Figure 5(a). The Jiles-Atherton (J-A) model based on magnetic domain wall motion theory was studied and modified to further explain the magnetomechanical effect[26,27]. The hysteresis loop was calculated through hysteresis loss and the energy conservation law. Excellent agreement was achieved between the predictions from the modified magnetomechanical model and the experimental results, as shown in Figure 5(b). In Figure 5(c), magnetic charge planes with the same magnetic charge density and opposite magnetic poles accumulated on either side of the defect zone when dislocation occurred due to stress concentration. Wang *et al*[28,29] researched the magnetic dipole model in detail and quantified the relationship between magnetic memory signals and the depth, width and location of defects. This model was successfully applied to the monitoring of fatigue crack propagation[14,30,31]. Shi *et al*[32] derived the magnetic dipole model from 2D to 3D stress concentration zones to extend the application range. From the perspective of microstructure, lattice distortion can also lead to spontaneous magnetic flux leakage signals.

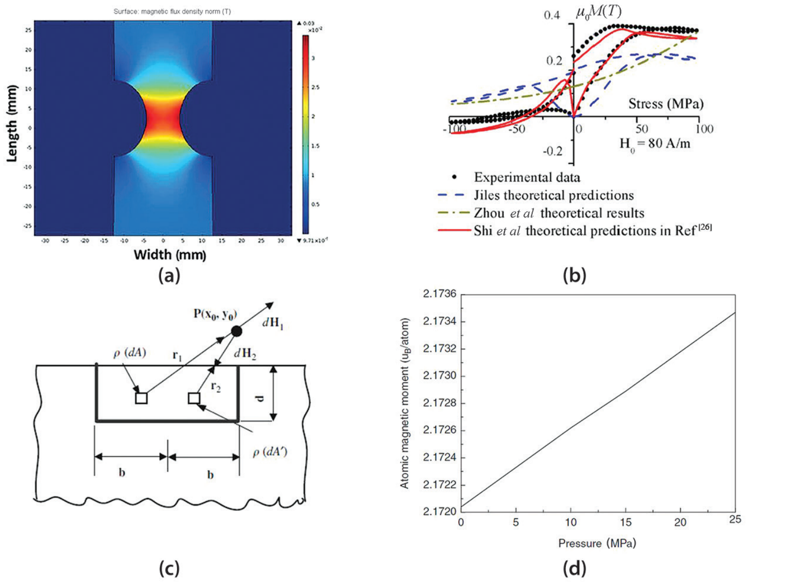


Figure 5. Theoretical models and calculation results for MMM: (a) finite element simulation[25]; (b) modified magnetomechanical model[26]; (c) magnetic dipole model[29]; and (d) quantum theory[34]

Liu *et al*[33,34] calculated the atomic magnetic moment in the spin polarisation system based on quantum theory. The result is shown in Figure 5(d); it indicates that stress and magnetic signals exhibit a good linear relationship.

It is worth noting that the magnetic memory signals susceptible to numerous interference factors can also bring substantial difficulties for stress quantitative evaluation[35]. Li *et al*[36] measured magnetic memory signals using installed magnetic sensor arrays and found that plastic deformation and residual stress around notches would increase the remnant flux leakage but that the effects were small. Gorkunov[37] also held that the affecting factors were numerous enough and that the contribution of each was rather difficult to discriminate and evaluate, thus the reliability of evaluating the stress-strain state and applying MMM was low. Besides, Augustyniak and Usarek[38] constructed a magnetic finite element simulation and even proved that quantitative *in-situ* NDT based on MMM was impossible. These results show that the reliability of MMM should be further improved from the perspective of engineering application. Research concerning MMM cannot afford to be given up as it provides obvious advantages in terms of early damage and service life assessment.

3.2 MBN

The MBN phenomenon was discovered by German physicist Barkhausen in 1919. Since then, MBN has become an important magnetic NDT technique due to its sensitivity to changes in applied stress, microstructural features and material composition[39], which makes determining stress concentration degree, surface hardness level, carburised layer depth, defect position and other evaluation indicators possible. During the magnetisation process, a magnetic domain wall α between two magnetisation directions with an angle difference of 180° is assumed, as shown in Figure 6. When the applied magnetic field is zero, the domain wall keeps the balance at the zero position in the X-axis. If the applied magnetic field is H, then the magnetic moment of the right domain will be oriented towards the left domain because the angle difference between the right domain and the magnetic field is $180° - \theta$, which is larger than that between the left domain and the magnetic field. Therefore, the domain wall moves to the X_1 position and the intensity of the critical magnetic field is H_0, as follows:

$$H_0 = \frac{1}{2\mu_0 M_s \cos\theta}\left(\frac{dE}{dX}\right)_{\max} \quad \text{........ (1)}$$

where μ_0 is the permeability of the vacuum, M_s is saturation magnetisation, E is the domain wall energy per unit area, X is the displacement and θ is the rotation angle when the magnetic moment of the domain is influenced by the applied magnetic field at the direction of easy magnetisation. The domain wall jumps from X_1 to X_2 when the intensity of the applied magnetic field exceeds H_0. The domain wall jumps from X_2 to X_3 when the applied magnetic field is increased further. These discontinuous jumps can be detected as voltage pulses in a pick-up coil on the surface of a ferromagnetic sample[40]. The information of inner defects can then be identified by analysing Barkhausen noise signals.

A series of studies has determined that Barkhausen noise signals with different frequency components can propagate at various depths of ferromagnetic samples. This type of skin effect can be used not only to evaluate stress distribution on the surface[41,42], but also to quantify the relationship between stress and depth[43,44], as shown in Figure 7. Amiri *et al*[45] further explained why MBN varies with stress by measuring changes in magnetostriction, hysteresis curves and magnetic domain structures. In addition, plastic deformation can lead to Barkhausen effect anisotropy. Vylezhnev *et al*[46] proposed the maximum electromotive force value of Barkhausen jumps e_m to monitor steel deformation condition. Stupakov *et al*[47] introduced new magnetic parameters with improved sensitivity-stability ratios to characterise plastic deformation and estimate deformation direction. Moreover, inspecting the initiation of a fatigue crack in steel structures is critical to prevent accidents and the wavelet signal can detect sub-millimetre cracks based on fractal signal processing[48]. As shown in Figure 8(a), wavelet variance dips sharply when a crack is initiated. Meanwhile, Figure 8(b) shows that the spectral parameter peaks after a crack is initiated and then descends to almost the initial level. MBN signals exhibit an advantage in reflecting microstructure. Henager and McCloy[49], Davut and Gür[50] and Vashista and Moorthy[51] inspected samples with different heat treatments and found that MBN signals were sensitive to the phase transformation of ferrite, pearlite and martensite.

With respect to theoretical models and numerical algorithms, Alessandro, Beatrice, Bertotti and Montorsi first proposed a

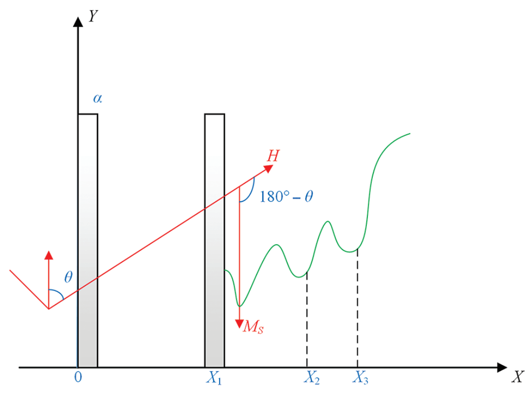


Figure 6. Schematic of MBN

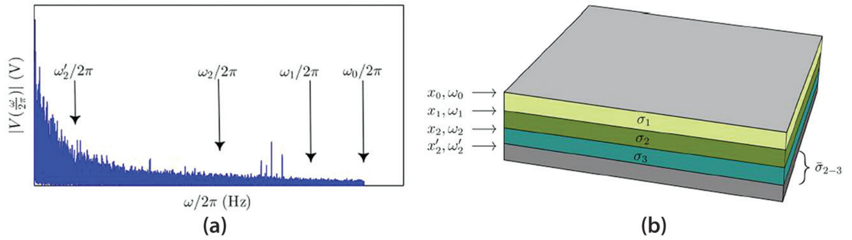


Figure 7. Typical measured MBN spectra with different cut-off frequencies that correspond to various depths[43]

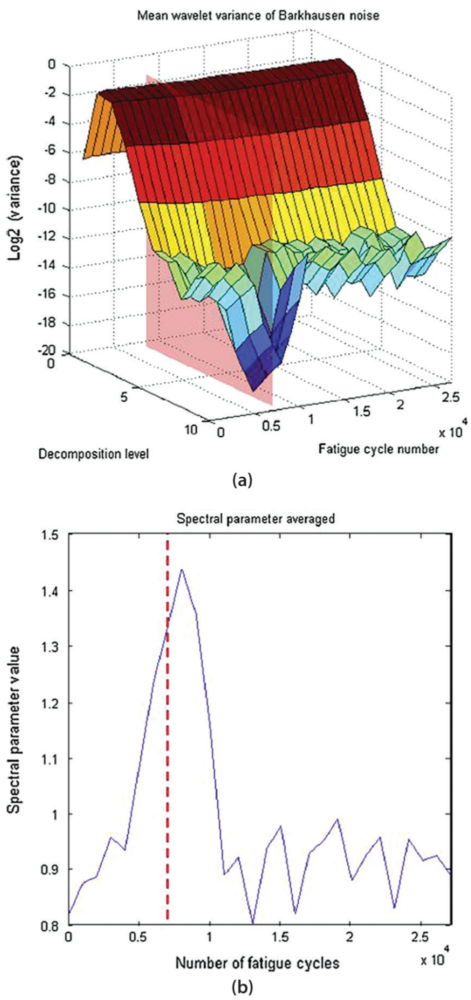


Figure 8. Wavelet-based fractal signal processing results of Barkhausen noise data[48]: (a) wavelet variance; and (b) spectral parameter

phenomenological model (ABBM), which was named after the authors[52]. In the ABBM model, the authors managed to capture the statistical properties of the Barkhausen effect by describing the stochastic motion of a domain wall. Thereafter, Colaiori[52] adopted the description of the dynamics of a magnetic elastic interface in a random medium to place the ABBM model in a more general framework. Harrison[53] also obtained analytical solutions that describe the major hysteresis loop, as shown in Figure 9(a), by incorporating the ABBM-Sablik model of Barkhausen noise into a positive feedback theory. Pérez-Benítez *et al*[54] introduced a method that uses trajectories traced in a type of neural network, known as self-organising maps, to distinguish the influences of varying parameters on MBN row signals. They subsequently proposed a microscopic model, shown in Figure 9(b), to study the influences of excitation parameters on MBN through the quasi-static magnetic formulation of Maxwell equations. The simulated MBN signals presented close similarities with the measured results[55]. Sorsa *et al*[56,57] quantitatively predicted residual stresses based on partial least squares regression and multivariable linear regression models, as shown in Figures 9(c) and 9(d), respectively. MBN signals should also be processed to improve detection precision. Excitation field interference from the induced electromotive force signals was removed by Pal'a and Bydžovský[58] by adjusting analogue and digital filters. Luo *et al*[59] analysed the power spectrum density of MBN based on an autoregressive model, as shown in Figure 9(e), and investigated the relationship between the energy of signal frequency components and mechanical properties; the results show that the desired signal components can be retained by reconstructing the discrete Gabor expansion. In general, deeper experimental and/or theoretical research on MBN has been carried out, which indicates that the technique has great potential for application in remanufacturing.

3.3 MAE

American scientist Lord discovered the MAE phenomenon in 1975. As a type of magnetic NDT technique, MAE evolved from acoustic emission and MBN. Under the influence of an external magnetic field, a type of elastic wave radiation produced by magnetostriction strains and the sudden movement of domain walls is released from ferromagnetic materials accompanied by Barkhausen jumps. This phenomenon is known as MAE. The pulse signal of MAE can be expressed by:

$$V_p = C\Delta\varepsilon^* \cdot \Delta V^* / \tau \qquad (2)$$

where V_p is the peak output voltage, C is the constant of the material, $\Delta\varepsilon^*$ is the inelastic strain tensor, ΔV^* is the volumetric strain of the domain and τ is the time of variation of $\Delta\varepsilon^*$. During the irreversible movement of 180° domain walls, no MAE signal occurs because the equivalent magnetostriction effect makes domain volume unstrained before and after Barkhausen jumps, as shown in Figure 10(a). However, when 90° domain walls move irreversibly, the magnetisation vector of ΔV^* will rotate 90° with a certain extent of strain, which results in the appearance of MAE signals, as shown in Figure 10(b). Moreover, the rotation of domains can also result in volumetric strain with magnetisation, as shown in Figure 10(c). Accordingly, MAE signals originate from the irreversible movement of 90° domain walls and the rotation of domains. The intensity of MAE signals strongly depends on stress under a constant external magnetic field.

Research on MAE has primarily focused on its physical mechanism. From the perspective of magnetism, the intensity of MAE signals exhibits a linear relationship with hysteresis loss and its activity along the hysteresis loop is proportional to the hysteresis loss in the same loop[60,61]. From the perspective of microstructure, most experts agree that MAE originates from domain wall creation or annihilation processes[61]. However, arguments remain on which type of domain wall plays the leading role in the MAE phenomenon. Augustyniak *et al*[62] proved that the only origin of MAE is the motion of non-180° domain walls, whereas Xu *et al*[63] regarded the motion of 180° domain walls as a source of MAE, as shown in Figure 11. Researchers from the Russian Academy of Sciences investigated the relationship between the parameters of MAE and the magnitude of longitudinal magnetostriction and the behaviour of magnetic domain structures[64], which can be used to distinguish various types of domain structure[65].

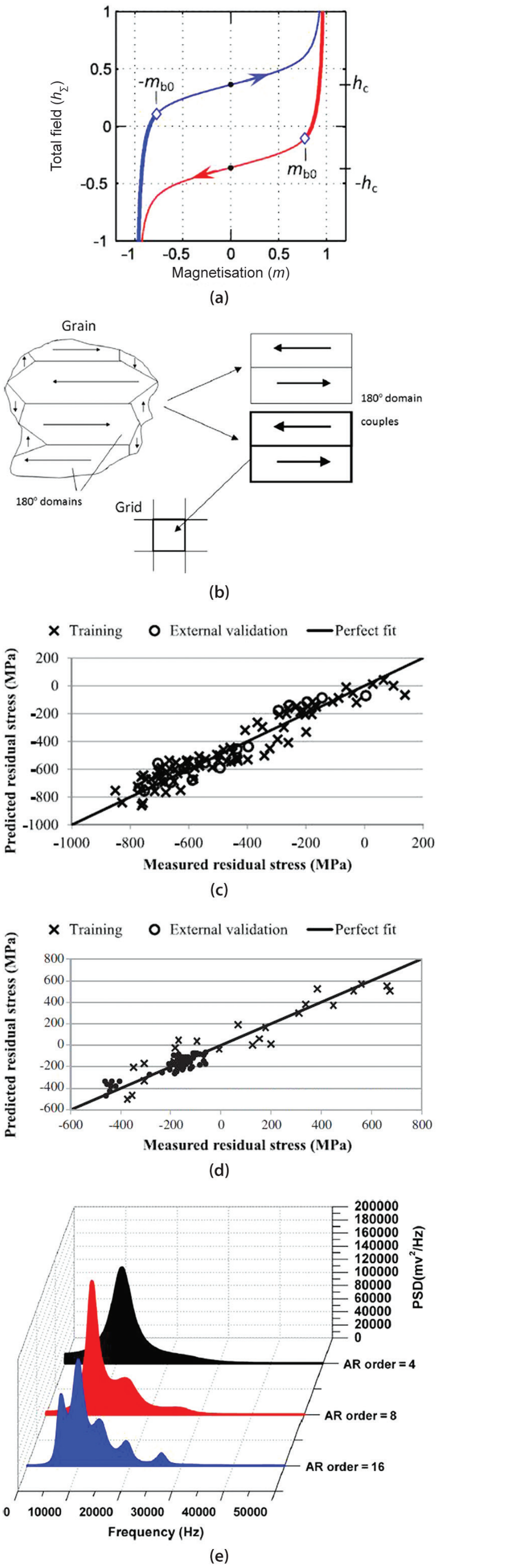


Figure 9. Theoretical models and calculation results for MBN: (a) ABBM model[53]; (b) microscopic model[55]; (c) partial least squares regression model[56]; (d) multivariable linear regression model[57]; and (e) autoregressive model[59]

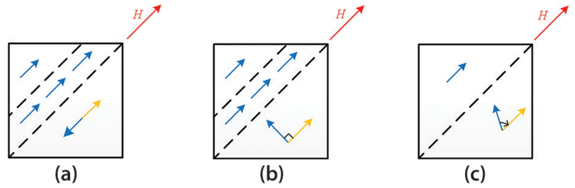


Figure 10. Schematic of MAE: (a) 180° domain walls; (b) 90° domain walls; and (c) rotation of domains

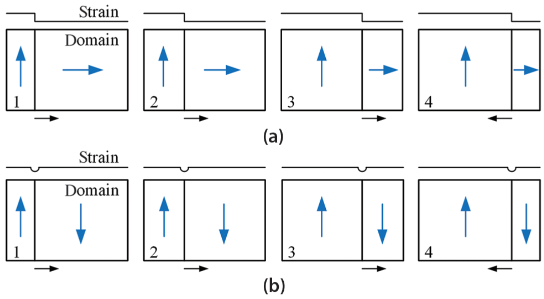


Figure 11. Two types of MAE source during the movement of domain walls[63]: (a) 90° domain wall; and (b) 180° domain wall

MAE signals are easily affected by various factors. Augustyniak *et al*[66-70] from Gdansk University of Technology in Poland conducted numerous studies. They systematically investigated the effects of magnetostriction, magnetising frequency and sample dimension on MAE signals based on numerical analysis, finite element simulation and experiments. Plastic deformation degree directly influenced service life. Consequently, Piotrowski *et al*[71] attempted to use MAE signals to evaluate plastic deformation levels in various ferromagnetic materials. This method needs to be frequently complemented by the MBN method to estimate plastic deformation accurately[72,73], as shown in Figure 12. Sablik *et al*[74] used the modified ABBM and J-A models to explain the MAE phenomenon when deformation enters the stage in which dislocation tangles are formed. In addition, a new measurement parameter, called MAE absolute energy, was developed to characterise microstructure, quantify hardness and determine residual stress in ferritic stainless steel[75,76]. All of the aforementioned studies provide a good theoretical basis for the application of MAE to remanufacturing engineering.

4. Present and potential application to remanufacturing

4.1 MMM

Many experts have evaluated the damage degree of the remanufacturing core based on the achievements of experiments and theories combined with MMM. The relationship between the deformation of an axle housing and magnetic memory signals was established by Huang *et al*[77] and fatigue crack propagation in a 510L steel axle housing was also detected using MMM (Figure 13), which provided solid references for remanufacturing[78]. Song *et al*[79,80] combined MMM with the X-ray diffraction technique and ANNs to predict the plastic deformation rate and residual life of the axle housing of a waste drive. In addition, engine crankshafts also play a key role in remanufacturing. MMM can be used to monitor the locations of stress concentration and fatigue crack propagation[81,82], thereby providing a basis and guidance for the remanufacture and life evaluation of retired crankshafts[83]. Fatigue cracking and stress concentration easily appeared on the inner face of a cylinder barrel with reciprocating motions of the cylinder piston and, thus, evaluating the quality of a cylinder barrel before remanufacture is critical. Eddy current and magnetic memory tests were applied by Shi *et al*[84,85] to detect the superficial defects of a cylinder barrel. The results indicated that the composite detection technology can characterise cracks and stress and effectively guarantee the quality of a remanufactured cylinder. Moreover, many remanufactured parts, such as sucker rods[86], cylinder head bolts[87], turbine blades, gears and train wheels[88], have been diagnosed using MMM.

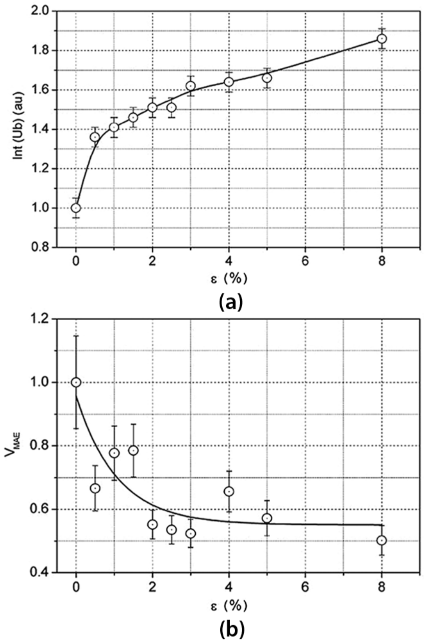


Figure 12. (a) MBN signals as functions of deformation level; and (b) MAE signals as functions of deformation level[72]

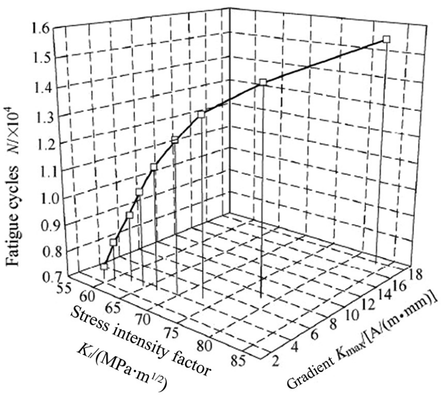


Figure 13. Relationship between stress intensity factor K_I, magnetic signal gradient K_{max} and fatigue cycles N[78]

When the remanufacturability of the remanufacturing core has been determined by NDT, it can be repaired by surface coating techniques; accordingly, repair quality evaluation is also an urgent problem. Liu *et al*[89-92] evaluated the stress and crack propagation of laser cladding coating via magnetic memory signals. Then, the relationship between the burial depth of a crack, the load and the magnetic signal normal component gradient value K was obtained[89], as shown in Figure 14. Hua *et al*[93] discussed the effects of fatigue damage caused by different laser cladding parameters and fatigue loads on magnetic memory signals. The results showed that fatigue damage location and degree can be predicted based on the changing curve of magnetic signals. Zeng *et al*[94] proved that magnetic signals are closely related to the state of fatigue and thermal damage of laser cladding remanufactured products, which enables the quantitative assessment of the residual life of cladding layers to be carried out. In addition, Huang *et al*[95] evaluated the cladding layers of plasma-transferred arc welding using MMM and discussed the variation in magnetic signals with stress.

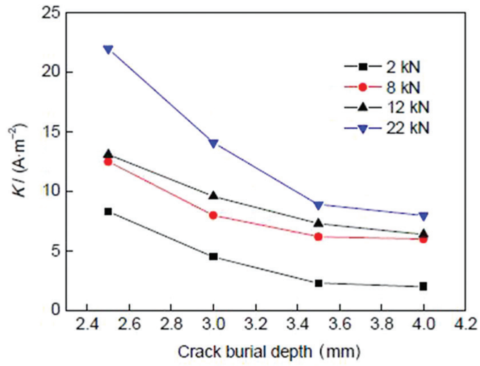


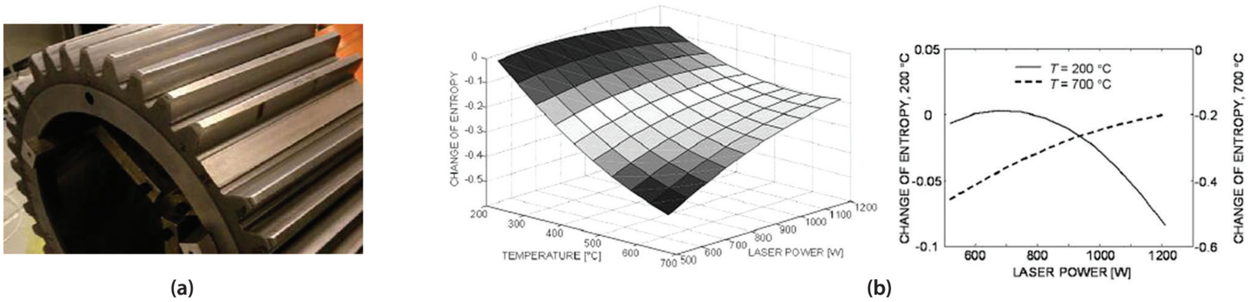
Figure 14. Relationship between the burial depth of a crack, the load and the magnetic signal gradient K[89]

4.2 MBN

Many scholars have evaluated the quality of steel gears with MBN signals that are correlated with hardness, hardened layer depth and thermal damage[96-99]. Santa-aho and Sorsa *et al*[100] discovered that the root mean square value of MBN voltage signals exhibited linear correlations with the values of residual stress and surface hardness. They established a linear regression model from the perspectives of time domain and entropy[101], as shown in Figure 15. These results not only monitored stress and microcracks on a hardened surface layer, but also provided guidance for gear repair with optimised laser processing parameters. This has the potential to effectively control the quality of remanufactured products. In addition, MBN signals can accurately quantify the grinding burn degree of bearings[102]. Čížek *et al*[103] found that the intensity of MBN considerably decreases with increasing flank wear of the roll bearing because of the increasing density of the dislocations that pin the Bloch walls and suppress their motion. Kolarits[104] also analysed various levels of induced grind injury for large bearing components by using MBN signals. Additionally, the MBN method has been used to monitor the manufacturing process and evaluate the surface quality, for example in the processes of welding[105], heat treatment[106] and shot peening[107], which can be further extended to the remanufacturing process.

4.3 MAE

At present, the MAE testing method is still in the exploration and technical accumulation stages with regard to its application in remanufacturing engineering. Piotrowski *et al*[108] separated useful MAE signals from background noise in order to promote the improved application of the MAE technique to thick-walled pipelines in an industrial environment. Wilson *et al*[109] found that the MAE method has a considerably greater measurement depth than MBN and, thus, it extends the application scope of this method and offers a complementary technique for characterising surface treatments, such as case hardening and peening of steel gears, as shown in Figure 16. Along with this, using MAE and MBN composite detection technology could provide a more effective approach for quality evaluation. Astudillo *et al*[110] studied A508 Class II forged steel, which is used for pressure vessels in nuclear power stations,



(a) (b)

Figure 15. Linear regression model of entropy: (a) laser-processed planet gear[100]; and (b) change in entropy as a function of laser processing temperature and laser input power[101]

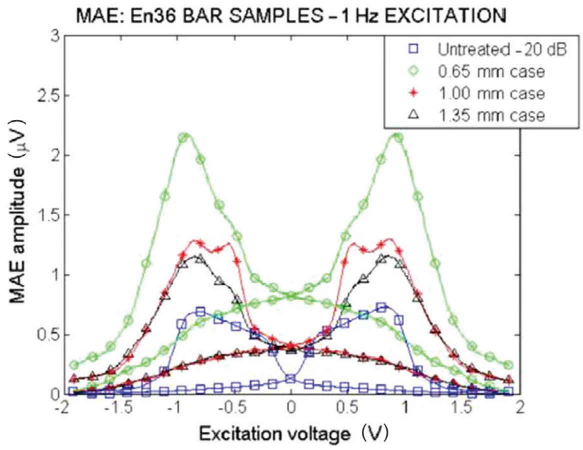


Figure 16. Profiles of untreated and case-hardened En36 samples for MAE with 1 Hz excitation[109]

using MAE and MBN composite detection technology. The results helped to validate evident connections between the magnetic anisotropy, texture and microstructure of materials.

4.4 Comparison of magnetic NDT methods

Based on previous studies, it can be concluded that the three aforementioned types of magnetic NDT technique have great potential with regard to remanufacturing. However, the application scopes of these techniques differ, as shown in Table 1. Although all of the testing methods work effectively in estimating the stress levels of ferromagnetic components, MMM signals induced by a geomagnetic field can only reflect subsurface information. In contrast, MBN and MAE can detect inner stress to a certain depth under an applied magnetic field, with MAE achieving the maximum detection depth. In addition, these magnetic NDT techniques can be used to characterise plastic deformation resulting from strain induced by stress. Crack initiation has also been successfully monitored using MMM and MBN. However, the location of cracks discussed by Andreikiv *et al*[111] can only be characterised theoretically by MAE without meeting the demands of engineering application. Moreover, MBN and MAE are able to reflect microstructure better than MMM. This result is attributed to the special detection mechanism of MBN and MAE signals, which is directly ascribed to the motion of domains influenced by grain boundary, lattice dislocation, the second phase and impurities.

Traditional analysis tools, such as stress analysis, fatigue mechanics and fracture mechanics, can also be used to evaluate stress, plastic deformation, cracks and microstructure. However, these analysis tools, which are generally adopted in NDT, can only reflect material characteristics. Simply applying these analysis tools to remanufacturing practices is insufficient. Unlike traditional analysis tools, the magnetic NDT techniques are frequently used to evaluate the material behaviour and damage degree of a specific structure. Their roles in remanufacturing are to determine where and when remanufacturing cores should be repaired and to assess the quality of remanufactured parts. That is, magnetic NDT techniques function as a bridge between damage evaluation and remanufacturing repair and, thus, their application scopes should not be confined to detection itself.

Table 1. Application scopes of magnetic NDT techniques in remanufacturing

Testing method	Stress	Plastic deformation	Crack	Microstructure
MMM	✓(Subsurface)	✓	✓	×
MBN	✓(Deeper)	✓	✓	✓
MAE	✓(Deepest)	✓	×	✓

The objects inspected for remanufacturing also differ because of the varying technical characteristics of magnetic NDT techniques, as shown in Table 2. MMM is primarily used to detect the large-scale structural components of automobiles, sucker rods and turbines because of its easy operation and time-saving advantages. MBN can not only identify various defects but can also evaluate the state of microstructures. Thus, this technique is appropriate for detecting gears and bearings, the surfaces of which should be machine finished and the failure mode of which is grinding burn. Thick-walled pipelines and pressure vessels, such as hollow components, are frequently inspected using MAE due to their high penetrability.

Table 2. Present and potential objects of inspection for magnetic NDT techniques in remanufacturing

Testing method	Specific object
MMM	Driving axle housing[77-80], engine crankshaft[81-83], cylinder barrel[84,85], sucker rod[86], turbine blade[88], gear[88]
MBN	Gear[100,101], bearing[102-104]
MAE	Thick-walled pipeline[108], gear[109], pressure vessel[110]

5. Problems and prospects

Recent demands for inspecting remanufacturing cores and increasing requirements for quality control in the repair process have led to the development of magnetic NDT techniques. Although these techniques have attracted considerable attention due to their unique advantages, problems and difficulties still exist with their current application in remanufacturing engineering:

- The quantitative criteria for core damage should be modified. The characteristic values of testing signals can only qualitatively reflect the damage degree of remanufacturing cores and approximately identify the location of defects. Consequently, accurately determining the remanufacturability of cores and the time to remanufacture is challenging. Given these weaknesses, physical mechanisms and theoretical models based on the testing signals, as well as the signal characteristics, should be further clarified. Quantitative criteria have been key to establishing life prediction models for remanufacturing cores.
- Testing signals are easily subjected to interference. Variations in environment temperature and background magnetic field negatively affect the testing signals during detection and are responsible for the lack of accuracy and reliability of the detection results. The service conditions of remanufacturing cores are generally complex, thereby also resulting in high mistake and miss rates in the results. In order to improve the reliability of inspection, the magnetic NDT techniques are expected to be combined to realise complementary advantages.
- The objects used for evaluation are not sufficiently comprehensive. Since the laser cladding technique is the research hotspot in the remanufacturing industry, repair quality evaluation of remanufactured products, mostly adopting MMM, has focused primarily on the laser cladding layers so far. The range of evaluation objects should also be extended to include the coatings prepared by other surface repair technologies used in remanufacturing, including plasma spraying, plasma-transferred arc welding and electroplating deposition. Along with this, more attention should be paid to the cores with high remanufacturing value in nuclear, aerospace and military fields, which are likely to bring more economic benefits. Furthermore, since all of the remanufacturing forming processes directly relate to the bonding strength of strengthened coatings and their repair quality, it is also necessary to implement online monitoring in the processes.
- Engineering application should be reinforced. The objects of magnetic NDT are still restricted to specific parts or samples in laboratories and cases of magnetic NDT in remanufacturing engineering application remain few. Thus, the measurement criteria of magnetic NDT in remanufacturing must be established, a suitable detection system should be developed and integrated into remanufacturing and personnel training must be strengthened.
- Relevant standards should be established and improved. The international remanufacturing standards have not received much attention worldwide. For example, several examples of terminology in remanufacturing remain ambiguous or inconsistent and various definitions of the term 'remanufacturing' are currently in circulation. Although the technical committee ISO/TC 135 has published over eighty international NDT standards, existing relevant magnetic NDT standards are not sufficiently sound, which impedes magnetic NDT application. Furthermore, these standards have not yet been applied to remanufacturing and seldom refer to the core damage assessment and repair quality evaluation. It is suggested that governments, enterprises and academics all over the world cooperate with one another to establish or improve a series of relevant international standards for magnetic NDT methods applied to remanufacturing.

Although the application cases of magnetic NDT in remanufacturing remain few, especially for MBN and MAE, these magnetic NDT techniques have great potential value. Over the past few decades, many experts have made major contributions towards characterising the material performance and defects by magnetic NDT. It is time to further combine these magnetic NDT techniques with remanufacturing and realise the core damage assessment and repair quality evaluation. Meanwhile, composite inspection technology in remanufacturing is recommended and should be improved in conjunction with other NDT techniques, such as ultrasound, infrared and eddy current testing. It is predicted that key issues will be completely solved in the future with the development of composite magnetic NDT techniques.

6. Conclusions

In recent years, three types of magnetic NDT technique (MMM, MBN and MAE) have been rapidly developed and their present and potential application to remanufacturing engineering is being investigated. These techniques can not only determine the failure mechanism, damage degree and residual life of remanufacturing cores, but can also evaluate the repair quality of remanufactured products. Moreover, these techniques exhibit the potential to monitor the remanufacturing forming process and provide guidance for the repair process. Although their application to this field currently faces considerable challenges, it is predicted that magnetic NDT techniques will play a more important role in remanufacturing engineering in the future.

Acknowledgements

This work is financially supported by the National Natural Science Foundation of China (Grant No 51675155, 51635010 and 51722502). The authors would also like to express gratitude to Dr Gerd Dobmann, Nondestructive Testing and Quality Assurance, Universität des Saarlandes, for the useful comments and discussions.

References

1. C M Lee, W S Woo and Y H Roh, 'Remanufacturing: trends and issues', International Journal of Precision Engineering and Manufacturing – Green Technology, Vol 4, No 1, pp 113-125, 2017.
2. M Matsumoto, S S Yang, K Martinsen and Y Kainuma, 'Trends and research challenges in remanufacturing', International Journal of Precision Engineering and Manufacturing – Green Technology, Vol 3, No 1, pp 129-142, 2016.
3. B S Xu, S Y Dong, S Zhu and P J Shi, 'Prospects and development of remanufacturing forming technology', Journal of Mechanical Engineering, Vol 48, No 15, pp 96-105, 2012.
4. Y L Zhang, H C Zhang, J X Zhao, Z M Zhou and J L Wang, 'Review of non-destructive testing for remanufacturing of high-end equipment', Journal of Mechanical Engineering, Vol 49, No 7, pp 80-90, 2013.
5. J J Kang, B S Xu, H D Wang and C B Wang, 'Progress of non-destructive detection technology on remanufacturing coatings', Rare Metal Materials and Engineering, Vol 41, No 1, pp 399-402, 2012.
6. C C Li, L H Dong, H D Wang, B S Xu and G L Li, 'Current research and development prospects of magnetic non-destructive assessment techniques for fatigue damage', Materials Review, Vol 29, No 6, pp 107-113, 2015.
7. B S Xu and L H Dong, Metal Magnetic Memory Testing Method in Remanufacturing Quality Control, National Defense Industry Press, Beijing, China, 2015.
8. J L Ren and J M Lin, 'Metal Magnetic Memory Testing Technique, China Electric Power Press, Beijing, China, 2000.
9. Z D Wang, Y Gu and Y S Wang, 'A review of three magnetic NDT technologies', Journal of Magnetism and Magnetic Materials, Vol 324, No 4, pp 382-388, 2012.
10. C L Shi, S Y Dong, B S Xu and P He, 'Stress concentration degree affects

spontaneous magnetic signals of ferromagnetic steel under dynamic tension load', NDT&E International, Vol 43, No 1, pp 8-12, 2010.
11. L H Dong, B S Xu, S Y Dong and Q Z Chen, 'Characterisation of stress concentration of ferromagnetic materials by metal magnetic memory testing', Nondestructive Testing and Evaluation, Vol 25, No 2, pp 145-151, 2010.
12. C C Li, L H Dong, H D Wang, G L Li and B S Xu, 'Metal magnetic memory technique used to predict the fatigue crack propagation behaviour of 0.45%C steel', Journal of Magnetism and Magnetic Materials, Vol 405, pp 150-157, 2016.
13. H H Huang, S L Jiang, R J Liu and Z F Liu, 'Investigation of magnetic memory signals induced by dynamic bending load in fatigue crack propagation process of structural steel', Journal of Nondestructive Evaluation, Vol 33, No 3, pp 407-412, 2014.
14. H H Huang, Z C Qian, C Yang, G Han and Z F Liu, 'Magnetic memory signals of ferromagnetic weldment induced by dynamic bending load', Nondestructive Testing and Evaluation, Vol 32, No 2, pp 166-184, 2017.
15. H M Li, Z M Chen and Y Li, 'Characterisation of damage-induced magnetisation for 304 austenitic stainless steel', Journal of Applied Physics, Vol 110, No 11, p 114907, 2011.
16. H M Li, H E Chen, Z S Yuan, W L Cai, Y Li *et al*, 'Comparisons of damage-induced magnetisations between austenitic stainless and carbon steel', International Journal of Applied Electromagnetics and Mechanics, Vol 46, No 4, pp 991-996, 2014.
17. J W Li and M Q Xu, 'Influence of uniaxial plastic deformation on surface magnetic field in steel', Meccanica, Vol 47, No 1, pp 135-139, 2012.
18. J C Leng, Y Liu, G Q Zhou and Y T Gao, 'Metal magnetic memory signal response to plastic deformation of low carbon steel', NDT&E International, Vol 55, No 3, pp 42-46, 2013.
19. J C Leng, M Q Xu, M X Xu and J Z Zhang, 'Magnetic field variation induced by cyclic bending stress', NDT&E International, Vol 42, No 5, pp 410-414, 2009.
20. S Bao, S N Hu, L Lin, Y B Gu and M L Fu, 'Experiment on the relationship between the magnetic field variation and tensile stress considering the loading history in U75V rail steel', Insight: Non-Destructive Testing and Condition Monitoring, Vol 57, No 12, pp 683-688, 2015.
21. S Bao, Y B Gu, M L Fu, D Zhang and S N Hu, 'Effect of loading speed on the stress-induced magnetic behaviour of ferromagnetic steel', Journal of Magnetism and Magnetic Materials, Vol 423, pp 191-196, 2017.
22. M Roskosz and P Gawrilenko, 'Analysis of changes in residual magnetic field in loaded notched samples', NDT&E International, Vol 41, No 7, pp 570-576, 2008.
23. M Roskosz and M Bieniek, 'Evaluation of residual stress in ferromagnetic steels based on residual magnetic field measurements', NDT&E International, Vol 45, No 1, pp 55-62, 2012.
24. L Q Zhong, L M Li and X Chen, 'Simulation of magnetic field abnormalities caused by stress concentrations', IEEE Transactions on Magnetics, Vol 49, No 3, pp 1128-1134, 2013.
25. W S Singh, R Stegemann and M Kreutzbruck, 'Three-dimensional finite element analysis of the stress-induced geometry effect on self-magnetic leakage fields during tensile deformation', Insight: Non-Destructive Testing and Condition Monitoring, Vol 58, No 10, pp 544-550, 2016.
26. P P Shi, K Jin and X J Zheng, 'A general non-linear magnetomechanical model for ferromagnetic materials under a constant weak magnetic field', Journal of Applied Physics, Vol 119, No 14, pp 196-203, 2016.
27. M X Xu, M Q Xu, J W Li and H Y Xing, 'Using modified J-A model in MMM detection at elastic stress stage', Nondestructive Testing and Evaluation, Vol 27, No 2, pp 121-138, 2012.
28. Z D Wang, K Yao, B Deng and K Q Ding, 'Theoretical studies of metal magnetic memory technique on magnetic flux leakage signals', NDT&E International, Vol 43, No 4, pp 354-359, 2010.
29. Z D Wang, K Yao, B Deng and K Q Ding, 'Quantitative study of metal magnetic memory signal *versus* local stress concentration', NDT&E International, Vol 43, No 6, pp 513-518, 2010.
30. H H Huang, S L Jiang, C Yang and Z F Liu, 'Stress concentration impact on the magnetic memory signal of ferromagnetic structural steel', Nondestructive Testing and Evaluation, Vol 29, No 4, pp 377-390, 2014.
31. M I M Ahmad, A Arifin, S Abdullah, W Z W Jusoh and S S K Singh, 'Fatigue crack effect on magnetic flux leakage for A283 grade C steel', Steel and Composite Structures, Vol 19, No 6, pp 1549-1560, 2015.
32. P P Shi and X J Zheng, 'Magnetic charge model for 3D MMM signals', Nondestructive Testing and Evaluation, Vol 31, No 1, pp 45-60, 2016.
33. B Liu, Y Fu and B Xu, 'Study on metal magnetic memory testing mechanism', Research in Nondestructive Evaluation, Vol 26, No 1, pp 1-12, 2015.
34. B Liu, Y Fu and R Jian, 'Modelling and analysis of magnetic memory testing method based on the density functional theory', Nondestructive Testing and Evaluation, Vol 30, No 1, pp 13-25, 2015.
35. W M Zhang, Z C Qiu, J J Yuan and X Yu, 'Discussion on stress quantitative evaluation using metal magnetic memory method', Journal of Mechanical Engineering, Vol 51, No 8, pp 9-13, 2015.
36. Z C Li, S Dixon, P Cawley, R Jarvis and P B Nagy, 'Study of metal magnetic memory (MMM) technique using permanently installed magnetic sensor arrays', AIP Conference Proceedings, Vol 1806, No 1, p 110011, 2017.
37. E S Gorkunov, 'Different remanence states and their resistance to external effects. Discussing the so-called magnetic memory method', Insight: Non-Destructive Testing and Condition Monitoring, Vol 57, No 12, pp 709-717, 2015.
38. M Augustyniak and Z Usarek, 'Discussion of derivability of local residual stress level from magnetic stray field measurement', Journal of Nondestructive Evaluation, Vol 34, No 3, Article 21, 2015.
39. H I Yelbay, I Cam and C H Gür, 'Non-destructive determination of residual stress state in steel weldments by magnetic Barkhausen noise technique', NDT&E International, Vol 43, No 1, pp 29-33, 2010.
40. B Augustyniak, P Maciakowski, L Piotrowski and M Chmielewski, 'Assessment with mechanical Barkhausen effect of residual stress in grain-oriented polycrystalline 3% Si-Fe sheet', IEEE Transactions on Magnetics, Vol 48, No 4, pp 1405-1408, 2012.
41. X Qi, J Y Liu, J L Tian and H T Chang, 'Non-destructive testing of ferromagnetic material by magnetoelasticity noise technique for fatigue damage', Journal of Harbin Institute of Technology, Vol 35, No 1, pp 54-57, 2003.
42. C Zhao, 'Research on application of Barkhausen in detecting 18Cr2Ni4WA steel internal stress', MSc thesis, Nanchang Hangkong University, Nanchang, 2015.
43. O Kypris, I C Nlebedim and D C Jiles, 'A new method for obtaining stress-depth calibration profiles for non-destructive evaluation using a frequency-dependent model of Barkhausen emissions', IEEE Transactions on Magnetics, Vol 49, No 7, pp 3893-3896, 2013.
44. O Kypris, I C Nlebedim and D C Jiles, 'Measuring stress variation with depth using Barkhausen signals', Journal of Magnetism and Magnetic Materials, Vol 407, pp 377-395, 2016.
45. M S Amiri, M Thielen, M Rabung, M Marx, K Szielasko *et al*, 'On the role of crystal and stress anisotropy in magnetic Barkhausen noise', Journal of Magnetism and Magnetic Materials, Vol 372, pp 16-22, 2014.
46. V P Vylezhnev, V S Malyshev and Y N Simonov, 'Effect of plastic

deformation on magnitude of Barkhausen effect in steel 40', Metal Science and Heat Treatment, Vol 57, No 5, pp 261-263, 2015.
47. O Stupakov, T Takagi and T Uchimoto, 'Alternative magnetic parameters for characterisation of plastic tension', NDT&E International, Vol 43, No 8, pp 671-676, 2010.
48. K Miesowicz, W J Staszewski and T Korbiel, 'Analysis of Barkhausen noise using wavelet-based fractal signal processing for fatigue crack detection', International Journal of Fatigue, Vol 83, No 2, pp 109-116, 2016.
49. C H Henager, J S McCloy, P Ramuhalli, D J Edwards and S Y Hu, 'Investigation of magnetic signatures and microstructures for heat-treated ferritic/martensitic HT-9 alloy', Acta Materialia, Vol 61, No 9, pp 3285-3296, 2013.
50. K Davut and C H Gür, 'Monitoring the microstructural evolution in spheroidised steels by magnetic Barkhausen noise measurements', Journal of Nondestructive Evaluation, Vol 29, No 4, pp 241-247, 2010.
51. M Vashista and V Moorthy, 'On the shape of the magnetic Barkhausen noise profile for better revelation of the effect of microstructures on the magnetisation process in ferritic steels', Journal of Magnetism and Magnetic Materials, Vol 393, pp 584-592, 2015.
52. F Colaiori, 'Exactly solvable model of avalanches dynamics for Barkhausen crackling noise', Advances in Physics, Vol 57, No 4, pp 287-359, 2008.
53. R G Harrison, 'Accurate mean-field modelling of the Barkhausen noise power in ferromagnetic materials using a positive-feedback theory of ferromagnetism', Journal of Applied Physics, Vol 118, No 2, p 023904, 2015.
54. J A Pérez-Benítez, J H Espina-Hernández and P Martínez-Ortiz, 'Unwrapping the influence of multiple parameters on the magnetic Barkhausen noise signal using self-organising maps', NDT&E International, Vol 54, No 3, pp 166-170, 2013.
55. J A Pérez-Benítez, J H Espina-Hernández, P Martínez-Ortiz, A F Chávez-González and J M D L Rosa, 'Analysis of the influence of some magnetising parameters on magnetic Barkhausen noise using a microscopic model', Journal of Magnetism and Magnetic Materials, Vol 347, pp 51-60, 2013.
56. A Sorsa, A Isokangas, S Santa-aho, M Vippola, T Lepistö *et al*, 'Prediction of residual stresses using partial least-squares regression on Barkhausen noise signals', Journal of Nondestructive Evaluation, Vol 33, No 1, pp 43-50, 2014.
57. A Sorsa, K Leiviskä, S Santa-aho and T Lepistö, 'Quantitative prediction of residual stress and hardness in case-hardened steel based on the Barkhausen noise measurement', NDT&E International, Vol 46, No 1, pp 100-106, 2012.
58. J Paľa and J Bydžovský, 'An alternative method to remove excitation field interference from magnetic Barkhause noise', Journal of Magnetism and Magnetic Materials, Vol 361, pp 88-93, 2014.
59. X Y Luo, Y L Wang, B Zhu, Y Zhang and Y S Zhang, 'Super-resolution spectral analysis and signal reconstruction of magnetic Barkhausen noise', NDT&E International, Vol 70, pp 16-21, 2015.
60. A Stupakov, O Perevertov and M Landa, 'Dynamic behaviour of magnetoacoustic emission in a grain-oriented steel', Journal of Magnetism and Magnetic Materials, Vol 426, pp 685-690, 2017.
61. K Praveena and S R Murthty, 'Magnetoacoustical emission in nanocrystalline Mn-Zn ferrites', Materials Research Bulletin, Vol 48, No 11, pp 4826-4833, 2013.
62. B Augustyniak, M J Sablik, F J G Landgraf, D C Jiles, M Chmielewski *et al*, 'Lack of magnetoacoustic emission in iron with 6.5% silicon', Journal of Magnetism and Magnetic Materials, Vol 320, No 20, pp 2530-2533, 2008.
63. Y H Xu, L Ma, F M Du, X Y Ma and D H L Ng, 'Magnetoacoustic emission and Barkhausen noise of cobalt nickel-oriented silicon steel and permalloy', Journal of Magnetism and Magnetic Materials, Vol 219, No 2, pp 166-172, 2000.
64. E S Gorkunov, Y N Dragoshanskii, V A Khamitov and V M Shevnin, 'Magnetoelastic acoustic emission in ferromagnetic materials: I. Effect of crystal anisotropy', Russian Journal of Nondestructive Testing, Vol 37, No 3, pp 163-180, 2001.
65. V S Ivanchenko, I I Glukhikh, L G Strokina and A P Kheinson, 'Magnetoacoustic emission of magnetites', Russian Geology and Geophysics, Vol 53, No 2, pp 214-220, 2012.
66. L Piotrowski, M Chmielewski and B Augustyniak, 'On the correlation between magnetoacoustic emission and magnetostriction dependence on the applied magnetic field', Journal of Magnetism and Magnetic Materials, Vol 410, pp 34-40, 2016.
67. B Augustyniak, L Piotrowski, M Augustyniak, M Chmielewski and M J Sablik, 'Impact of eddy currents on Barkhausen and magnetoacoustic emission intensity in a steel plate magnetised by a C-core electromagnet', Journal of Magnetism and Magnetic Materials, Vol 272-276, pp 543-545, 2004.
68. M Augustyniak, B Augustyniak, M Chmielewski and W Sadowski, 'Numerical evaluation of spatial time-varying magnetisation of ferritic tubes excited with a C-core magnet', Journal of Magnetism and Magnetic Materials, Vol 320, pp 1053-1056, 2008.
69. B Augustyniak, L Piotrowski and M Chmielewski, 'Impact of frequency and sample geometry on magnetacoustic emission voltage properties for two steel grades', Journal of Electrical Engineering, Vol 59, No 7, pp 33-36, 2008.
70. M Augustyniak, B Augustyniak, L Piotrowski, M Chmielewski and W Sadowski, 'Evaluation by means of magnetoacoustic emission and Barkhausen effect of time and space distribution of magnetic flux density in ferromagnetic plate magnetised by a C-core', Journal of Magnetism and Magnetic Materials, Vol 304, pp 552-554, 2006.
71. L Piotrowski, B Augustyniak, M Chmielewski and Z Kowalewski, 'Possibility of application of magnetoacoustic emission for the assessment of plastic deformation level in ferrous materials', IEEE Transactions on Magnetics, Vol 47, No 8, pp 2087-2092, 2011.
72. L Piotrowski, B Augustyniak, M Chmielewski, F J G Landgraf and M J Sablik, 'Impact of plastic deformation on magnetoacoustic properties of Fe-2%Si alloy', NDT&E International, Vol 42, No 2, pp 92-96, 2009.
73. B Augustyniak, M Chmielewski, L Piotrowski and Z Kowalewski, 'Comparison of properties of magnetoacoustic emission and mechanical Barkhausen effects for P91 steel after plastic flow and creep', IEEE Transactions on Magnetics, Vol 44, No 11, pp 3273-3276, 2008.
74. M J Sablik, B Augustyniak, M F Campos and F J G Landgraf, 'Modelling of effect of plastic deformation on Barkhausen noise and magnetoacoustic emission in iron with 2% silicon', IEEE Transactions on Magnetics, Vol 44, No 11, pp 3221-3224, 2008.
75. D O'Sullivan, M Cotterell, S Cassidy, D A Tanner and I Mészáros, 'Magnetoacoustic emission for the characterisation of ferritic stainless steel microstructural state', Journal of Magnetism and Magnetic Materials, Vol 271, pp 381-389, 2004.
76. D O'Sullivan, M Cotterell, D A Tanner and I Mészáros, 'Characterisation of ferritic stainless steel by Barkhausen techniques', NDT&E International, Vol 37, No 6, pp 489-496, 2004.
77. H H Huang, J Y Yao, R J Liu and S L Jiang, 'Damage detection of axle housing based on metal magnetic memory testing technology', Journal of Electronic Measurement and Instrumentation, Vol 28, No 7, pp 770-776, 2014.
78. H H Huang, R J Liu, X Zhang, X Wang and Z F Liu, 'Magnetic memory testing towards fatigue crack propagation of 510L steel', Journal of Mechanical Engineering, Vol 49, No 1, pp 135-141, 2013.

79. S X Song, J R Zhao, Z Y Tang, T Ma and T Liu, 'Plastic damage research for drive axle housing remanufacturing', China Mechanical Engineering, Vol 24, No 4, pp 538-541, 2013.
80. S X Song, J R Zhao and T Liu, 'The prediction for the residual life of waste drive axle housing basing on neural network', Advanced Materials Research, Vol 308-310, pp 246-250, 2011.
81. N Xue, L H Dong, B S Xu, C Chen and S Y Dong, 'Characterisation of fatigue damage of crankshaft remanufacturing core by two-dimensional magnetic memory signal', Advanced Materials Research, Vol 538-541, pp 1588-1593, 2012.
82. J B Liao, H F Zhou and D Sun, 'Research for the crack dynamic monitoring of crank shaft of marine diesel engine based on magnetic memory technology', Information Technology Journal, Vol 11, No 4, pp 516-519, 2012.
83. C Ni, L Hua, X K Wang, Z Wang, X P Qin *et al*, 'Coupling method of magnetic memory and eddy current non-destructive testing for retired crankshafts', Journal of Mechanical Science and Technology, Vol 30, No 7, pp 3097-3104, 2016.
84. C L Shi, S Y Dong, B S Xu, P He and J M Lin, 'Eddy current and metal magnetic memory testing for superficial defects of old cylinder barrel before remanufacturing', Proceedings of the 9th National Annual Conference on Nondestructive Testing, pp 624-629, 2010.
85. C L Shi, S Y Dong, W X Tang and H Zhan, 'Eddy current and metal magnetic memory testing non-destructive evaluation for superficial defects of old cylinder barrel', Materials Science Forum, Vol 850, pp 107-112, 2016.
86. J C Leng, Z M Wu, H Zhang and M X Xu, 'Research progress of detection on remanufacturability of sucker rod', Materials Review, Vol 30, No 8, pp 62-67, 2016.
87. J H Yu, 'Magnetic memory testing and intensity failure analysis of fractured bolt of cylinder head on hydrogen gas compressor', Advanced Materials Research, Vol 503-504, pp 772-775, 2012.
88. Y L Zhang, D Zhou, P S Jiang and H C Zhang, 'The state-of-the-art surveys for application of metal magnetic memory testing in remanufacturing', Advanced Materials Research, Vol 301-303, pp 366-372, 2011.
89. B Liu, K Gong, Y X Qiao and S Y Dong, 'Evaluation of influence of present crack burial depth on stress of laser cladding coating with metal magnetic memory', Acta Metallurgica Sinica, Vol 52, No 2, pp 241-248, 2016.
90. B Liu, S J Chen, S Y Dong, C F Fang, Q X Hu *et al*, 'Stress measurement of laser cladded ferromagnetic coating with metal magnetic memory', Transactions of the China Welding Institution, Vol 36, No 8, pp 23-26, 2015.
91. B Liu, Z J Shao and S Y Dong, 'Research on depth evaluation of surface crack in laser cladding coating with metal magnetic memory technology', Applied Mechanics and Materials, Vol 651-653, pp 73-77, 2014.
92. B Liu, 'Ultrasonic and metal magnetic memory testing method for stress and flaw non-destructive evaluation of remanufacturing metal coating', PhD thesis, Harbin Institute of Technology, Harbin, China, 2012.
93. L Hua, W Tian, W H Liao and C Zeng, 'Experimental study of laser cladding specimen under fatigue load by magnetic memory methods', Machinery Design & Manufacture, Vol 8, pp 186-189, 2014.
94. C Zeng, W Tian and L Hua, 'Characterisation of metal magnetic memory of thermal damage correlated with initial cumulative fatigue damage for laser cladding remanufacturing technology', Key Engineering Materials, Vol 525-526, pp 77-80, 2012.
95. H H Huang, G Han, C Yang and Z C Qian, 'Stress evaluation of plasma-sprayed cladding layer based on metal magnetic memory testing technology', Journal of Mechanical Engineering, Vol 52, No 20, pp 16-22, 2016.
96. R Cao, P Wang, G Y Tian and S Ding, 'The relationship between effective hardened layer depth and Barkhausen noise of gear material', Nondestructive Testing, Vol 35, No 10, pp 59-62, 2013.
97. J Siiriäinen, S J Kendrish, T J Rickert and R M Fix, 'Barkhausen noise and its use for quality control of the production of transmission gears', Advanced Materials Research, Vol 41-42, pp 407-419, 2008.
98. B Karpuschewski, O Bleicher and M Beutner, 'Surface integrity inspection on gears using Barkhausen noise analysis', Procedia Engineering, Vol 19, No 1, pp 162-171, 2011.
99. S Santa-aho, M Vippola, A Sorsa, J Latokartano, M Lindgren *et al*, 'Development of Barkhausen noise calibration blocks for reliable grinding burn detection', Journal of Materials Processing Technology, Vol 212, No 2, pp 408-416, 2012.
100. S Santa-aho, M Vippola, A Sorsa, M Lindgren, J Latokartano *et al*, 'Optimised laser processing of calibration blocks for grinding burn detection with Barkhausen noise', Journal of Materials Processing Technology, Vol 212, No 11, pp 2282-2293, 2012.
101. A Sorsa, K Leiviskä, S Santa-aho, M Vippola and T Lepist, 'BARKHAUSEN: A study on laser-processed grinding burn simulation and analysis based on Barkhausen noise measurement', Insight: Non-Destructive Testing and Condition Monitoring, Vol 52, No 6, pp 293-297, 2010.
102. J Fu, 'Based on Barkhausen effect grinding burn of bearing collar detection system design', PhD thesis, Harbin University of Science and Technology, Harbin, China, 2015.
103. J Čížek, M Neslušan, M Čilliková, A Mičietová and O Melikhova, 'Modification of steel surfaces induced by turning: non-destructive characterisation using Barkhausen noise and positron annihilation', Journal of Physics D: Applied Physics, Vol 47, pp 445301-445317, 2014.
104. F M Kolarits, 'Improved grinding quality inspection of large bearing components using Barkhausen noise analysis', AIP Conference Proceedings, 40th Annual Review of Progress in Quantitative Nondestructive Evaluation, Vol 1581, pp 1272-1279, 2014.
105. N Anbuchezhian, K Srinivasan and R Kandasamy, 'Residual stress prediction in welds via the Barkhausen noise technique', Key Engineering Materials, Vol 495, No 6, pp 209-212, 2011.
106. M R Mitchell, R E Link, X Qi, W Wang, X Zheng *et al*, 'Research on the relationship between magnetic Barkhausen noise and ferromagnetic materials with different heat treatments', Journal of Testing & Evaluation, Vol 36, No 6, pp 525-533, 2008.
107. S Sava and C H Gr, 'Monitoring variation of surface residual stresses in shot peened steel components by the magnetic Barkhausen noise method', Insight: Non-Destructive Testing and Condition Monitoring, Vol 52, No 12, pp 672-677, 2010.
108. L Piotrowski, B Augustyniak and M Chmielewski, 'On the possibility of the application of magnetoacoustic emission intensity measurements for the diagnosis of thick-walled objects in the industrial environment', Measurement Science and Technology, Vol 21, No 3, pp 35702-35709, 2010.
109. J W Wilson, G Y Tian, V Moorthy and B A Shaw, 'Magnetoacoustic emission and magnetic Barkhausen emission for case depth measurement in En36 gear steel', IEEE Transactions on Magnetics, Vol 45, No 1, pp 177-183, 2009.
110. M R N Astudillo, M I L Pumarega, N M Núñez, A Pochettino and J Ruzzante, 'Magnetic Barkhausen noise and magnetoacoustic emission in pressure vessel steel', Journal of Magnetism and Magnetic Materials, Vol 426, pp 779-784, 2017.
111. O E Andreikiv, V R Skal'S'Kyi, D V Rudavs'Kyi, O M Serhienko and Y Y Matviiv, 'Magnetoacoustic diagnostics of thin-walled ferromagnets with plane cracks', Material Science, Vol 46, No 6, pp 795-799, 2011.