Magnetic Barkhausen emission technique for detecting the overstressing during bending fatigue in case-carburised En36 steel

V. Moorthy, B.A. Shaw and P. Hopkins

Design Unit, University of Newcastle Upon Tyne, Newcastle Upon Tyne, NE1 7RU, UK,

Transmission Group, MPS IPT, Ministry of Defence (Navy), Bristol, BS34 8JH, UK

Abstract
The effect of bending fatigue at different maximum stress levels on the magnetic Barkhausen emission (MBE) has been studied in case-carburised En36 steel specimens. The low frequency MBE profile has been measured after unloading the specimen at different number of fatigue cycles. It has been found that, beyond 1000 MPa, the MBE peak height decreases just after few thousand cycles and the percentage reduction in the MBE peak increases with maximum bending stress level. The reduction in MBE peak at lower stresses (<1400 MPa) is attributed mainly to the effect of residual stresses becoming more compressive below the surface due to the application prior tensile stress. At higher stresses (1500 MPa), the variation in the MBE peak also indicates the effect of cyclic hardening and softening with progressive fatigue cycles. The MBE profiles measured after monotonic loading and unloading with different maximum stress levels also show similar reduction in the MBE peak with increase in pre-stress level. However, at higher stresses (>1400 MPa), the cyclic loading shows larger reduction in the MBE peak than the monotonic loading. This is attributed to the effect of cyclic microplasticity induced enhancement of dislocation density in addition to the residual stress modification. This study clearly shows the MBE technique can be used to detect the maximum stress level seen by the specimen beyond 1000 MPa. Any overstressing of this case-carburised steel beyond the fatigue limit of 1150 MPa can be easily detected from the percentage reduction in the MBE peak. Since the crack propagation stage is insignificant in these hard steels, the detection of any overstressing using the MBE technique would be very useful in assessing and preventing the impending catastrophic failure.
Key words: magnetic Barkhausen emission, case-carburised steel, bending stress, residual stress.

1. Introduction

Magnetic Barkhausen emission (MBE) is caused by the irreversible movement of magnetic domain walls during cyclic magnetization process in ferromagnetic materials. The domain wall movement and hence the MBE are strongly influenced by the microstructural and stress states of the ferromagnetic material. The MBE technique has been considered as a potential non-destructive testing (NDT) method for evaluation of microstructure and stress in ferromagnetic steels [1-15]. Previous studies [8-15] on the effect of stress on MBE generally show that, due to stress-induced alignment of magnetic moments, the tensile stress increases the MBE while the compressive stress decreases the MBE in the direction of stress in positive magnetostrictive materials like iron and steels. It has also been shown that the plastic deformation strongly affects the MBE [12-14].

Karjalainen et al. [16,17] have conducted cyclic bending tests on normalized low carbon steel at stresses below and above fatigue limit to determine the effect of fatigue loading on MBE. These studies have shown that the MBE can be used to distinguish whether the load is above or below the fatigue limit, thereby allowing prediction of the fatigue life without knowing the actual load level. They have also observed that, at loads above the fatigue limit, the MBE can detect the fatigue hardening and softening processes. Tiitto [18] showed that stress relaxation due to fatigue and overloading can be easily detected by MBE measurements. Govindaraju et al. [19] used the MBE for identifying the fatigue softening, saturation, crack propagation stages during low-cycle fatigue (LCF) in medium strength steel (A533B). Moorthy et al [20] have shown that the low frequency MBE profile can be used to assess the various stages of deformation and fracture during LCF such as cyclic hardening, cyclic softening, saturation and surface crack initiation and propagation in 9Cr-1Mo ferritic steel. These studies indicate that MBE can be used to monitor accumulation of fatigue damage on components exposed to cyclic loading and predict the remaining service life. However, the effect of fatigue on the MBE in case-hardened ferritic steels has not been reported previously.
Since the case-carburised steels have high hardness near the surface, once the crack is initiated, the failure of the component occurs immediately. Hence, it is very useful, if any NDT technique can identify the damage prior to crack initiation. In case-carburised steels, the sharp gradient in the hardness-depth profile would significantly vary the deformation behaviour in the near-surface and subsurface regions. Hence, it is expected that the application of stress, beyond certain level, would alter the residual stress distribution in the depth direction. This would result in significant change in the MBE. Although many studies have previously been conducted on the effect of stress on MBE, in most cases only single parameter like RMS value, MBE energy etc. was used to evaluate the stress. Also, in most of these studies, high frequency MBE measurements have been used to correlate with surface residual stresses. Since the high frequency MBE signal has shallow skin-depth (10µm), it would not detect the stress redistribution in the subsurface region. Previous studies [6,7] show that the low frequency MBE profile indicates the variations in the microstructural gradient in the depth direction in different case-depth specimens. Hence, it is expected that the low frequency MBE profile would also indicate any variations in the residual stress distribution in the depth direction caused by monotonic or cyclic plastic deformation. This study has been carried out to understand the effect of bending fatigue at different stress amplitudes on the low frequency MBE in case-carburised En36 steel.

2. Experimental

The En36 steel widely used in gear manufacturing has been selected for this study. The chemical composition of this steel is given elsewhere [15]. Rectangular bar specimens having 10×12×120 mm size were made and then case-carburised at 935°C with target surface carbon content of 0.72% (wt.) followed by slow cooling. The specimens were again reheated to 820°C for 2hrs followed by oil quenching and tempering at 175°C for 2 hrs. The microhardness-depth profile measurements were carried out using Buehler Microhardness tester with 100 g load. The grain boundary oxidization layer near the surface has been removed by surface grinding. The grinding parameters were selected in such a way to avoid grinding-burn and re-hardening.

The low frequency MBE measurements were made using a Laboratory based MBE system developed in-house at the University of Newcastle Upon Tyne, UK. The details of the MBE system and measurement procedure are given elsewhere [7]. The MBE measurements were
made using 0.2 Hz magnetic excitation frequency and the MBE signal was acquired after 1 kHz high-pass filter and amplification. Residual stress measurements were made using X-ray diffraction method with Cr-Kα X-radiation and the \{211\} reflections with StressTech XSTRESS-3000 system. In order to measure the residual stress-depth profile, the specimens were chemically etched using 10% HF + 40% HNO₃ + 50% H₂O followed by electro-polishing with 10% Perchloric acid and 90 % Butoxyethanol. The time of chemical etching is varied to achieve the desired depth of layer removal.

The specimens were subjected to tension-tension four-point bending fatigue at different maximum bending stress levels ranging from 900 MPa to 1700 MPa with a R-ratio of 0.01 in INSTRON fatigue testing machine using a sine-wave loading at 10 Hz. The MBE measurements were made on the tensile side of the specimen after unloading at different number of cycles at each maximum bending stress level. In order to compare with the effect of monotonic loading, a specimen was subjected to one cycle of loading and unloading with different maximum bending stress levels and the MBE measurements were made on the tensile side of the specimen after unloading from each maximum stress level.

3. Results and Discussion

3.1 Micro-hardness profile

Typical variation of the microhardness in the depth direction for as-ground specimen is shown in Fig. 1. The case-depth in these specimens is defined as the depth below the surface at which the Vickers’ hardness value drops to 550 HV as per the Gear standards. The case-depth for these specimens is about 0.95 mm. The microhardness-depth profile shows sharp gradient in hardness. It is expected that, such variations in hardness profile and hence the gradient in the microstructural and mechanical properties would significantly vary the deformation behaviour within the case-depth. Therefore, cyclic or monotonic plastic deformation, beyond certain stress level, would tend to redistribute the residual stresses, which in-turn would affect the magnetization process and hence the MBE profile.

3.2 Effect of bending fatigue on the MBE

The MBE profiles obtained at different number of fatigue cycles for specimens subjected to maximum bending stress levels of 1050 MPa, 1250 MPa and 1500 MPa are shown in Fig. 2(a-c). The MBE profile is shown as a plot of variation in the RMS voltage of the MBE signal as a function of the voltage applied to the electromagnetic yoke. The MBE profile is shown
for a full cycle of magnetization, but the X-axis is shown only for range of ±15V for better clarity of the profile. The MBE shows good symmetrical profile on both sides of the magnetization cycle as it should be like a magnetic hysteresis loop. The variations in the MBE peak height with number of fatigue cycles for all specimens are shown in Fig.3. Since the MBE signal is attenuated by the electromagnetic eddy current effects, based on the electromagnetic skin depth relation, it is estimated that the detection depth (skin depth) of the low frequency MBE signal would be approximately about 600 - 700 µm from the surface in this case-carburised steel [7]. Hence, any change in the MBE profile is attributed to the changes in the magnetization process occurring within this depth. The variations in the initial MBE peak (Fig.3) among different specimens are due to small variations in case-depth and surface grinding induced residual stress modifications. It can be observed that the MBE profile remains more or less unchanged with increasing number of cycles at 925 MPa (Fig.3). Beyond that stress, the MBE peak has been found to decrease to a certain level and the extent of initial reduction in the MBE peak increases with the maximum stress level (Fig.3).

The fatigue endurance limit for these specimens has been estimated to be about 1150 MPa as evident from the S-N plot shown in Fig. 4. From 1050 MPa up to 1400 MPa (Fig.3), the MBE peak drops down from the initial value to certain level and remains more or less at the same level with increasing number of fatigue cycles till the crack formation. But, at 1500 MPa, it can be observed from Fig. 2(c) that the MBE peak decreases to a minimum level after 250000 cycles and then again increases significantly after 1600000 cycles. Such MBE behaviour has also been observed earlier under low cycle fatigue in 9Cr-1Mo steel [20]. This variation in the MBE peak with progressive number of cycles (Fig.2(c)) indicates the cyclic hardening followed by cyclic softening associated with dislocation generation and rearrangements taking place in larger volume of the specimen before microcrack formation. The cyclic hardening associated with dislocation generation and formation of dislocation tangles reduces the displacement of the magnetic domain walls and hence the MBE peak. The cyclic softening associated with rearrangement of dislocations into cell structure would increase the domain wall displacement and hence the MBE peak [20]. However, such variations in the MBE behaviour could not be clearly observed at lower as well as at higher stress amplitudes. At lower stress amplitudes, the effective stress may not be sufficient to produce significant movement of dislocations. At higher stress amplitudes, the localised crack growth occurs at
much early stage without allowing sufficient number of cycles required for developing changes in the dislocation substructure in larger volume of the specimen.

Figure 2(c) also shows that the MBE peak has increased on the crack as compared to that away from crack. This indicates that the crack location can be detected with scanning of the MBE pick-up sensor. However, it has been observed that the crack growth stage represents only very small fraction in the fatigue life of these case-carburised steel. It has been observed that, after the crack initiation, the specimens fail within just few hundred cycles. Hence, in these case-hardened steels, any prediction of crack growth behaviour becomes meaningless. It has been found that the level of stress amplitude seen by the sample can be detected from the reduction in the MBE peak from as low as 1050 MPa which is below the fatigue limit for these specimens. These results indicate the MBE technique can be more effectively used to assess the maximum level of bending stress seen by the component rather than detecting the various stages of cyclic deformation prior to crack initiation in these case-carburised steel.

The reduction in the MBE peak should be caused either by the development of more compressive residual stress within the case-depth region or by the increase in dislocation density or by both. At lower stress levels (< 1500 MPa), even though, the MBE behaviour (Fig.2(a-b)) does not suggest occurrence of cyclic plastic deformation in different stages as observed at 1500 MPa (Fig. 2(c)), the initial reduction in the MBE peak suggests that there is a definite plasticity induced residual stress redistribution taking place within the skin-depth of the MBE. That means, the reduction in the MBE peak should be caused by increased compressive residual stresses within the case-depth region. The increasing extent of reduction in the MBE peak with maximum bending stress level indicates that the residual stresses within the skin-depth of the MBE (600 – 700 µm below the surface) become more and more compressive with increasing stress amplitude. The plastic deformation under tension taking place in the subsurface region (>500 µm depth) would have resulted in the distribution of more compressive residual stresses in the near-surface region (<500 µm depth) in order to accommodate the strain.

3.3 Comparison of monotonic and cyclic deformation
It is expected that, any change in the residual stress distribution within the case-depth could occur even after just one loading and unloading cycle with a maximum stress level sufficient
enough to cause plastic deformation within the case-depth. In order to compare the effect of maximum stress level on the MBE peak under monotonic and cyclic loading conditions, the specimen had been subjected to one cycle of loading and unloading with different maximum stress level and the MBE profile has been measured after unloading from each maximum stress level. Figure 5 shows the effect of monotonically applied pre-stress level on the MBE profile. It can be observed from Fig.5 that that the MBE peak decreases with increase in maximum stress level just after one cycle (monotonic loading) similar to the effect of cyclic loading (Fig.3). This indicates that the MBE peak is affected by the same effect under both monotonic and cyclic loading conditions. This would be the development of more compressive residual stresses within the case-depth region.

The residual stress-depth profiles for a specimen in the as-ground condition and for specimens unloaded from a maximum tensile bending stress of 1250 MPa and 1700 MPa (monotonic loading) are shown in Fig.6. The residual stress-depth profile supports the argument that the modification of residual stress distribution below the surface causes the reduction in the MBE peak in specimens subjected to tensile bending under both monotonic and cyclic loading conditions. It has been found that, apart from the initial specimen to specimen variations, the surface residual stress did not change significantly after bending. But, just below the surface, from 20 µm up to a depth of 500 µm, the compressive residual stress values have significantly increased after bending. It can also observed from Fig.6 that the increase in bending stress level increases the maximum compressive residual stress level and also extends the depth of enhanced compressive region. This clearly indicates that the residual stresses below the surface gradually become more and more compressive with increasing tensile bending stress level and this effect decreases the MBE peak due to unfavourable alignment of magnetic domains. In case-hardened steel components where the fatigue crack initiates from the surface, the increase in the subsurface compressive residual stresses may not be beneficial.

The percentage reduction in the MBE peak height as a function of maximum bending stress level under monotonic and cyclic loading conditions is shown in Fig.7. It can be noticed that the % reduction in the MBE peak increases with maximum bending stress under both monotonic and cyclic loading conditions, but, with significant difference at higher stresses. It can be noticed that, at lower stress levels up to 1300 MPa, the % reduction in the MBE peak is more or less the same for both monotonic and cyclic loading conditions. But, at higher
stress levels, the % reduction in the MBE peak is larger under cyclic loading than under monotonic loading (Fig.7). This clearly indicates the additional influence of enhanced development of tangled dislocation substructure under cyclic loading at higher stress levels. It is expected that the cyclic micro-plasticity would contribute to the modification of dislocation substructure more significantly than the monotonic plastic deformation. However, under both cyclic and monotonic loading conditions, the residual stress redistribution should occur to accommodate the strain generated by the macro-plastic deformation. It is known that the progressive cyclic plasticity is associated with dislocations generation causing cyclic hardening of the material followed by rearrangement of dislocations into low energy configuration resulting in cyclic softening of the material [20]. Such cyclic hardening is expected to shift the MBE peak position to higher magnetic field and the cyclic softening would shift the peak to lower magnetic field strength [20]. The variations in the MBE peak position (given as voltage applied to the electromagnetic yoke corresponding to the MBE peak, which is directly proportional to applied magnetic field strength) are shown in Figs. 8 and 9 for specimens subjected to cyclic and monotonic loading conditions respectively. It can be observed from Fig.8 that, under cyclic loading, the MBE peak position increases and then decreases. The extent of increase is also larger at higher bending stress level (1500 MPa). But, under monotonic loading, the MBE peak position did not change significantly even after unloading from a tensile bending stress of 1700 MPa (Fig.9). Comparison of Figs. 8 and 9 clearly shows the difference between cyclic and monotonic loading conditions at higher stresses caused by the additional influence of enhanced dislocations generation and rearrangement phenomena associated with progressive cyclic plasticity. The analysis of both MBE peak height and peak position would be useful in distinguishing the effect of residual stresses and modification of dislocation substructure.

In high cycle bending fatigue, even though, the component is subjected to stress levels below the fatigue limit, occasionally the overstressing can occur and this would result in generation more compressive residual stresses below the surface. This would cause finite reduction in the MBE peak from the initial value. Even at a maximum stress level of 1250 MPa, the reduction in MBE peak is 13% (Fig.7). At 1400 MPa, a reduction of about 30% and 20% has been observed in the MBE peak under cyclic and monotonic loading conditions respectively. Considering the good repeatability of the low frequency MBE profiles with progressive number of cycles shown in Fig.2, it is easy to detect even a 10% change in the MBE peak.
The percentage reduction in the MBE peak can be quite reliably considered as an indication of the maximum tensile bending stress level seen by the component. Hence by measuring the change in MBE, any overstressing of the component can be detected as well as estimated. This would help in assessing and evolving the criteria for further service of the component or replacement avoiding catastrophic failure.

4. Conclusions

1. The low frequency MBE measurements can be used to detect the overstressing of the case-carburised En36 steel components subjected to bending fatigue.

2. It has been observed that, beyond a bending stress level 1000 MPa, the MBE peak decreases from the initial level just after few thousand cycles. The percentage of initial reduction in the MBE peak is about 9% at 1050 MPa and it increases almost linearly with the maximum bending stress level to more than 30% at 1500 MPa. The change in the MBE peak detects a bending stress of 1050 MPa which is below the fatigue limit of 1150 MPa in these steels.

3. At lower stress levels up to 1400 MPa, the MBE peak decreases from the initial value to a certain level characteristic of the maximum bending stress and then remains more or less the same with increasing number of fatigue cycles till the crack formation. At higher stress levels (1500 MPa), the variations in the MBE peak with progressive number of cycles indicates the cyclic hardening and softening stages before crack initiation. But, the very rapid crack growth stage does not give any advantage for such identification of different stages in these steels.

4. The residual stress-depth profile measurements clearly show that the reduction in the MBE peak is caused by the modification of residual stress distribution by becoming more compressive below the surface. At higher bending stresses, the cyclic plasticity enhanced dislocation density also contributes to the reduction in the MBE peak resulting in larger reduction as compared to monotonic loading.

Acknowledgements
The authors acknowledge the interest and support of the Research committee of the University of Newcastle and the Ministry of Defence (Navy), UK. The Authors would like to thank Mr. Philip Clarke, M/s David Brown Engineering Ltd., UK for his help in heat-treating the specimens.

References


Fig. 1. Typical microhardness-depth profile in as-ground specimen.
Fig. 2(a).

En36 steel
Maximum stress = 1050 MPa

(a)

RMS voltage of the MBE signal, mV

Voltage applied to the electromagnet, mV

Fig. 2(b).

En36 steel
Maximum Stress = 1250 MPa

(b)

RMS voltage of the MBE signal, mV

Voltage applied to the electromagnet, mV

Number of cycles
- 0
- 500000
- 6000000
- 10000000
Fig. 2 (c).

Fig. 2. The MBE profiles measured at different number of fatigue cycles for specimens tested at maximum bending stress levels of (a) 1050, (b) 1250 and (c) 1500 MPa.
Fig. 3. Variation in MBE peak height as a function of number of fatigue cycles for specimens tested at different maximum bending stress levels.

![Graph showing variation in MBE peak height](image)

**En36 steel**
- Case-depth = 0.95 mm
- R-ratio = 0.01

**Number of cycles to failure**

Fig. 4. S-N curve for the case-carburised and surface ground En36 Steel specimens (Arrow indicates no failure). The dashed line shows the fatigue limit.

![S-N curve graph](image)

Fig. 5. The MBE profiles measured after 1 cycle at each maximum stress level in a case-carburised and surface ground En36 Steel specimen (monotonic loading).

![MBE profiles graph](image)
Fig. 6. Residual stress-depth profiles for the as-ground specimen and for specimens unloaded from 1250 MPa and 1700 MPa after 1 loading cycle in four-point bending (monotonic loading).

Fig. 7. Percentage reduction in the MBE peak in specimens subjected to cyclic and monotonic loading at different maximum bending stress levels.
Fig. 8. Variations in MBE peak position (given as the voltage applied to the electromagnetic yoke corresponding to the MBE peak) with number of fatigue cycles for specimens subjected to bending stress levels of 1250 MPa and 1700 MPa.

Fig. 9. Variation in the MBE peak position (given as the voltage applied to the electromagnetic yoke corresponding to the MBE peak) with maximum bending pre-stress.
levels for a specimen subjected to monotonic loading (measured after 1 cycle at each stress level).