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**Surface and subsurface stress evaluation in case-carburised steel using high and low frequency magnetic Barkhausen emission measurements**

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**Abstract**

The effect of near-surface and subsurface stresses on the Magnetic Barkhausen Emission (MBE) profile has been studied in case-carburised and tempered En36 steel. The high and low frequency MBE measurements were made, on both tensile and compressive sides of the rectangular bar specimens with case-depth of 0.95 mm loaded in cantilever beam, under different stress levels as well as after unloading from different higher stress levels. The high frequency MBE profile showed a single peak while the low frequency MBE profile showed two peaks. Under applied elastic stresses, both types of measurement showed increase in MBE under tension and decrease in MBE under compression. But, the MBE profiles measured after unloading from higher stresses showed different behaviour. On the tensile side, the high frequency MBE profile did not change significantly due to pre-stress. But, in the low frequency MBE profile, the first peak increases and the second peak decreases with increase in pre-stress. On the compressive side, the peak height of high frequency MBE profile decreased gradually with increase in pre-stress. The first peak of the low frequency MBE profile also decreased gradually with increase in pre-stress level. But, the second peak of the low frequency MBE profile decreased by about 10% at a pre-stress level of -1094 MPa and remained more or less the same even after unloading from -1783 MPa. The MBE behaviour has been correlated to the residual stress (RS)-depth profile measured using X-ray diffraction method. This correlation clearly indicates that the high frequency MBE reflects only the changes in surface RS level. It does not indicate RS changes occurring at depths >20 µm below the surface. The low frequency MBE profile reflects the changes in the RS distribution occurring in the near-surface as well as deeper subsurface layers.
Keywords: magnetic Barkhausen emission, applied stress, residual stress, case-carburized ferritic steel.

1. Introduction

Magnetic Barkhausen Emission (MBE) technique is non-destructive testing (NDT) method for evaluation of microstructures and stresses in ferromagnetic steels [1-11]. Certain advantages of the MBE technique such as higher depth of information, faster measurement, portable equipment, capable of measurement on components having complex geometries like gears etc. over the X-ray diffraction method make this as a potential NDT technique for residual stress (RS) evaluation in ferromagnetic steels. Several studies [7-13] made earlier show the effect of applied and residual stresses on MBE in different ferritic steels. From these studies, the general practice for MBE measurements can be broadly classified into two categories, namely, high frequency MBE and low frequency MBE. The high frequency MBE measurement typically involves the use of higher frequency of external magnetic excitation (fex) (>10 Hz) and analysis of MBE signal in the frequency range of 2 to 1000 kHz [7-11]. The low frequency MBE measurement is typically performed at lower magnetic excitation frequency (fex) (<1 Hz) and the MBE signal is analysed in the frequency range of 0.1 - 100 kHz [3,4,6,12]. The maximum depth from which the MBE signal can be detected on the surface (skin-depth) poses a limitation for evaluation of variation in microstructure and stresses in the depth direction. The skin-depth of the MBE is considered to be much lower in high frequency MBE measurement compared to low frequency measurement due to the effects of magnetic field penetration and attenuation of high frequency MBE signal.

The objective of this study is to understand and evaluate the effect of variation in applied and residual stresses in the depth direction on the high and low frequency MBE profiles in case-hardened ferritic steel. In case-carburised steels, the sharp gradient in the microstructure and hardness in the depth direction would significantly vary the deformation behaviour and hence alter the RS redistribution in the depth direction. Earlier studies [14,15] 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 RS redistribution in the depth direction caused by deformation processes.

2. Experimental

The En36 steel used in gear manufacturing had been selected for this study. The chemical composition of this steel is given elsewhere [8]. The rectangular bar specimens (10x12x120mm size) were carburised to a case-depth of 1 mm. The details of case-carburising heat treatment and test specimens preparation are given elsewhere [12,13]. The low frequency MBE measurements have been made using a set-up similar to that described in [12,13,15]. A continuously varying bi-polar symmetrical triangular waveform at a frequency (fex) of 0.2 Hz is fed from a function generator to a bi-polar power amplifier which amplifies the waveform signal and drives a U-shaped electromagnetic yoke made with commercially pure Iron core at ±20 V / ±1A. This generates a maximum applied magnetic field strength (H_{max}) of ±20 kA/m at the centre of the poles of the electromagnet with a pole gap distance of 25 mm. This electromagnetic yoke generates higher magnetic field strength than that used in our earlier studies [12,13,15]. Also, a new ferrite-cored MBE pick-up coil has been used which has higher sensitivity than that used in our earlier studies [12,13,15]. The enhanced magnetic field strength and sensitivity of the MBE pick-up enabled us to detect the MBE signal from much deeper subsurface layers more clearly. The MBE signal has been amplified to a gain of 72 dB and filtered using a 1 kHz high-pass frequency filter. However, majority of the MBE signal comes in the frequency range of 1-20 kHz. The MBE signal and the voltage applied to the electromagnet are acquired using a 2-channel, 12-bit ADC (Pico Technology-ADC-212) through the PicoScope software. The average of MBE signals generated in 4 magnetization cycles has been calculated. The RMS voltage profile of the average MBE signal plotted as a function of the voltage applied to the electromagnet has been used for analysis.

The high frequency MBE measurements have been made using the commercially available μ-Scan / Rollscan 500-2 system supplied by Stresstech, Finland. A standard flat-surface probe with ferrite-cored electromagnet with a pole gap distance of 3 mm and
a ferrite-cored MBE pick-up fixed at the centre of the pole gap has been used. The MBE measurements have been made in the RH125 mode of the system which generates the excitation magnetic field at a frequency \((f_{\text{ex}})\) of 125 Hz. The magnetization gain has been fixed at 30 so that a smooth sine-waveform excitation can be achieved. This generates a \(H_{\text{max}}\) of \(\pm 4\) kA/m at the leg-face of the pole of the electromagnet. The MBE signal gain has been fixed at 40 and the signal has been analysed in the frequency range of 70-200 kHz. The average value of 12 rectified signal bursts, smoothened by sliding average method, is plotted as a function of percentage of the voltage applied to the electromagnet.

In this high frequency MBE measurement system, the RMS value of the MBE voltage pulses induced in the pick-up coil during the magnetization period is calculated and multiplied by a factor of 100 and displayed on a LCD. This displayed number is named as “Magnetic Barkhausen index” or “Rollscan M number” (Rollscan is the commercial name of the system). This parameter has also been used for analysis, because this is widely used in industries as simple quality control parameter.

For correlation with MBE, the residual stress (RS) measurements have been made by the X-ray diffraction method using XSTRESS-3000 system supplied by Stresstech, Finland. All the RS determinations have been made following the standard \(\sin^2\Phi\) method [16]. The entire X-ray controls and measurements are done automatically by the software programme. In this \(\Psi\)-multiple exposure measurement, the centre of specimen surface is exposed to Cr-K\(\alpha\) X-radiation incident at \(\Psi\) angles of 0° (normal to the surface), \(\pm 30^\circ\) and \(\pm 45^\circ\). This was done by tilting the X-ray collimator (3 mm diameter) to both sides of the normal to the surface along the specimen length (which is the \(\phi\) angle and is also the applied stress direction). At each \(\Psi\) angle, the diffracted X-rays corresponding to \{211\} planes of ferrite phase (bcc \(\alpha\)-iron) are detected by placing the detectors at diffraction 2\(\theta\) angle of 156° on both sides of the collimator. The detectors are positioned in an angular arc which is perpendicular to the collimator tilting direction so that the detectors are focussed to the same diffracted X-ray beam at all \(\Psi\) angles. The \(d_{211}\) spacing was calculated for each \(\Psi\) angle and the RS value along specimen length (\(\phi\)-applied stress direction) was calculated from the slope of the best fit line in the plot of \(d_{211}\) spacing versus \(\sin^2\Psi\) using the Young’s modulus value of 196 GPa. In order to measure the
residual stress-depth profile, the small central area (5 mm diameter) of the specimen surface was 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 RS value was determined at each depth to construct the RS-depth profile.

The 120 mm long rectangular bar specimens were subjected to bending in a cantilever beam set-up with extended arm for loading. The top surface of the bar specimen undergoes tension and the bottom surface undergoes compression in bending. Since the specimen length (120 mm) is small compared to the cantilever arm length (890 mm), the stress variation along the specimen length is not very large. However, the central area of the specimen (60 mm from specimen edge) is taken as location for both MBE and residual stress (RS) measurements. Under elastic bending of the specimen in the cantilever beam, the MBE device is placed on the top surface specimen to measure the applied tensile stress effect. The MBE device is shifted to bottom surface of the specimen to measure the applied compressive stress effect. The applied stresses are calculated based on the standard bending moment equation taking into account the geometry of the cantilever beam and the specimen size. This was repeated for different applied elastic stress levels.

For introducing the effect of residual stress alterations, the specimen was subjected to higher applied bending stress levels (top surface of the specimen +1094 MPa and bottom surface -1094 MPa) and then completely unloaded to zero external stress. The RS distribution is expected to be altered differently on both top and bottom surfaces due to constrained plastic deformation of subsurface layers of this material at higher pre-stress levels. The “pre-stress” or “prior applied bending stress” refers to the maximum bending stress applied to the specimen prior to unloading. The MBE and surface RS measurements are made on this specimen after unloading (i.e. the specimen was removed from the cantilever beam set-up) to evaluate the effect of altered residual stresses on MBE signal pattern. To vary the RS alteration to different extent, the specimens were stressed to different higher applied stress levels (±1324, ±1553, ±1783 MPa) and then completely unloaded to zero external stress. After unloading from each of these applied pre-stress levels, both the MBE and surface RS measurements were made on both top and
bottom sides of the same specimen so that their correlation would be more appropriate and valid. To evaluate the progressive effect of these prior applied stress levels on the RS redistribution and compare with MBE response, the RS–depth profiles were measured on as-ground specimen, one specimen unloaded from ±1324 MPa and on another specimen unloaded from ±1783 MPa. Both applied stress effect and RS effect on MBE were also studied on other specimens to validate its repeatability.

3. Results and Discussion

3.1 Micro-hardness profile

The microhardness profile for these specimens is given in [13]. 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. It can be observed [13] that the hardness-depth profile show sharp gradient which indirectly indicates the extent of variations in the near-surface and subsurface microstructures and hence the mechanical properties. It is expected that, such gradient in the hardness-depth profile would significantly alter the deformation behaviour and hence the RS redistribution in the near-surface and subsurface regions. This in-turn would alter the magnetization process and hence the MBE profile.

3.2 Effect of applied elastic bending stress on the MBE profile

The typical effect of applied tensile and compressive stresses on the high and low frequency MBE profiles are shown in Figs.1(a-b) and 2(a-b) respectively. These MBE profiles are measured on the same specimen subjected to different stress levels. The X-axis for the low frequency MBE profile in Fig.2(a-b) is shown only for the voltage range of ±15V for better clarity. It can be observed that the high frequency MBE profiles (Fig.1) show only a single peak and the peak height increases with tensile stress (Fig.1(a)) and decreases with the compressive stress (Fig.1(b)). The low frequency MBE profile shows two peaks (Fig.2(a-b)), peak 1 at lower applied voltage (linearly proportional to applied magnetic field strength) and peak 2 at higher voltage. Both the MBE peaks increase with tensile stress and decrease with compressive.
The reason for single peak MBE profile in high frequency measurements and two-peak MBE profile in low frequency MBE measurements can be explained based on the effect of skin-depth of the MBE signal. The maximum depth from which the MBE signal is detected (skin-depth) depends on many factors such as $H_{\text{max}}$ and its excitation frequency ($f_{\text{ex}}$), permeability of the medium, distance between the poles of the electromagnet, sensitivity of the MBE pick-up coil, analyzing frequency of the MBE signal etc. It is well known that the electromagnetic field strength decays exponentially in an infinitely expanded space into the depth direction perpendicular to the surface. Therefore, unless sufficiently strong magnetic field strength at lower excitation frequency is applied to the material, larger skin-depth of MBE signal can not be achieved. It is also known that the MBE signal is attenuated by the eddy current opposition to an extent that depends on the frequency of the signal. The MBE signal could be generated in wide frequency bandwidth ranging from excitation frequency to greater than 1 MHz. Since the high frequency signals are more strongly attenuated, it should be appropriate to use lower analyzing frequency to enhance the skin-depth of the MBE signal. However, the lower-end of the analyzing frequency range has to be optimized in order to avoid the interference from upper harmonic of the external magnetic excitation frequency ($f_{\text{ex}}$). For case-carburised En36 steel with the electrical conductivity value of $3.15 \times 10^6 \ \Omega^{-1} \ m^{-1}$ [17], assuming a relative permeability value of 200, the approximate frequency dependent skin-depth of the MBE signal estimated from the standard electromagnetic skin-depth relation [18] would be about 635 $\mu$m for 1 kHz signal and 76 $\mu$m for 70 kHz signal. However, the actual detection depth of the MBE signal would significantly vary depending on the other measurement parameters mentioned above and affect the MBE profile. For example, the low frequency MBE profiles for the same batch of specimens measured earlier [12,13] (using an electromagnet with lower $H_{\text{max}}$ and a MBE pick-up coil having lower sensitivity) showed only a single peak whereas the present study shows clear two peaks in the MBE profile (Fig.2).

It has been shown and explained in an earlier study [15] that, in case-carburised steels, the magnetization process in the near-surface (approximately <300 $\mu$m depth from surface) and in the subsurface (approximately >300 $\mu$m depth from surface) would occur in different magnetic field ranges. The low hardness subsurface region would easily
magnetize at lower magnetic field strength giving rise to MBE peak 1 and harder near-surface region would undergo magnetization only at higher field strength resulting in MBE peak 2 (Fig.2). The observation of two-peak profile is possible only in the low frequency MBE measurement due to its higher $H_{\text{max}}$, higher skin-depth of the low frequency MBE signal and the high sensitivity of the MBE pick-up. Also, it can be observed that the peak 1 height is less than peak 2 in spite of the fact that the subsurface region has low hardness and is expected to give stronger MBE signal. This is due to the effect of attenuation of the MBE signal generated at the deeper layers. Since the high frequency MBE measurements are made with lower $H_{\text{max}}$ and higher excitation frequency and higher analyzing frequency, the skin-depth of the MBE signal is expected to be very shallow limited to near-surface layers and hence the MBE profile shows only single peak. Therefore, the high frequency MBE profile can be related to only changes in the near-surface region whereas the low frequency MBE profile can be related to changes occurring in much larger depths.

The effect of applied elastic tensile and compressive stresses on the MBE activity (Figs.(1-2)) is similar to that observed in other studies in the literature [8-11]. This is attributed to the favourable alignment of magnetic domains under tensile stress which enhances MBE activity and unfavourable alignment under compressive stress which reduces the MBE activity. It can be observed from Fig.1(a-b) that, in the high frequency MBE profiles, under applied stresses, the overall voltage (applied magnetic field) range in which there is detectable MBE activity tend to increase with tensile stress level Fig.1(a) and decreases with compressive stress level Fig.1(b). But, in the low frequency MBE profiles, the overall voltage (applied magnetic field) range in which there is detectable MBE activity did not change with tensile stress Fig.2(a). Within a fixed range of field strength, the MBE activity increases with tensile stress. Under compressive stress, it can be clearly observed that the MBE peak 2 position shifts to higher voltage with compressive stress and the MBE activity occurs in the extended magnetic field range Fig.2(b). This difference between the behaviour of low and high frequency MBE profiles clearly indicates the effect of $H_{\text{max}}$ applied in low and high frequency MBE measurements. In low frequency MBE measurements, the $H_{\text{max}}$ is sufficiently high to strongly magnetize the specimen even under compressive stress whereas in the high
frequency MBE measurement, the $H_{\text{max}}$ is not sufficient enough to take the specimen over a major magnetic hysteresis cycle.

In the high frequency MBE measurements, under applied tensile elastic stress, the peak height increased by $\sim 3.5$ times over a stress range of 452 MPa (Fig. 1(a)) while under applied compressive stress, it decreased by $\sim 4$ times for the same range (Fig. 1(b)). In the low frequency MBE measurements, the peak 1 is increased by $\sim 1.5$ times and peak 2 increased by $\sim 2$ times over an applied tensile stress range of 425 MPa (Fig. 2(a)). Under compression, the peak 1 decreased by $\sim 1.8$ times and peak 2 by $\sim 2.1$ times for the same stress range (Fig. 2(b)). The higher rate of reduction of MBE peak under compressive stresses could be due to the added influence of residual compressive stresses already present in the specimen caused by case-carburization heat treatment process. The amount of changes in the MBE level to the effect of applied stresses in low frequency MBE measurement is smaller than that in high frequency MBE measurement. This is mainly due to the effect of rate of change of applied magnetic field ($dH/dt$) and the effect of averaging of the MBE signal over depth. It is known that the MBE level depends on the $dH/dt$ and hence the high frequency MBE measurement is expected to give larger change in MBE level as compared to low frequency MBE measurement where the $dH/dt$ is low and also the MBE signal is averaged over larger depth. The effect of averaging over larger depth can also be observed even from the difference in the amount of changes in the peak 1 and peak 2 of the low frequency MBE profile. The amount of changes in peak 1 is less than that in peak 2, particularly on the tensile side (Fig. 2(a)). This is due to the effect of increasing stress gradient in the depth direction in a bar specimen subjected to cantilever beam bending, which would result in relatively higher stresses near the surface than the subsurface. It is also important to notice that the stress sensitivity of MBE signal also depends on material properties like chemical composition, microstructure and hardness etc.

### 3.3 Effect of pre-stress on the MBE profile

The typical effects of higher level of tensile and compressive pre-stresses on the high and low frequency MBE profiles are shown in Figs. 3(a-b) and 4(a-b) respectively. These MBE profiles were measured on the tensile and compressive sides of the same
specimen after unloading from different stress levels. It is known that the MBE is strongly affected by the variation in microstructure and stresses. Since these tests were carried out at room temperature, there is no change in the basic microstructure of the specimens. It has been shown earlier that the large increase in dislocation density tends to decrease the MBE due to reduction in the mean free path of the displacement of magnetic domain walls [6]. It has also been shown earlier that, during cyclic deformation, the rearrangement of tangled dislocations into low energy dislocation substructure increases the MBE peak. However, this requires large number of stress cycles with high amplitude [13,19]. At the monotonically applied stress levels used in this study, the changes in dislocation density and its substructure would not be very significant within the case-depth region due to higher hardness. However, it can be expected that the deeper subsurface region (case-core interface) would plastically yield and result in significant redistribution of residual stresses in the near-surface and subsurface regions within the case-depth due to accommodation of strain. Hence, it is more appropriate to relate the variations in the MBE with the changes in the RS values.

It can be observed from Fig.3(a-b) that the tensile pre-stress did not significantly alter the high frequency MBE profile whereas the compressive pre-stress, decreases the MBE peak with increase in pre-stress level. The RMS value (Rollscan M number) of the high frequency MBE (Fig.5) also reflects the same behaviour. The low frequency MBE profiles (Fig. 4(a-b)) show very different behaviour to the effect of pre-stress. It can be observed from Fig. 4(a) that the peak 1 increases whereas the peak 2 decreases with increase in tensile pre-stress level. On the compressive side, the MBE peak 1 decrease gradually with increase in pre-stress level while the peak 2 decreases to certain level and then remains more or less the same (Fig. 4(b)). It is also interesting to note that, on the tensile side (Fig.4(a)), the peak 2 position did not change significantly whereas on the compressive side (Fig.4(b)), the MBE peak 2 position (and the profile) shifts to higher field with increase in pre-stress level.

The high frequency MBE behaviour (Figs.3 and 5) suggests that, on the tensile side, the pre-stress would not have significantly changed the near-surface RS values while on the compressive side, the RS values would have become more compressive in the near-surface layers. On the other hand, the low frequency MBE behaviour (Fig. 4(a))
indicates that, on the tensile side, the near-surface RS values would have become more compressive (indicated by peak 2) and the subsurface RS values would have become less compressive (indicated by peak 1) with increase pre-stress level. The low frequency MBE profiles measured on the compressive side (Fig.4(b)) indicate that the near-surface RS values would not have changed progressively to a large extent (indicated by peak 2) compared to tensile side (peak 2 in Fig.4(a)) and the subsurface RS values would have become more compressive (indicated by peak 1) with increasing compressive pre-stress level.

It is important to note that the low frequency MBE profile shows significant changes in the MBE peak 1 which is an indication of RS alterations occurring in the subsurface layers. Such information is not possible to obtain from high frequency MBE measurements. The peak 2 of the low frequency MBE profile and high frequency MBE profile indicate changes occurring in the near-surface layers, but differently (Fig.3 and 4). The reason for this difference in high and low frequency MBE behaviour should be due to the large difference in the skin-depth of the MBE signal.

### 3.4 Correlation of pre-stress induced residual stress redistribution with the MBE

The variation in the surface RS values after unloading the specimen from different pre-stress levels is shown in Fig.6. The RS-depth profiles for, a specimen in the as-ground condition, a specimen unloaded after pre-stressing to ±1324 MPa and a specimen unloaded from ±1783 MPa are shown in Fig.7. The error in these RS measurements varies by as much as ±43 MPa. However, the error bars are not included in the plots (Figs.6 and 7) for the sake of clarity. It is worth mentioning here that, the surface RS values vary significantly from specimen to specimen even in normal as-ground condition. This is caused by inherent variations in the grinding process. To this effect, the high frequency MBE also showed larger variation between specimens in normal as-ground condition compared to low frequency MBE. This is again due to the effect of averaging of deeper layers involved in the low frequency MBE profile. Another separate study is in progress to evaluate the grinding damage induced RS alterations. However, in this study, the effect of pre-stress on the progressive changes in the surface RS values and the redistribution of RS-depth profile can be relatively compared and correlated. The
correlation of pre-stress induced modification in RS values with MBE has been made based on the RS changes occurring in the surface, near-surface (< 300 µm depth) and subsurface (> 300 µm depth) regions.

It can be observed from Fig.6 that the surface RS value remains more or less the same on the tensile side of the specimen whereas it becomes increasingly more compressive on the compression side. The pre-stress alters the RS values below the surface in the depth direction significantly as can be observed from Fig.7. On the tensile side, the RS values has become increasingly more compressive (from 20 µm upto about 200 µm depth) and then again gradually become less compressive. It can also be noted from Fig.7 that the pre-stress level affects the RS distribution. The increasing tensile pre-stress level increases the maximum compressive RS value and also tends to increase the depth at which it occurs (Fig.7). On the compressive side, apart from the changes on surface (Fig.6), the RS values are more or less the same as the as-ground specimen upto about 200 µm and then slowly become less compressive at higher depth (Fig.7).

Normally, in materials with homogeneous microstructure, the constrained plastic deformation under applied tensile stress is expected to produce compressive residual stress and vice versa. But, in case-carburised steel, the sharp gradient in hardness-depth profile would cause significant constraint on the deformation behaviour of near-surface and subsurface layers. Since the near-surface (< 300 µm depth) hardness is quite high, extensive plastic deformation with large increase in dislocation density is unlikely even at the stress level of 2000 MPa. However, the subsurface (> 300 µm depth) can undergo significant plastic deformation and the resultant strain accommodation would cause significant alterations in the RS distribution, both near the surface as well as in the subsurface regions as can be observed from Fig.7. These effects are reflected by the behaviour of MBE profiles.

3.4.1 Near-surface residual stress redistribution

Comparing the high frequency MBE plot in Fig.5 (Rollscan M number) with the changes in the surface RS values shown in Fig.6 (The MBE (Figs. 3 to 5) and RS (Fig.6) were all measured on the same specimen), it can be considered that the high frequency MBE clearly reflects the changes in the surface RS values due to pre-stress. But, it does
not reflect the changes in RS values occurring below the surface even at 20 µm depth. In particular, on the tensile side, the RS value become more compressive below the surface (Fig.7) and is expected to decrease the MBE level. But the high frequency MBE did not change significantly on the tensile side of the specimen (Figs.3(a) and 5). Hence, it can be concluded that the high frequency MBE reflects only the changes in RS value on the surface and it could not reveal the changes occurring at depths > 20 µm below the surface. However, it may be possible to enhance the skin-depth of the high frequency MBE by using higher magnetic field strength and lowering the analyzing frequency of the MBE signal well below 70 kHz used in this study.

As mentioned earlier, the peak 2 of the low frequency MBE profile can be related to the changes occurring in the near-surface region up to ~ 300 µm depth below surface. The variation in the peak 2 of the low frequency MBE profile (Fig.4(a-b)) clearly reflects the changes in the RS distribution taking place in the near-surface region (< 300 µm depth in Fig.7). On the tensile side, the gradual decrease in the MBE peak 2 (Fig.4(a)) reflects the effect of RS values becoming more compressive below the surface (Fig.7). On the compressive side, after the initial reduction, the more or less constant value of the MBE peak 2 (Fig.4(b)) support the fact that the RS values below the surface did not changes significantly with pre-stress level (< 300 µm depth in Fig.7). However, the shift in the MBE peak 2 profiles to higher field (Fig. 4(b)) may be considered as an indication that the surface RS value becomes increasingly more compressive with pre-stress level as observed from Fig.6 The low frequency MBE profile clearly indicates the net changes in the RS values in deeper layers below the surface compared to high frequency MBE. But it may not clearly distinguish the changes occurring at the surface alone, particularly, when the changes below the surface dominate.

3.4.2. Subsurface residual stress redistribution

The peak 1 of the low frequency MBE profile can be considered to indicate the changes occurring in the subsurface region (> 300 µm depth below surface). The gradual increase in the height of peak 1 with increasing tensile pre-stress level (Fig.4(a)) indicates that, on the tensile side, the RS values in the subsurface layers (> 300 µm depth below surface) would have become less compressive compared to as-ground specimen. On the
compressive side, the gradual decrease in the height of peak 1 with increasing pre-stress level (Fig.4(b)) indicates that, the RS values in the subsurface layers (> 300 µm depth below surface) would have become more compressive compared to as-ground specimen. But, such effect is not revealed in the measured RS-depth profiles on both sides (Fig.7). In fact, the measured RS profile indicates that, on the tensile side, the RS values are more compressive in the depth upto about 500 µm compared to as-ground specimen and more or less unaffected at higher depth (Fig.7). This is expected to decrease the MBE peak 1. But, in fact, Fig.4(a) clearly shows the opposite effect that the MBE Peak 1 increases with tensile pre-stress level. On the compressive side, the measured RS-depth profile (Fig.7) indicates the RS values at larger depth become less compressive compared to as-ground specimen and this is expected to increase the MBE peak 1. But again, Fig.4(b) clearly shows opposite effect that the MBE peak 1 decreases with compressive pre-stress level.

Considering the fact that the skin-depth of the low frequency MBE signal would not be greater than the case-depth of these specimens (0.95 mm), it is more appropriate to relate to the changes in the MBE peak 1 to that occurring within the case-depth region. As mentioned earlier, since the original microstructure and the dislocation density within the case-depth region would not change significantly due to pre-stress, it can be argued that the systematic variation in the peak 1 of low frequency MBE profile is definitely due to the RS changes occurring in the subsurface layers (> 300 µm depth below surface). But, they do not correlate with measured RS values as mentioned above. Hence, it is required to find out the reasons for this discrepancy between the measured RS values at deeper layers and the behaviour of the MBE peak 1. The RS-depth profile measurement has been made by successive removal of layers of the specimen by chemical etching followed by electrochemical polishing before stress measurement by X-ray diffraction. It is well known that, any material removal can disturb the over-all equilibrium and result in redistribution of residual stresses. This can cause significant variation in the measured RS value in the exposed surface compared to its original value (before any layer removal). Since the alteration of residual stress occurs after each material removal and its effect is cumulative, the deviation of the measured values from the original stress values is particularly more and very significant at larger depths. It has been shown that the
measured RS value deviates by more than 40% from their original (or corrected value) at depth >200 µm below the surface [20]. Normally, the correction to measured RS values at a given depth is evaluated using an equation represented in terms of the measured RS value on the surface (at the original thickness) and its higher order derivatives [20].

In order to understand the effect of correction on the measured RS-depth profile, a first term correction method described in [20] has been followed and applied to measured RS values. Figure 8 shows the measured and corrected RS-depth profiles for as-ground specimen and a specimen subjected to a pre-stress of ±1783 MPa. On the tensile side, the corrected RS values become less compressive, particularly in the subsurface region (>500 µm depth). But, it is not significantly less, compared to the corrected RS values in as-ground specimen to support the increase in MBE peak 1 with tensile pre-stress (Fig.4(a)). On the compressive side also, the corrected RS values become less compressive and even become tensile beyond 800 µm depth. This behaviour is just opposite to that required to support the decrease in the MBE peak 1 with compressive pre-stress (Fig.4(b)). This residual stress correction did not support the arguments made from the behaviour of MBE peak 1 on both tensile and compressive sides. However, this stress correction is based on linear elastic theory and is normally applied in structural materials having uniform microstructure and mechanical properties across the section and also the correction had been shown to be valid only to shallow depths. Also, this type of correction factor largely depends on the surface residual stress value. In case-hardened steel used in this study, the mechanical properties would vary significantly in the depth direction and would result in non-linear deformation in the near-surface and subsurface layers. In this case, the residual stress redistribution within the case-depth region is mainly due to accommodation of strain generated by plastic deformation of deeper core region. Hence, any significant layer removal would alter the RS distribution in deeper core region and this would also have an effect on the RS distribution within case-depth region. Hence, it may not be appropriate to apply this type of stress correction to such situations. It needs further understanding to predict the actual RS-depth profile in case-hardened steels. If we consider only the core material, neglecting the case-depth region, it can be expected that the tensile pre-stress would induce compressive RS and vice versa. Hence, it can be argued that, some balancing RS redistribution is taking place in-between the core (>1000
µm depth) and the near-surface regions (<300 µm depth), which might affect the low frequency MBE peak 1. However, it can be certainly considered that the low frequency MBE profile reflects the changes in the RS values within the case-hardened region. Further study is in progress to understand the subsurface RS distribution and its effect on the MBE by varying the magnetic field penetration depth.

4. Conclusions

1. The high frequency MBE profile shows only a single peak whereas the low frequency MBE profile shows two peaks in case-carburised En36 steel. This attributed to the shallow skin-depth of the MBE signal in high frequency measurements and higher skin-depth in low frequency MBE measurements.
2. The peak 1 and peak 2 of the low frequency MBE profile are attributed to the effect of magnetization process in the subsurface layers (>300 µm depth) and near-surface layers (<300 µm depth) respectively.
3. Both low and high frequency MBE profiles show similar variations to the applied stresses. But, they show different behaviour to the effect of pre-stresses.
4. The high frequency MBE clearly reflects the changes in the surface RS values due to pre-stress. But, it did not indicate the changes in RS values occurring at depths > 20 µm below the surface. This is attributed to the limitation on the skin-depth of the high frequency MBE signal. However, it is considered that, by increasing the applied magnetic field strength and decreasing the analyzing frequency to optimum level, it may be possible to increase this detection depth.
5. The variation in the peak 2 of the low frequency MBE clearly reflects the pre-stress induced RS changes occurring in the near-surface region (<300 µm depth).
6. The variation in the peak 1 of the low frequency MBE profile suggests that the pres-stress induced RS values in the subsurface (> 300 µm depth) become less compress on the tensile side and more compressive on the compressive side. But the measured RS-depth profile did not show such effect in the subsurface layers. Such discrepancy between the variation in the MBE peak 1 and measured RS values is attributed to the error in the measured RS values at larger depths due to
redistribution of residual stresses caused by material removal during depth profile stress measurements.

7. This study clearly shows that the high frequency MBE can be used to evaluate the changes in surface residual stresses. The low frequency MBE profile would be very useful to evaluate the residual stress redistribution at much larger depths.

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Fig.1. The high frequency MBE profiles for different applied stress levels (a) Tensile side and (b) compressive side.

Fig.2. The low frequency MBE profiles for different applied stress levels (a) Tensile side and (b) compressive side.

Fig.3. The high frequency MBE profiles for different pre-stress levels (a) Tensile side and (b) compressive side.

Fig.4. The low frequency MBE profiles for different pre-stress levels (a) Tensile side and (b) compressive side.

Fig.5. The variation in the Rollscan M number (RMS value of the high frequency MBE signal multiplied by 100) for different prior applied bending stress levels (MBE measured after unloading from each stress level).

Fig.6. The variation in the surface residual stress value for different prior applied bending stress levels (RS measured after unloading from each stress level).

Fig.7. The variations in residual stress values as a function of depth below surface for, a specimen in the as-ground condition, a specimen unloaded from ± 1324 MPa and a specimen unloaded from ± 1783 MPa.

Fig.8. Comparison of measured and corrected residual stress values as a function of depth below surface for a specimen in the as-ground condition and for a specimen unloaded from ± 1783 MPa.
Fig. 1(a-b)
Fig. 2(a-b)
En36 steel
Case-depth = 0.95 mm
Tensile side
fex = 125 Hz

(a)

Pre-stress, MPa
0
1094
1324
1553
1783

Average MBE value, % of 5V
% of voltage applied to electromagnet

En36 steel
Case-depth = 0.95 mm
Compressive side
fex = 125 Hz

(b)

Pre-stress, MPa
0
-1094
-1324
-1553
-1783

Average MBE value, % of 5V
% of voltage applied to electromagnet

Fig. 3(a-b)
Fig. 4(a-b)
Fig. 5

Case-depth = 0.95 mm

Rollscan M value, A.U

Prior applied bending stress, MPa

Tensile side

Compressive side

Fig. 6

Surface residual stress, MPa

Case-depth = 0.95 mm

Prior applied bending stress, MPa

Tensile side

Compressive side
Fig. 7

Fig. 8