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Magnetic Barkhausen emission technique for evaluation of residual stress alteration by grinding in case-carburised En36 steel

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Abstract

The effect of residual stress changes caused by grinding on the Magnetic Barkhausen Emission (MBE) has been studied in case-carburised En36 steel. Both high and low frequency MBE measurements were made on specimens with case-depth of 0.55 and 0.8 mm subjected to varying level of grinding damage. The high frequency MBE profile shows single peak while the low frequency MBE profile shows two peaks. The first peak is not affected by grinding damages. But, the second peak increases and shifts to lower field systematically indicating the changes in microstructure and residual stresses. Both high and low frequency MBE measurements have been correlated to residual stress (RS)-depth profile measured using X-ray diffraction method. The high frequency MBE indicates the changes in surface RS, but does not indicate changes in RS at depths >10 μm. The low frequency MBE profile indicates the changes in RS below the surface.

Keywords: magnetic Barkhausen emission, grinding, residual stress, case-carburized steel.

1. Introduction

Magnetic Barkhausen Emission (MBE) technique is non-destructive testing (NDT) method for evaluation of microstructures and stresses in ferromagnetic steels [1-16]. Certain advantages of the MBE technique such as higher depth of information, faster measurement, portability of 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 assessing the grinding damages in ferromagnetic steels. Several studies [5-14] made earlier show the effect of 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 (>10 Hz) and analysis of the MBE signal in the frequency range of 2 to 1000 kHz [5-12]. The low frequency MBE measurement is typically performed at lower magnetic excitation frequency (<1 Hz) and the MBE signal is analysed in the frequency range of 0.1 - 100 kHz [1-4, 13-16]. The maximum depth of MBE signal that can be detected on the surface (skin depth) poses is 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 variations in the grinding process parameters result in defects manifesting as grinding-burn and/or rehardening. These grinding defects are associated with significant alterations to the microstructure and residual stresses in the near-surface and/or in the subsurface region of the components. Normally, the conventional Nital (Nitric acid in alcohol) etch testing would identify the microstructural damage on the surface. However, in some cases, it is possible that, due to the immediate effect of coolant flow, the surface layers may not get damaged, but high heat input is likely to affect the subsurface layers. In some cases, regrinding is done to remove the previously damaged surface layers. However, if the regrinding is not done properly to remove the entire damaged layer, the subsurface layers may still contain damage and could not have been detected. Hence, it would be very useful to assess both the near-surface and subsurface damages in ascertaining the structural integrity of the component.

Earlier studies showed that the high frequency MBE measurements reveal the changes in the surface residual stresses caused by grinding and deformation processes [11,12]. It has been shown earlier [15,16] that the low frequency MBE measurement indicates the variations in the microstructural gradient in the depth direction in different case-depth specimens due to the large skin-depth of the MBE signal. It has also been shown recently [13,14,17] that the low frequency MBE profile would also indicate the redistribution of residual stresses occurring near the surface as well as in deeper subsurface layers caused by constrained plastic deformation. The objective of this study is to understand and evaluate the effect of surface grinding induced changes in residual stresses on the high and low frequency MBE profiles in a case-carburised En36 steel.

2. Experimental

The En36 steel used in gear manufacturing had been selected for this study. The chemical composition of this steel is given elsewhere [7]. One set of rectangular bar specimens having 10×12×120 mm size denoted as “C” were case-carburised to a case-depth of 0.75 mm and another set denoted as “D” to higher case-depth of 1 mm. The details of case-carburising heat treatment are also given in [13,14]. In order to remove the oxidised grain boundary layers near the surface and to achieve the plane parallel surfaces and exact dimension, these as-heat treated specimens were subjected to normal surface finish grinding process. During this grinding process, the grinding parameters were carefully selected in order to avoid or minimize any grinding damage. Then, these specimens were subjected to abusive grinding in the same surface grinding machine. The grinding direction is along the length of the specimen. The grinding damages to different levels were introduced by varying the depth of cutting, feed rate and coolant flow rate. The depth of cutting was varied from 5 to 20 μm. In this surface grinding machine, the feed rate and coolant flow rate are controlled manually and were not quantified. The feed rate was varied between medium and high levels and coolant flow rate was varied between high and low conditions. The top (T) and bottom (B) sides of the specimens were subjected to different levels of grinding damage using different set of grinding parameters.

The low frequency MBE measurements have been made using a set-up similar to that described in [13,14,16]. 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 of 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 [13,14,16]. Also, a new ferrite cored MBE pick-up coil has been used which has higher sensitivity than that used in our earlier studies [13,14,16]. 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 [16]. 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 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 (fex) 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_{max} of ±4 kA/m at the leg-face of the pole of the electromagnet. The MBE signal gain has been fixed at 30 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.

Surface and depth profile of residual stress (RS) measurements have been made using X-ray diffraction technique. The RS along the grinding direction (specimen length) was measured using the standard $\sin^2\Psi$ method described in [14,17]. The retained austenite measurements have also been made using X-ray diffraction method based on the ratios of area under {211} and {200} diffraction peaks corresponding to ferrite phase and {220} and {200} peaks corresponding to austenite phase.

3. Results and Discussion

3.1 Micro-hardness profile

The typical microhardness profiles for these two types of specimen after finish grinding are given 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 after finish grinding for specimens denoted as "C" is ~ 0.55 mm and for specimens denoted as "D" is ~ 0.8 mm. Table 1 shows the comparison of hardness, residual stress and retained austenite content on the surface of as-heat treated and different ground specimens. The abnormal grinding did not cause large reduction in the surface hardness level. However, it caused significant changes to the surface residual stresses. Considering the error involved in the X-ray diffraction measurement of retained austenite content which is about 5%, it is difficult to attribute significant variations among different specimens. However, it could be relatively considered that the lower case-depth "C" specimens may have slightly higher retained austenite level than "D" specimens. During the grinding process, due to the immediate cooling effect, it is likely that the surface hardness might not have reduced significantly, but the thermal effect could have softened the microstructure below the surface and reduced the subsurface hardness significantly. The synergistic influence of plastic deformation and thermal effect induced modification of microstructure during abnormal grinding process would also alter the residual stress distribution below the surface. Such reduction in the hardness and changes in the residual stresses would strongly alter the magnetization process and hence the MBE profile. It would be interesting to know, how the high and low frequency MBE profiles reflect these alterations due to variations in grinding process.

3.2 Comparison of as-heat treated and ground specimens

It is expected that the initial surface finish grinding operation would reduce the case-depth of the specimen. In some cases, it is also likely that the microstructure and residual stresses may be altered due to inherent variations in the grinding parameters causing significant thermal effects. The comparison of MBE in as-heat treated specimens and ground specimens with lowest damage are shown in Figs. 2 and 3 for high and low frequency MBE measurements respectively. It can be noticed that the high frequency MBE profile shows only single peak (Fig.2) whereas the low frequency MBE profile shows two peaks (Fig.3). The basic difference in the high and low frequency MBE profile is attributed to the effect of difference in the skin-depth of the MBE signals in high and low frequency measurements.

The maximum depth from which the MBE signal is detected (skin-depth) depends on many factors such as H_{max} and its excitation frequency (fex), permeability of the medium, distance between the poles of the electromagnetic yoke, sensitivity and frequency response of the MBE pick-up coil, analyzing frequency range 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 MBE signal analyzing frequency range has to be optimized in order to avoid the interference from the upper harmonics of the external magnetic excitation frequency (fex). For case-carburised En36 steel with the electrical conductivity value of $3.15 \text{ X } 10^6 \ \Omega^{-1} \text{ m}^{-1}$ [18], 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 [19] would be about 635 μm for 1 kHz signal and 76 μm 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 as-heat treated specimens “D” (1 mm case-depth) measured earlier [16] (using an electromagnet with lower H_{max} and a MBE pick-up coil having lower sensitivity) showed only a single peak whereas the present study shows two-peak MBE profile (Fig.3).

It has been shown and explained in an earlier study [16] that, in case-carburised steels, the magnetization process in the near-surface (approximately <300 μm depth from surface) and in the subsurface (approximately >300 μm depth from surface) would occur in different magnetic field ranges. The low hardness subsurface region (>300 μm depth) would easily magnetize at lower magnetic field strength giving rise to MBE peak 1 and harder near-surface region (<300 μm depth) would undergo magnetization only at higher field strength resulting in MBE peak 2 (Fig.3).

The observation of two-peak profile is possible only in the low frequency MBE measurement due to its higher H_{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_{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 (Fig.2). 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.

It can be observed that the high frequency MBE shows large increase in the peak height of the both types of specimen (C and D) after grinding (Fig.2). In the as-heat treated condition also, the specimen “C” shows slightly higher MBE peak than “D”. This may be attributed to the difference in their surface RS values (Table 1). The large increase in peak after grinding is due to the combined effect of surface RS value becoming less compressive and reduction in near-surface hardness value due to grinding.

It can be noticed from the low frequency MBE profiles (Fig.3) that, both peak 1 and peak 2 increased after grinding. In as-heat treated condition, the peak 1 is larger in specimen “C” than in “D”. This is attributed to the lower case-depth of the specimen “C” (0.75 mm) than specimen “D” (1 mm). The lower hardness in the subsurface layers of “C” results in higher MBE peak 1 as explained in the previous study [16]. After the surface finish grinding, the case-depth of specimens “C” and “D” decreased to 0.55 mm (C2T) and 0.8 mm (D3T) (Fig.1) respectively. This effect can be found from the increase in the peak 1 of the MBE profile for both types of specimen (Fig.3). This is because of the fact that, as the case-depth decreases, the relative amount of the MBE signals from the low hardness subsurface region (>300 μm depth) reaching the surface increase and that result in increase in peak 1 height [16]. Also, near the surface (<300 μm depth), the combined effect of RS values becoming less compressive and reduction in hardness value due to grinding would increase the MBE peak 2 as can be observed from Fig.3. It can also be noticed that the ascending profile of the MBE peak 2 shifts to lower voltage (proportional to applied magnetic field) in ground specimens. This is more significant in specimen D3T compared to C2T. This suggests that the surface finish grinding might have caused softening of the microstructure near the surface to a larger extent in D3T than in C2T.

It can be considered that the high frequency MBE profile would show only changes to the near-surface properties due to grinding whereas the two-peak low frequency MBE profile would indicate the reduction in case-depth after large amount of layer removal by normal grinding as well as the modification of near-surface properties due to abnormal grinding.

3.3 Effect of abusive grinding damage on the MBE profile

The effect of abusive grinding damages in these two types of specimen on the high and low frequency MBE profiles are shown in Figs. 4(a-b) and 5(a-b) respectively. It has been observed that the scatter in the peak height of the high frequency MBE profile is normally within ±2% of 5V full scale (Fig.4). The scatter in the peak height of the low frequency MBE profile is within ±50 mV (Fig.5).

It can be observed from Fig.4(a) that the high frequency MBE peak is significantly high only in Specimen C3B and it is more or less same for other “C” category specimens. In “D” category specimens (Fig.4(b)), both D2T and D2B show more or less same peak height whereas the D3T shows the lowest peak height and D3B shows the highest peak. It can also be noticed that, in both types of specimen, there is no significant and systematic variations in the peak position of the high frequency MBE profiles (Fig.4(a-b)).

In the low frequency MBE profile, there is no significant change in the peak 1 in both types of specimen (Fig.5(a-b)). This indicates that the abusive grinding process did not alter the microstructure and residual stresses in the deeper subsurface layers (>300 μm depth) However, the peak 2 varies to a large extent indicating that the material changes due to abusive grinding occurred significantly in the near-surface layers (<300 μm depth). Among the “C” category specimens (Fig.5(a)), C2T shows the lowest peak 2 height. The MBE peak 2 profiles for C2B and C3T are almost overlapping with each other, indicating the existence of the same microstructure and RS properties in these two specimens. The specimen C3B shows the largest peak 2 value in this group. Among the “D” category specimens, the D2T shows the highest peak 2 (Fig.5(b)) and is also the highest comparing the “C” category specimens (Fig.

5(a)). The specimen D3T shows the lowest peak 2 height. It can be noticed from Fig. 5(a-b) that the MBE peak 2 position shifts to lower field systematically with increase in peak 2 height which indicates that the microstructure in the near-surface layers (<300 μm depth) would have softened due to abnormal grinding. It is also interesting to notice from Fig.5(a-b) that, only the ascending profile of the peak 2 shifts to lower field while the descending profile at higher field remains unchanged. This indicates that the maximum hardness on the surface would not have varied significantly in these specimens, which is also evident from Table 1. Previous studies [13,17] on the effect of applied and residual stresses in this case-carburised steel show that the low frequency MBE peak 2 position does not change significantly under applied tensile stresses whereas it shifts to higher magnetic field under applied compressive stress. Normally, the abusive grinding results in less compressive or even tensile residual stresses near the surface [11]. Hence, the shift in the peak 2 position to lower magnetic field (Fig.5) can be considered as an indication of the extent of microstructural softening below the surface caused by abusive grinding.

The variation in the MBE peak height is due to the combined effect of changes in the microstructure and residual stresses. It would be difficult to separate the effect of these two factors, particularly in high frequency MBE measurements which does not involve strong H_{max} to achieve major magnetic hysteresis loop and hence do not show significant variations in the MBE peak position. But, in low frequency MBE measurements involving strong H_{max}, since the shift in peak position can indicate the alteration in microstructural state, the effect of residual stress may be evaluated from the variations in MBE peak height for a given microstructural state. However, it has been observed in this study that the RS-depth profile is affected more strongly and the retained austenite-depth profile did not show significant alteration due to grinding process. Hence, in this study, the changes in the MBE peak are correlated only to alteration in residual stresses ignoring the effect of microstructural changes that might have also occurred.

3.4 Correlation of MBE with residual stresses

Typical residual stress-depth profile for a normal as-ground specimen is shown in Fig.6. It can be observed that the RS is compressive on the surface as well as below the surface and it reaches a maximum compressive value at ~ 400 μm depth below the surface and also remains compressive even at 1000 μm depth below the surface. The abusive grinding process is expected to alter the RS distribution more strongly in the near-surface region. Hence, the residual stress-depth profile measurements have been made upto 50 μm depth below the surface in all specimen surfaces subjected to abusive grinding and are shown in Figs.7 and 8 for “C” and “D” category specimens respectively. The error bar for each RS measurement is also shown in Figs. 7 and 8. It can be observed that the surface RS as well as the subsurface RS values (in the entire depth of measurement) become less compressive or even become tensile in some cases (Figs.7 and 8) compared to normal as-ground specimen (Fig.6). It is also interesting to note that the RS-depth profile goes through a maximum change at 10 μm depth below the surface in all abusively ground specimens.

3.4.1 High frequency MBE

In “C” category specimens, while correlating surface residual stresses (Table 1 and Fig.7) with high frequency MBE profiles in Fig. 4(a), it can be observed that, except for the specimen C2T, the high frequency MBE peak can be directly related to the surface RS values. Similarly, for “D” category specimens, it can be noticed that the MBE peak (Fig. 4(b)) correlates well with variations in the surface RS values (Table 1 and Fig.8). However, discrepancy arises while comparing the correlation of surface RS values with the MBE peaks in both “C” and “D” category specimens. For example, the specimens C2B, C3T and C3B show lower MBE peak (Fig.4(a)) compared to specimens D2T and D2B (Fig.4(b)) in spite of their more tensile surface RS values (Table 1). This discrepancy may be due to the small variations in retained austenite content which are not resolved in X-ray diffraction measurement and other finer microstructural alterations.

The high frequency MBE peak does not correlate well with RS distribution below the surface. For example, the specimen D2T has the highest tensile RS values at depths >10 μm (Fig.8). But the specimen D3B shows the highest peak (Fig.4(b)). Also, the specimens D2B and D3T have more or less the same RS values below the surface (Fig.8). But, the peak height of D2B is much higher than D3T (Fig.4(b)). Such discrepancy clearly shows that the variations in the high frequency MBE peak can be explained only by the difference in the surface RS values and it does not reflect the RS changes occurring at depths >10 μm below the surface for these specimens. Our earlier study on plastic bending induced RS alterations also showed that the high frequency MBE can be related only to the surface RS values and could not be related to RS alterations occurring at depths >20 μm below the surface [17].

The correlation of high frequency MBE with surface residual stresses for different specimens are shown in Fig.9. It can be noticed that the high frequency MBE shows more scatter among different set of specimens. It is known that the thermo-plastic deformation during abusive grinding process would result in alteration of microstructure such as tempering of martensite and conversion of retained austenite to martensite in the near-surface layers. These metallurgical transformations may have opposite effect and hence may not result in significant changes in surface hardness levels (Table 1). But, both these microstructural changes are normally expected to enhance the magnetization level and hence the MBE level. In high frequency MBE measurement which involves only minor magnetic hysteresis due to lower H_{max}, the changes in the magnetization process due to alteration in both the residual stress and the microstructure could occur in the same narrow magnetic field ranges (ΔH). Hence, the high frequency MBE peak height would likely be affected by the net effect of alteration in both RS and microstructure. Therefore, the large scatter in the correlation of high frequency MBE with RS would be caused by this combined influence of residual stresses and microstructural alterations.

3.4.2 *Low frequency MBE*

As explained earlier, the low frequency MBE peak 2 can be related to RS alteration occurring both on the surface as well as below the surface upto ~ 300 μm depth [14,17]. In “C” category specimens, the MBE peak 2 height (Fig.5(a)) varies exactly according to surface RS values (Table 1). It is also interesting to note that the peak 2 profiles for C2B and C3T overlap with each other (Fig.5(a)). This is clearly supported by the overlapping RS-depth profiles for these two specimens (Fig.7). In “D” category specimens also, the variation in peak 2 height (Fig.5(b)) reflects the changes in the surface RS values, except for the D2T specimen (Table 1 and Fig.8). As mentioned earlier, since the low frequency measurement has larger detection depth (skin-depth) of the MBE signal, the MBE peak 2 should be more appropriately related to the average change in material properties in the near-surface region. The highest MBE peak 2 height for D2T specimen (Table 1 and Fig.5(b)) suggests that, it should have the largest tensile RS values in the near-surface region. This is clearly supported by the RS-depth profile (Fig.8) which shows that, for D2T specimen, the RS values at depths ≥ 10 μm below the surface are higher than that in all other specimens (Figs.7 and 8).

The low frequency MBE measurement also shows better correlation, when the MBE peaks in both “C” and “D” category specimens are related to RS-depth profile. For example, it can be observed that the peak 2 height for C2T and D3T are more or less the same (Fig.5(a) and 5(b)). In support of this, the RS-depth profiles for specimens C2T and D3T are also more or less the same (Figs.7 and 8). Similarly, the specimens C3B and D3B with more or less similar MBE peak 2 height (Table 1) is supported by the similar RS-depth profiles (Figs.7 and 8).

The correlations between the low frequency MBE peak 2 with surface RS value and the average RS in 50 μm depth for different specimens are shown in Fig.10. It can be observed that, for surface RS values, the low frequency MBE shows better correlation except the specimen D2T. However, for average RS within 50 μm depth, it shows better correlation including D2T due to its higher subsurface tensile RS values. This relatively better correlation of low frequency MBE with RS values suggests that the low frequency MBE peak height is less sensitive to other microstructural alterations unlike high frequency MBE. In low frequency MBE measurement which involves major magnetic hysteresis loop due to higher H_{max}, the changes in the magnetization process due to alteration in the microstructure could occur in widely varying magnetic field ranges [2]. Such effect can be observed from Fig.5(a-b) which shows systematic shift in the MBE peak 2 positions caused by different extent of microstructural softening in different specimens. Hence, any additional effect of alteration in residual stresses for a given microstructure is reflected in the variation in MBE peak height. For example, the specimens D2T and D3B show more or less the same peak 2 position, but their peak 2 heights are different (Fig.5(b)). This indicates that they may have same microstructure, but different RS-depth profile as can be observed from Fig.8. However, it is important to note that the microstructural alteration would also contribute changes in MBE peak height [2-3] and could cause anomaly in some cases while correlating residual stresses alone. For example, the specimen D2B shows MBE peak 2 value more or less close to C2B and C3T in spite of the its significantly lower RS values (Table 1 and Fig.7 and 8). However, the shift in the ascending peak 2 profile shows the difference in their extent of microstructural softening (Fig.5(a-b)). This study clearly reveals that the low frequency MBE peak height and its position respectively show distinct correlation with residual stress variations and the extent of microstructural softening caused by grinding damages.

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 is 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. When the grinding process involves large amount of layer removal, the reduction in case-depth can be evaluated from the increase in peak 1 height. The alterations in residual stresses and microstructure near the surface can be assessed from the variations in the MBE peak 2.
3. The high frequency MBE clearly reflects the changes in the surface RS values due to grinding damages. But, it could not indicate the changes in RS values occurring at depth > 10 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.
4. The variation in the peak 2 height of the low frequency MBE profile clearly reflects the RS changes occurring in the near-surface region (<50 μm depth).
5. This study clearly shows that the high frequency MBE can be used to evaluate the changes in surface residual stresses, but not at depths >10 μm below the surface. The low frequency MBE profile would be very useful to evaluate the residual stress distribution at much larger depths. However, when the alteration of residual stresses in the subsurface layers dominate, it may be

difficult to evaluate the surface RS values alone using the low frequency MBE profile.

6. The high frequency MBE shows relatively large scatter while comparing different set of specimens. This is attributed to lower H_{max} which results in the influence of microstructural and RS alterations on the magnetization process acting in the more or less same narrow magnetic field ranges. However, in low frequency MBE measurement using higher H_{max}, the effect of microstructural alterations would be revealed by the large shift in the MBE peak position. Hence, the additional effect of RS alterations could be enhanced and reflected in the variations in the MBE peak height. This results in less scatter in the correlation of low frequency MBE peak height with residual stresses alone.

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Table 1: Comparison of hardness, surface residual stress, surface retained austenite content, high frequency MBE peak height and low frequency MBE peak 2 height for different specimens.

Specimen Identification	Surface Vickers Hardness (HV)	Surface residual stress (MPa)	Surface retained austenite content (Vol. %)	High frequency MBE peak height (% of 5V)	Low frequency MBE peak 2 height (mV)
C-as-heat treated	666	-149	18	17	1577
C2T	648	-101	24	30	1734
C2B	644	100	17	33	1899
C3T	644	96	21	32	1882
C3B	639	254	16	47	2133
D-as-heat treated	671	-221	15	14	1488

D2T	648	-34	13	51	2620
D2B	661	-14	17	49	1856
D3T	652	-169	12	26	1689
D3B	644	313	15	57	2048

List of Figures:

different abusively ground specimens. The scatter in the peak height of the low frequency MBE profile is within ±50 mV.

Figures in Colour

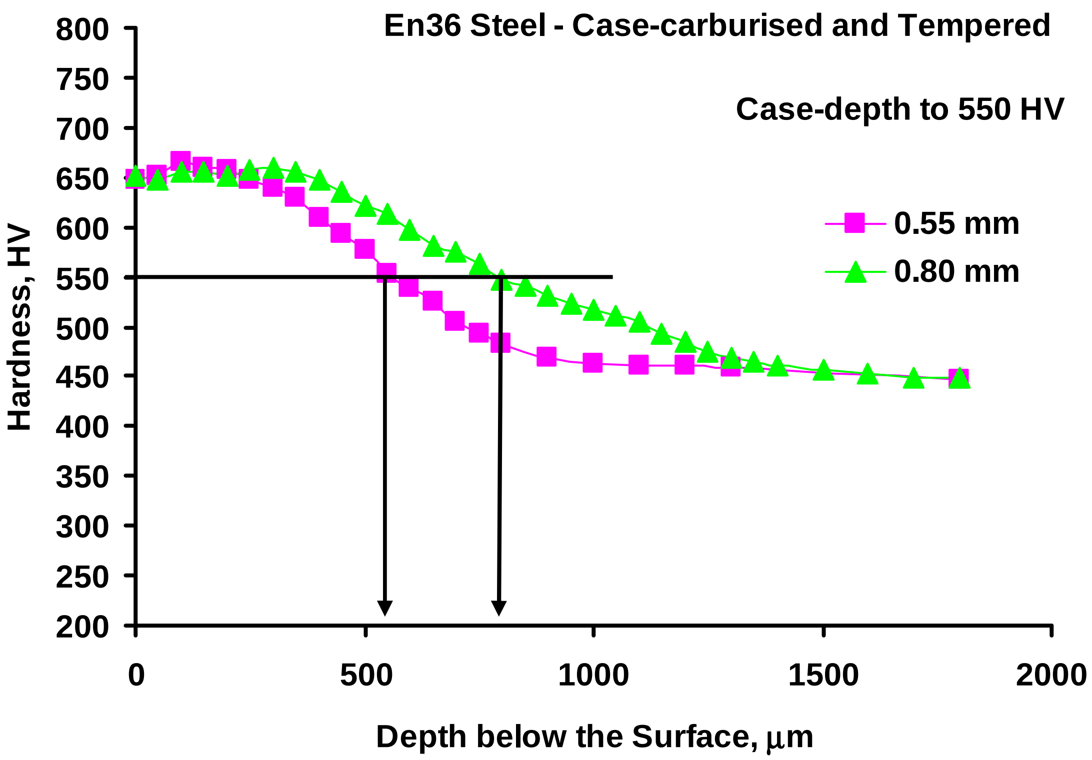


Fig.1

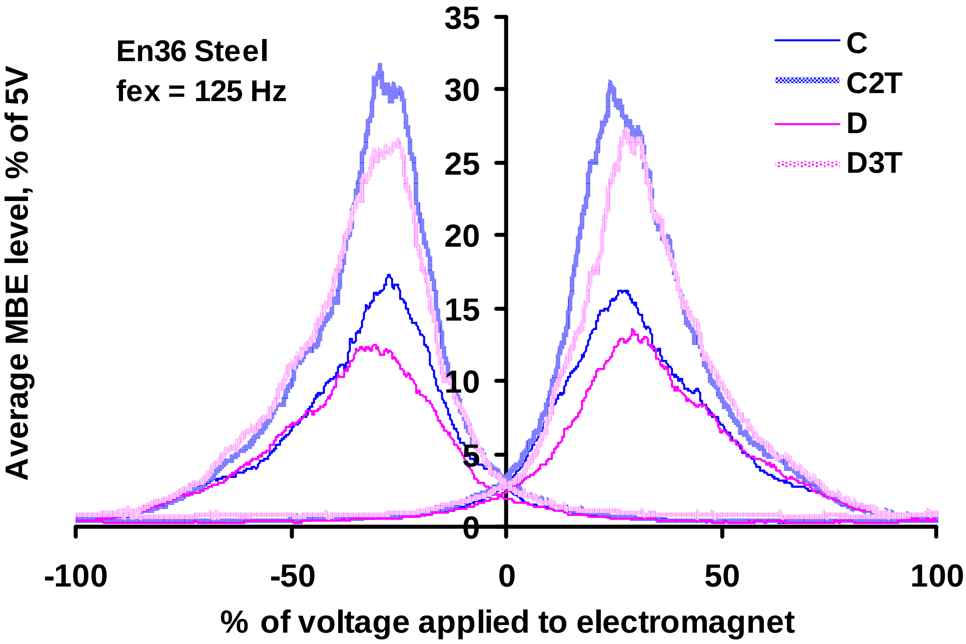

En36 Steel
fex = 125 Hz
C
C2T
D
D3T
Average MBE level, % of 5V
% of voltage applied to electromagnet
35
30
25
20
15
10
5
0
-100
-50
0
50
100

Fig.2

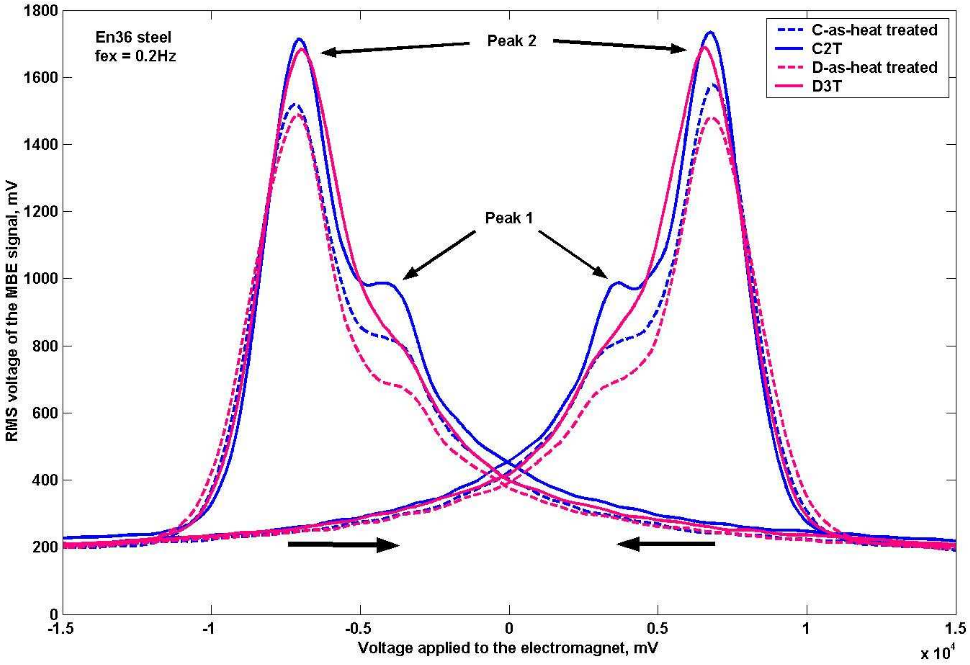
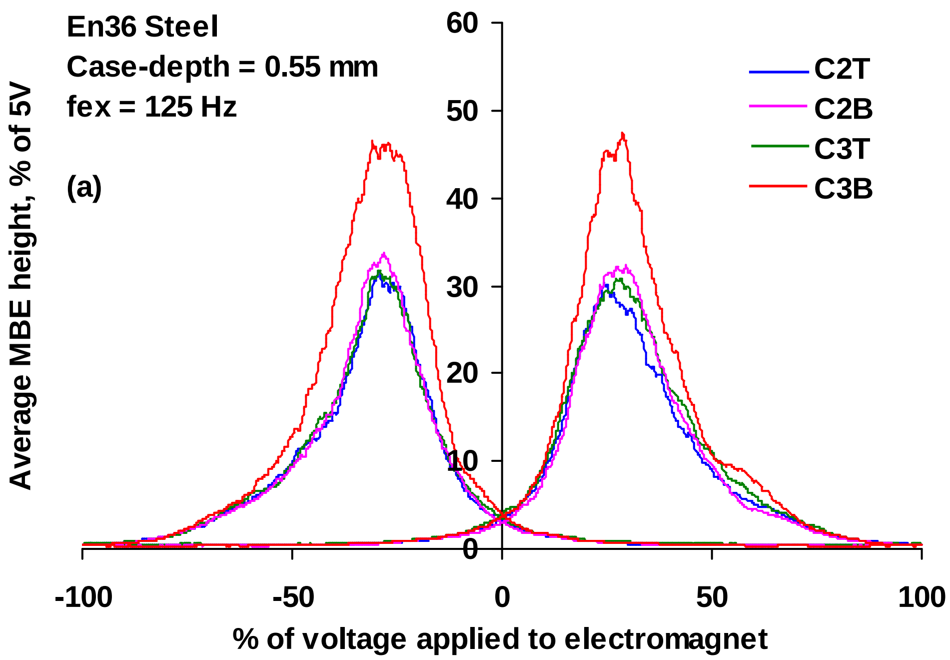

En36 steel
fex = 0.2Hz
Peak 2
Peak 1
C-as-heat treated
C2T
D-as-heat treated
D3T
RMS voltage of the MBE signal, mV
Voltage applied to the electromagnet, mV
x 10^4

Fig.3


En36 Steel
Case-depth = 0.55 mm
fex = 125 Hz
(a)
C2T
C2B
C3T
C3B
Average MBE height, % of 5V
% of voltage applied to electromagnet

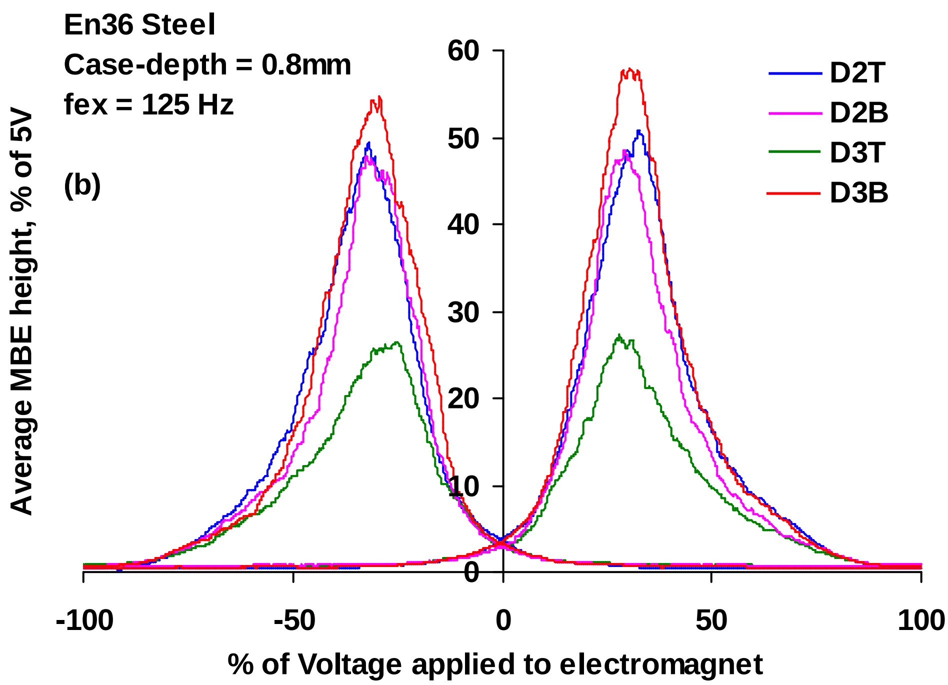
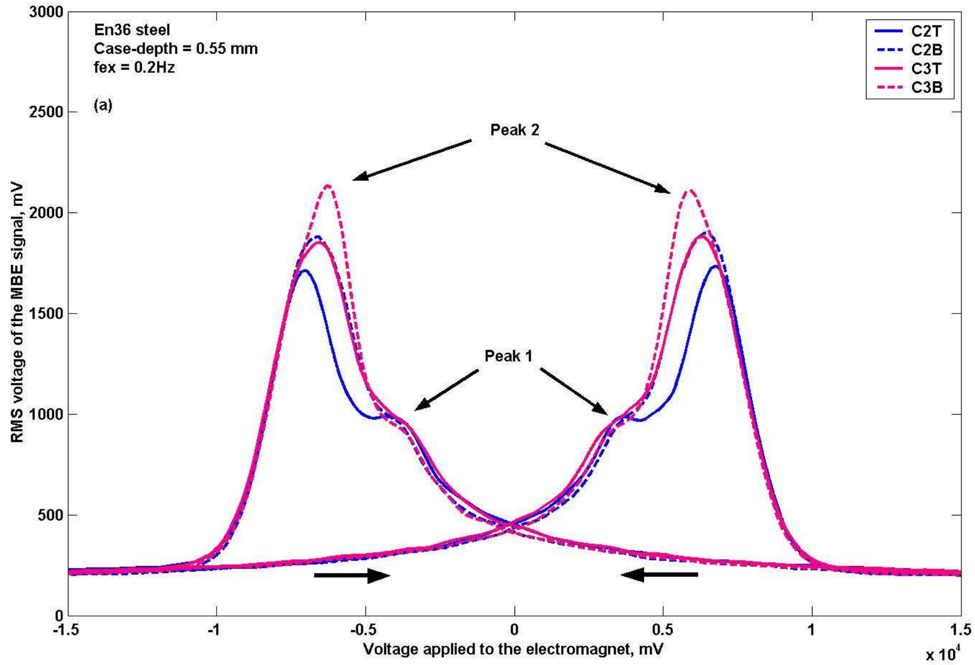

En36 Steel
Case-depth = 0.8mm
fex = 125 Hz
(b)
Average MBE height, % of 5V
D2T
D2B
D3T
D3B
60
50
40
30
20
10
0
-100
-50
0
50
100
% of Voltage applied to electromagnet

Fig.4(a-b)


En36 steel
Case-depth = 0.55 mm
fex = 0.2Hz
(a)
C2T
C2B
C3T
C3B
Peak 2
Peak 1
RMS voltage of the MBE signal, mV
3000
2500
2000
1500
1000
500
0
-1.5
-1
-0.5
0
0.5
1
1.5
Voltage applied to the electromagnet, mV
x 10^4

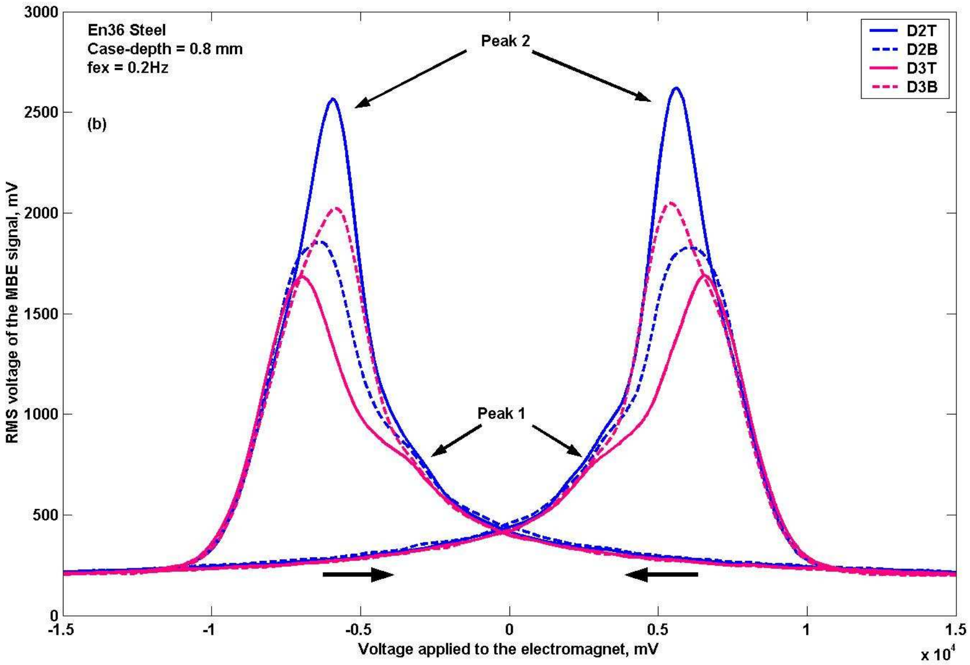
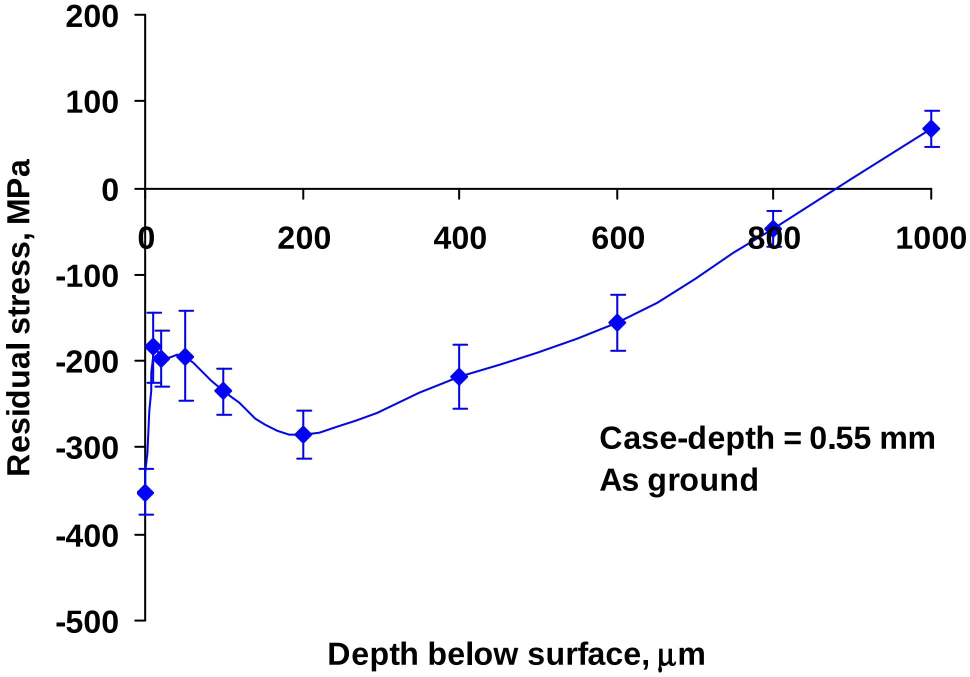
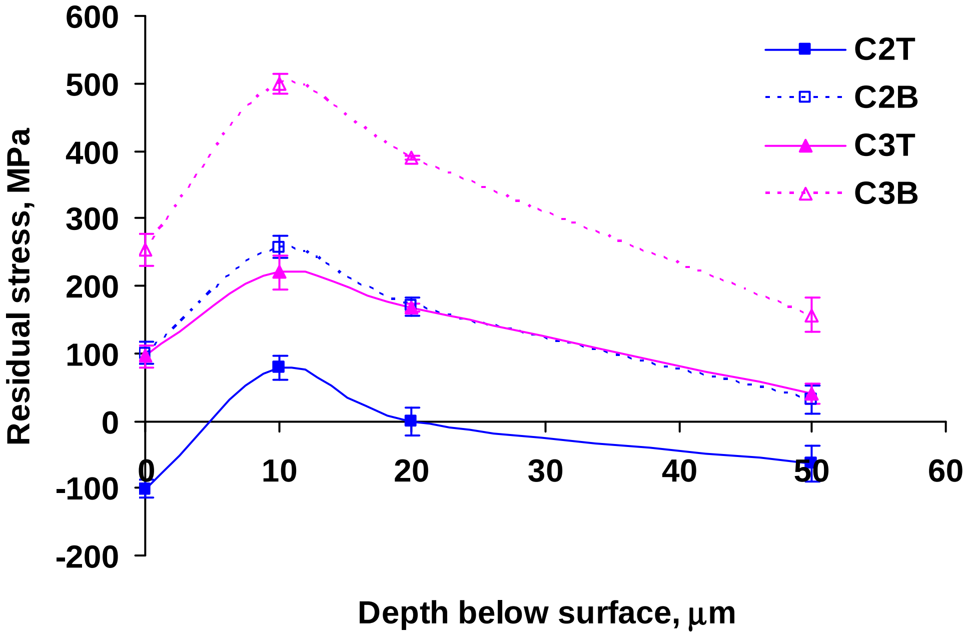

En36 Steel
Case-depth = 0.8 mm
fex = 0.2Hz
(b)
Peak 2
Peak 1
D2T
D2B
D3T
D3B
RMS voltage of the MBE signal, mV
Voltage applied to the electromagnet, mV
x 10^4
3000
2500
2000
1500
1000
500
0
-1.5
-1
-0.5
0
0.5
1
1.5

Fig.5(a-b)



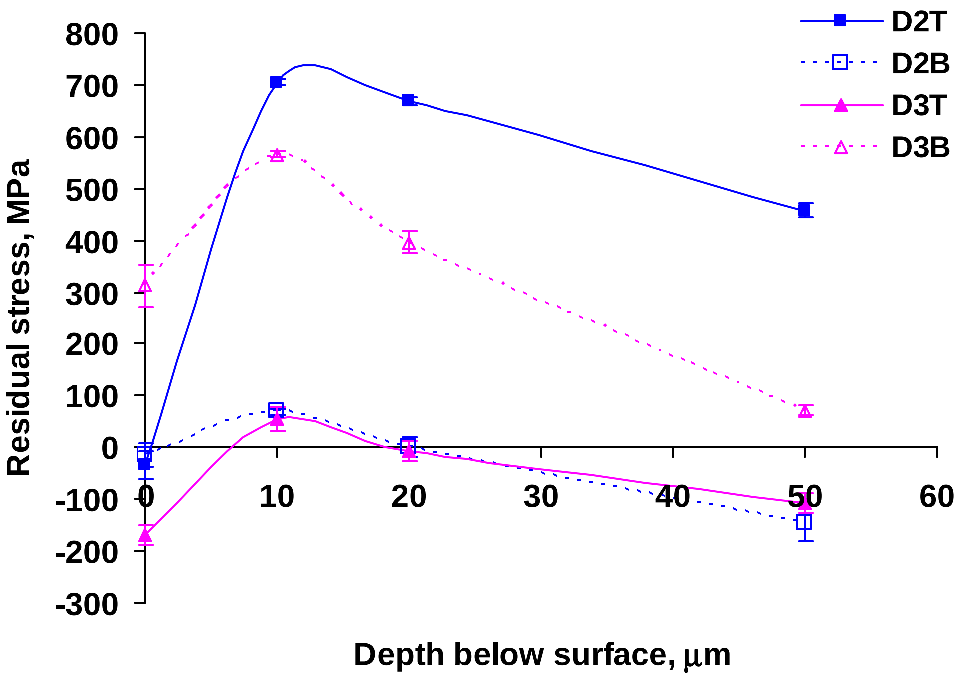
200
100
0
-100
-200
-300
-400
-500
0
200
400
600
800
1000
Residual stress, MPa
Depth below surface, μm
Case-depth = 0.55 mm
As ground

Fig.6



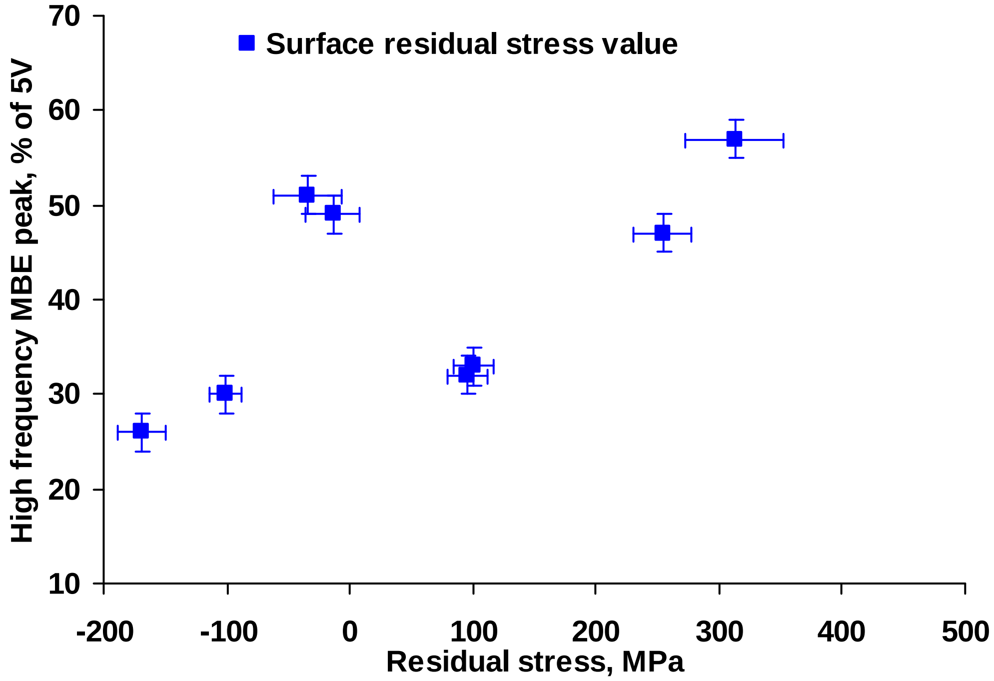
600
500
400
300
200
100
0
-100
-200
Residual stress, MPa
0
10
20
30
40
50
60
Depth below surface, μm
C2T
C2B
C3T
C3B

Fig.7



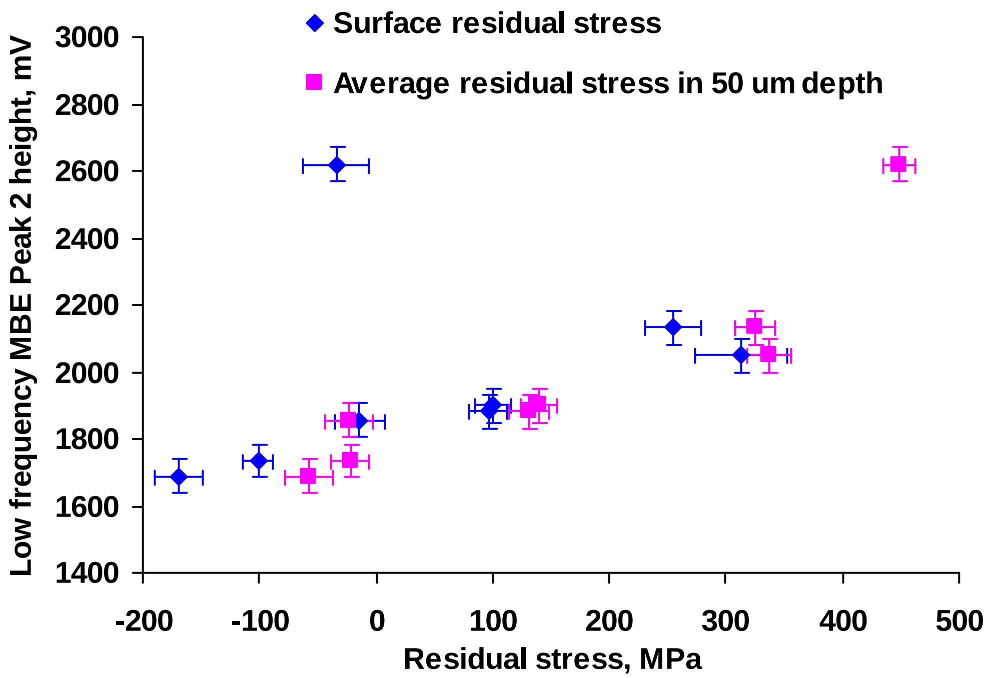
800
700
600
500
400
300
200
100
0
-100
-200
-300
Residual stress, MPa
0
10
20
30
40
50
60
Depth below surface, μm
D2T
D2B
D3T
D3B

Fig.8



Surface residual stress value
High frequency MBE peak, % of 5V
Residual stress, MPa
70
60
50
40
30
20
10
-200
-100
0
100
200
300
400
500

Fig.9



Surface residual stress
Average residual stress in 50 um depth
Low frequency MBE Peak 2 height, mV
Residual stress, MPa
3000
2800
2600
2400
2200
2000
1800
1600
1400
-200
-100
0
100
200
300
400
500

Fig.10