EVALUATION OF SURFACE MODIFICATIONS IN HIGH STRENGTH STEEL

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ABSTRACT

This paper reports on the application of micromagnetic inspection techniques to the evaluation of the surface condition of shot peened, high strength HP9430 steel. It is shown from the results that the modification of the surface condition resulting from different shot peening intensities can be detected from the amplitude of the micromagnetic signals emitted from the surface under alternating magnetic field excitation. It is further demonstrated that the production of residual stresses in the surface of a steel, as a result of shot peening, causes a broadening of the range of critical field strengths for domain wall activation. Consequently the spectrum of activation fields obtained on a plot of micromagnetic activity versus magnetic field strength can be used as an indication of the shot peened condition of the material.

OBJECTIVE

The objective of the present work was restricted and well defined: to investigate the use of micromagnetic inspection techniques for detection of modifications of the surface in steel specimens, and to identify methods of inspection which have a high sensitivity to surface modification whether by mechanical or other means. The first stage of the work was simply to identify measurement techniques that were sensitive to changes in the surface condition resulting from shot peening. These techniques could then be developed later for quantitative comparison of the level of surface stress with the measurement parameter.

INTRODUCTION

In recent years the use of magnetic inspection methods for nondestructive evaluation has received increasing attention. The reasons for this are twofold: the magnetic properties of materials are strongly dependent on the structure of a material and magnetic measurement systems can be relatively easily adapted for use as nondestructive inspection techniques.

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Surface modification of materials is widely used to improve their mechanical performance. For example, shot peening is used to leave residual compressive stress in the surface layer. This increases the fatigue life of the material by inhibiting the growth of fatigue cracks which nucleate at the surface of the material. One serious difficulty with a process such as shot peening is to determine the resulting residual surface stress and the depth of the shot peened layer. This remains a challenge for nondestructive evaluation because of the widespread use of shot peening, the difficulties associated with reliable quality assurance and control, and the consequences of incorrect or inadequate shot peening in terms of the reduced lifetime of components.

The dependence of magnetic properties of materials on their structure has been demonstrated in a number of investigations which even date back into the last century Ewing (1). However modern interest in the evaluation of materials by magnetic methods as a specific group of techniques probably dates from the work of Forster (2), although the magnetic particle technique is one method with a longer history dating back a further twenty years Jiles (3).

In this work we have used micromagnetic activity as a method for assessing the material condition. Micromagnetic activity we define as those effects arising from localized discontinuous changes in magnetization. There are several means by which the micromagnetic activity can be classified. These include voltage pulses in a flux coil resulting from discontinuous changes in magnetic induction caused by a changing magnetic field (classical Barkhausen effect); acoustic pulses usually in the ultrasonic frequency range (typically a few Megahertz) resulting also from discontinuous changes in magnetization caused by the action of a changing magnetic field (magnetoacoustic emission); voltage pulses induced in a flux coil as a result of discontinuous changes in magnetic induction caused by a changing applied stress (magnetomechanical effect). Also there is the related phenomenon of acoustic pulses caused by discontinuous changes in magnetization as a result of a changing applied stress. This last phenomenon is closely related to the Kaiser effect, in which discontinuous changes in strain appear in a stress v. strain hysteresis loop, for example, during fatiguing.

The main point of our definition here is that the classical Barkhausen effect is itself merely a particular case of the more general phenomenon of micromagnetic activity due to discontinuous, localized magnetization changes.

EXPERIMENTAL PROCEDURE

Five specimens of HP9430 high strength steel were provided by McDonnell Aircraft Company for the investigation. These consisted of cylindrical tubes of inner diameter 8 cm, outer diameter 10 cm and length 10 cm. The specimens were shot peened to intensities of 0.0045, 0.008 and 0.010 Almens using at pressures of 30, 40 and 50 psi, respectively. Each specimen was shot peened along half of its axial length while the other half was left unpeened. This enabled direct comparison to be made between the material "before" and "after" shot peening, assuming that the unpeened material was generally representative of the entire specimen before peening. Measurements were made at several locations to determine the variability of properties where the conditions were nominally identical, as well as to compare differences between the peened and unpeened regions.

Two diameters were chosen at right angles to each other and lines were drawn on the outer cylindrical surfaces of the specimens corresponding to the loci of intersection of these diametrical planes with the surfaces of the cylinder. Scans were made along these four lines each of which traversed a region of shot peened and unpeened material. These scan lines are shown in fig. 1.

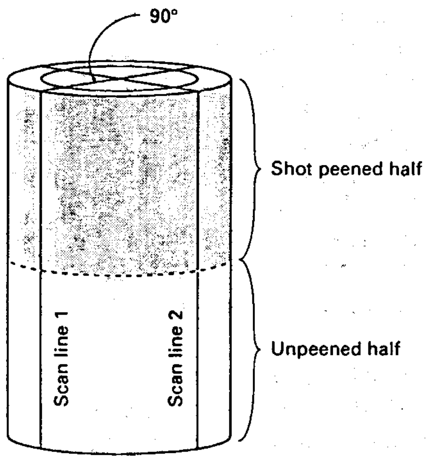


Fig. 1 Specimen showing locations of peened and unpeened regions and orientation of scan lines.

Magnetic Barkhausen measurements were made with fixed applied field frequency and amplitude, and fixed detection parameters (gains and frequencies of filters), along each of the scan lines. The measurements were taken at intervals of 1 mm along a scan line of 50 mm which were equally displaced about the interface between the shot peened and unpeened material. Therefore the change in mechanical properties occurred at about 25 mm in all cases, and any systematic changes in the detected signal resulting from the shot peening were expected to occur at this location.

Scans of Barkhausen activity as a function of frequency were also investigated at a few fixed locations both on shot peened and unpeened material. These measurements were indicative of changes in the magnetic properties with depth and hence led to an indirect method of profiling the depth dependence of stress resulting from shot peening.

It was considered that the combination of longitudinal scans of Barkhausen peak amplitude M_{max} and location of peak H_{cm}, together with depth profiling were the two most promising types of measurement for assessing spatial extent and quality of shot peening, Theiner (4,5). These measurements, if successful, would enable the location and extent of shot peened areas to be identified and the intensity of the shot peening to be determined.

RESULTS

(i) Variation of broad frequency band emissions with shot peening intensity

Measurements of the Barkhausen activity were made along the four scan lines on each of the five samples. In each case the scans began from the unpeened condition and progressed by a series of steps from the unpeened region to the peened region. At each location the Barkhausen signal was excited using a magnetic field of amplitude H = 5900 A/m using a sinusoidal waveform at a frequency of 50 Hz.

In this part of the investigation, the Barkhausen emissions were detected over the entire frequency range 20-160 kHz and the rectified voltage was displayed, corresponding to the change in flux resulting from the discontinuous Barkhausen emissions. This signal was then analyzed to determine the field level H_{cm} at which the maximum Barkhausen activity occurred, and the voltage level corresponding to the maximum Barkhausen activity, M_{max}.

The resulting variations of M_{max} with position are shown in figs. 2-4. The boundary between the unpeened and peened regions of the material occurred in all cases at about 25 mm. From the results it can be seen that the value of M_{max} is reduced when passing from the unpeened to the shot peened state in every scan. The average values of M_{max} both in the unpeened and the shot peened regions are shown for all measurements in Table 1. From this it is clear that the value of M_{max} in the shot peened regions is also dependent on the intensity of shot peening. The variation of M_{max} with the shot peening intensity in Almens is shown in fig. 5.

On the other hand, the field strength at which the maximum Barkhausen intensity occurs was less sensitive to shot peening but did show progressive changes. This field level is an indirect measurement of the coercivity in most cases, and can often reveal a double peak which is indicative of different coercivities in two phases of a material. For example, earlier work, Theiner (6), Bach (7), has shown that a double peak arises in some materials as a result of the presence of a magnetically hard phase and a magnetically soft phase in the same material. Such a double peaked structure of the rectified Barkhausen voltage was observed in the present work, with the hard peak corresponding to the base material while the soft peak corresponded to the shot peened layer. Results indicated that the value of H_{cm} increased with shot peening intensity byup to 25%. The magnitude of the increase in H_{cm} was dependent on the intensity of shot peening.

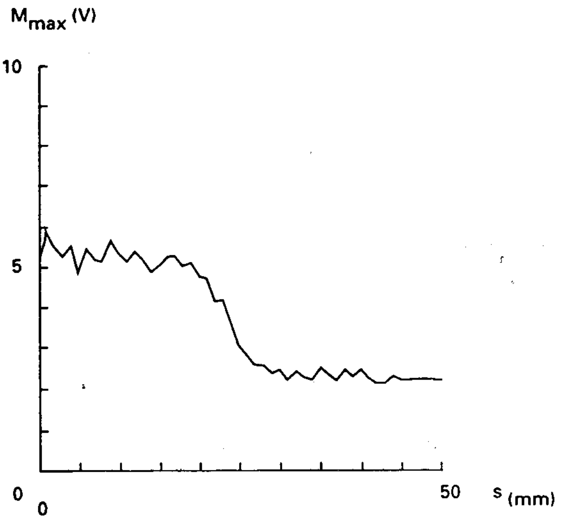


Fig. 2 Variation of micromagnetic activity peak, M_{max}, with position on Specimen A (0.0045 A).

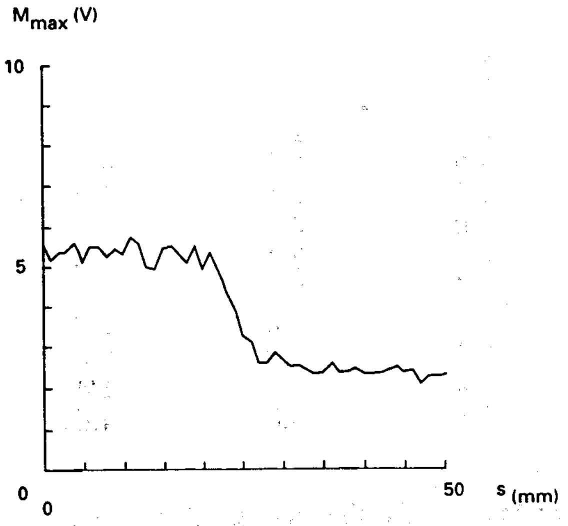


Fig. 3 Variation of micromagnetic activity peak, M_{max}, with position on specimen D (0.008A).

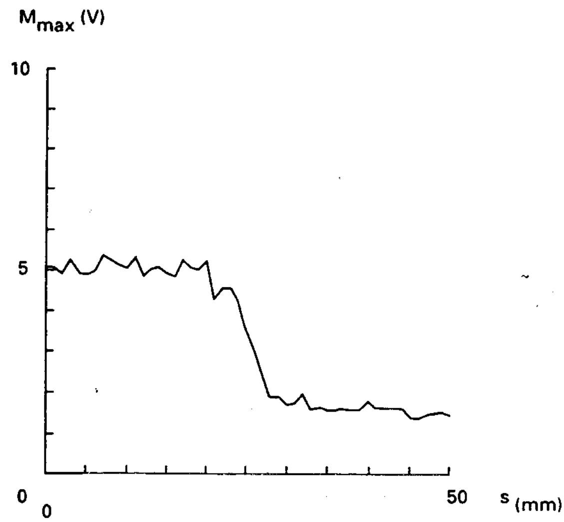


Fig. 4 Variation of micromagnetic activity peak, M_{max}, with position on specimen E (0.010 A).

Scan Position No. / Specimen		1	2	3	4
A	P	2.2	2.2	2.0	2.1
	U	5.5	5.3	4.5	5.2
B	P	2.6	2.5	2.4	2.6
	U	5.0	4.7	4.7	5.0
C	P	2.3	2.1	2.0	2.0
	U	5.4	5.3	5.3	5.2
D	P	2.1	2.0	1.9	2.2
	U	5.3	5.0	5.0	5.2
E	P	1.4	1.4	1.4	1.4
	U	3.8	5.0	4.6	4.3

Table 1: Average values of M_{max} in the shot peened (P) and unpeened (U) regions of each specimen

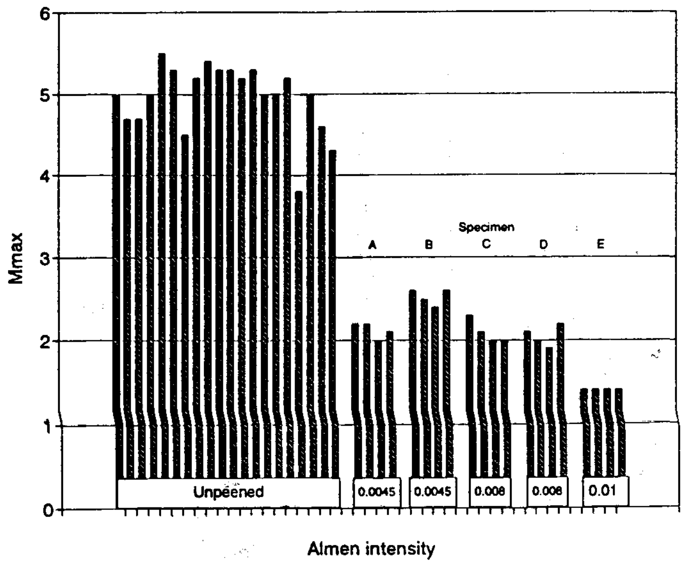


Fig. 5 Variation of the micromagnetic activity peak, M_{max}, with intensity of shot peening.

(ii) Variation of micromagnetic emissions with frequency over narrow frequency bands

In a second group of measurements the frequency dependence of Barkhausen signals was measured at one shot peened and one unpeened location on each specimen. The objective was to investigate the depth dependence of the magnetic signals and therefore to provide a depth profile of the shot peening. In connection with this it was essential to compare the frequency dependence of the signals from both the peened and unpeened material to ensure that any differences as a function of frequency were principally due to the surface modification of the sample and not simply the frequency dependence of Barkhausen signal under normal, unmodified conditions.

The measurements were made using a magnetizing frequency of 50 Hz with a sinusoidal field waveform. The maximum field intensity was H_{max} = 6 kA/cm and an amplifier gain of 30 dB was used. The signals were detected using a band pass filter with adjustable frequency ranges. The ranges used for these measurements were 20 - 50 kHz, 50 - 80 kHz, 80 - 100 kHz, 100 - 120 kHz and 120 - 160 kHz. Generally the depth of penetration of electromagnetic signals depends on $f^{-1/2}$ when f is the frequency, although it should be noted that the classical penetration depth equation

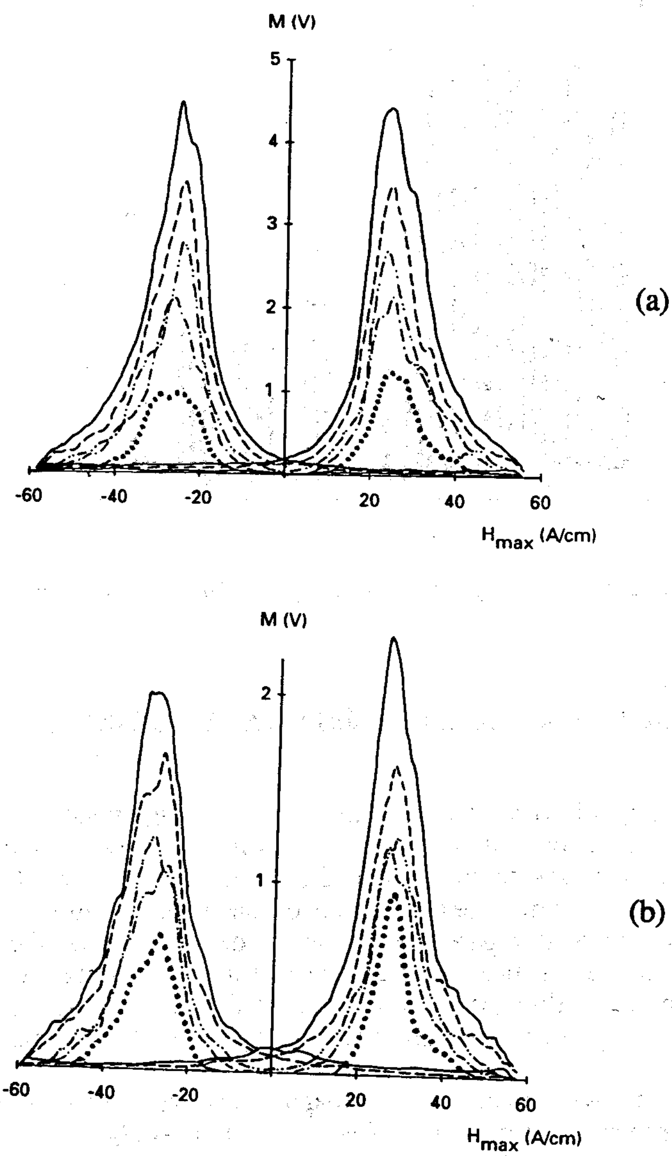
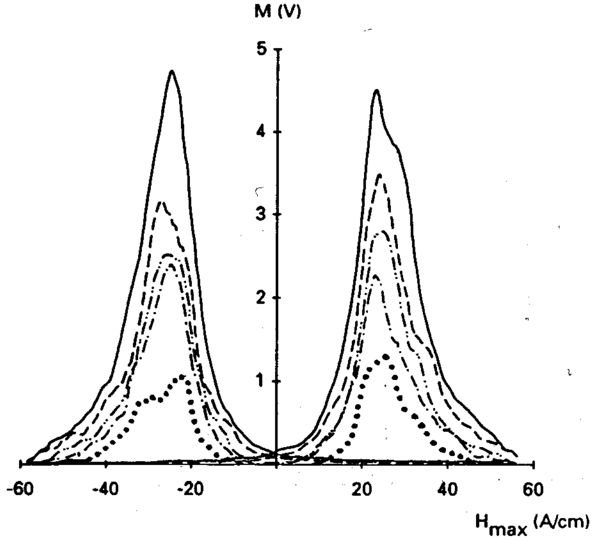
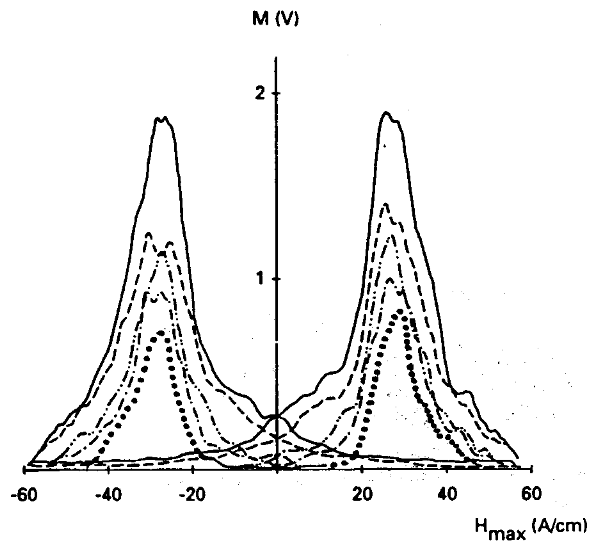


Fig. 6 Variation of micromagnetic intensity M with magnetic field H at various frequencies for Specimen B (0.0045 A) (a) Unpeened; (b) Peened. —— 120-160 kHz; — — 100-120 kHz; —••— 80-100 kHz; —•— 50-80 kHz; •••• 20-50 kHz.

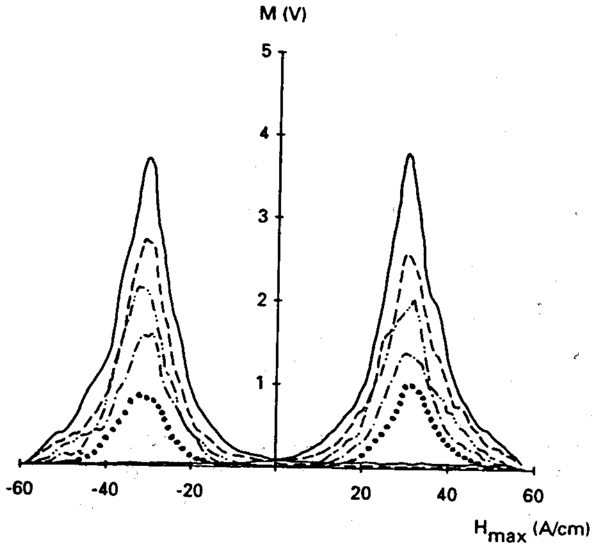


(a)

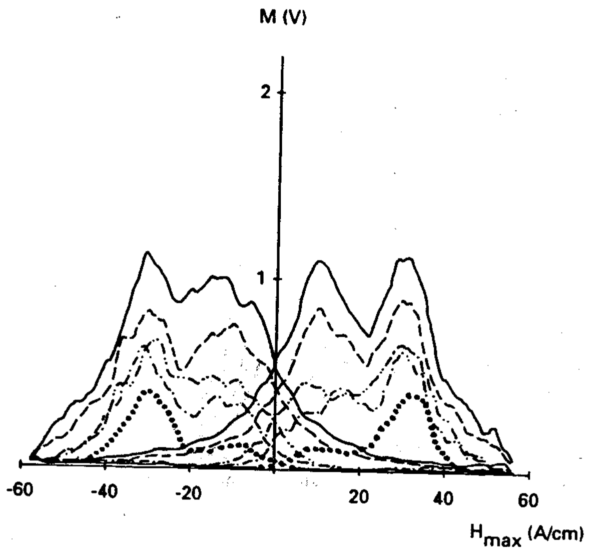


(b)

Fig. 7 Variation of micromagnetic intensity M with magnetic field H at various frequencies for Specimen C (0.008 A) (a) Unpeened; (b) Peened. —— 120-160 kHz; — — 100-120 kHz; —·— 80-100 kHz; —·— 50-80 kHz; ···· 20-50 kHz.



(a)



(b)

Fig. 8 Variation of micromagnetic intensity M with magnetic field H at various frequencies for Specimen E (0.01 A) (a) Unpeened; (b) Peened. —— 120-160 kHz; — — 100-120 kHz; —•— 80-100 kHz; —·— 50-80 kHz; •••• 20-50 kHz.

$\delta = (\pi\mu\sigma f)^{-1/2}$ only applies to a plane electromagnetic wave impinging on a plane surface, and therefore is not strictly valid in this case; or in most other cases for that matter.

The important concept here, however, is that by adjusting the band pass frequency of the detector, signals from deeper lying states can be systematically excluded from the measurement. Typically, even at the lowest frequency range of detection, the signals that are detected come only from a 1 mm thick layer in the surface. As the frequency of detection is increased, the layer from which measurements are taken becomes progressively narrower, until at 160 kHz it is typically 0.1 mm in depth.

Results of the measurements are shown in fig. 6-8. In fig. 6a, the detected signal M is shown as a function of magnetic field and frequency range for the unpeened region of specimen B. The corresponding results from the shot peened region of the same specimen are shown in fig. 6b. It is clear from these results that there was a reduction of the intensity of Barkhausen emissions of typically 50% as a result of shot peening. This was observed at all frequency bands investigated. It was also apparent that a broadening of the peak occured which we attributed to a change in the critical field strengths for the domain walls resulting from the shot peening. The value of H_{cm}, the field strength at which maximum micromagnetic activity occured, was also changed by the shot peening, and seemed to be increased by typically 100 A/m. Similar results were observed for specimens C and E are shown in figs. 7 and 8, so that the reduction in M_{max}, increase in H_{cm} and broadening of the range of critical field strengths, all seemed to be totally general results occurring as a consequence of shot peening. Table 2 shows the dependence of critical field strengths on frequency and intensity of shot peening.

Specimen E was somewhat different from the others, not only because of the higher shot peening intensity which it was subjected to, but also because even in the unpeened regions there was more variability in the properties than was observed in the other specimens. These results are shown in fig. 8, from which it can be seen that unpeened positions 1 and 4 had noticeably higher values of H_{cm} than did positions 2 and 3. This means that in positions 1 and 4 the material was significantly harder than in positions 2 and 3, probably as a result of local differences in the heat treatment conditions of the material when fabricated. These differences seemed to be almost eliminated by the shot peening process, which resulted in a much more uniform distribution of properties around the circumference of the specimen.

DISCUSSION

The effect of shot peening on the micromagnetic Barkhausen parameters of the high strength steels used in the present work led primarily to a decrease in the Barkhausen signal amplitude M_{max} measured over the broad frequency range 20 - 160 kHz. In addition, the analysis of the results as a function of frequency both in the

Specimen No.		A	B	C	D	E
Shot peening intensity		(0.0045A)	(0.0045A)	(0.008A)	(0.008A)	(0.01A)
Frequency band of detected signal						
20-50 kHz	U	26.13	24.94	24.04	22.9	26.77
	P	27.59	27.69	28.18	28.17*	31.4
50-80 kHz	U	24.47	25.81	24.41	22.92	24.66
	P	26.3	26.12	27.49	28.49*	31.4*
80-100 kHz	U	24.23	24.43	24.98	21.27	24.71
	P	27.82	28.97	27.29	27.89	28.47
100-120 kHz	U	24.5	24.65	25.81	24.04	25.3
	P	27.59	27.32	28.31	28.11	28.29*
120-160 kHz	U	25.5	24.97	24.35	21.25	24.84
	P	26.29	27.56	26.1	28.13	31.01*

* Double peak structure observed. Value of corresponding peak only shown in table.

Table 2: Variation of H_{cm} with frequency from specimen to specimen

unpeened and the shot peened condition led to the emergence of a low field peak corresponding to a low coercivity at higher frequencies. This would normally be indicative of a softer phase, since lower coercivity is normally associated with lower mechanical hardness. In addition, the higher frequency signals are associated with Barkhausen emissions occurring closer to the surface. Therefore one tentative conclusion here is that the shot peening of this initially hard material resulted in the production of a surface layer that was actually softer than the bulk material.

Such a decrease in hardness with plastic deformation has been observed before, Jiles (8,9). It seems to be associated with the presence of a high dislocation density in the starting material. In other cases related effects, such as fatigue softening, occur in the early stages of fatigue stressing of high hardness materials. This fatigue softening has also been detected by magnetic property measurements, using coercivity measurements for example.

One explanation of such a phenomenon is that in its initial conditions the material has a very high density of dislocations. These dislocations are moved during the deformation process and this results in a sweeping out of dislocations leaving a reduced dislocation density in certain regions of the material. This can result in a softening of the material as a result of plastic deformation. In the present materials, which are known to be high strength, high hardness materials, this is the most probable cause of the softening. The softening is therefore manifested by the appearance of a low coercivity peak which emerges as the frequency of detected signal increases and the penetration depth decreases.

The variation of M_{max} with shot peening intensity is a different phenomenon. In this case it amounts to a decrease in signal intensity with shot peening intensity. The most likely reason for this is simply that the critical field strengths for the domain wall-defect interactions are being altered by the shot peening. This results in a broadening of the spectrum of critical fields associated with reduction in the maximum intensity of signal in the shot peened specimens. The amplitude of this micromagnetic activity peak is dependent on the shot peened intensity, as shown in fig. 5.

If the range of critical field strengths of the domain wall defect interactions is increased by the effect of shot peening, then the expected result would also be a reduction of the differential permeability at the coercive point. This is commensurate with a reduction in M_{max}, and in fact this has also been shown elsewhere, Jiles (10). Such a result cannot be easily analyzed in terms of the theory of hysteresis, Jiles (11) because this theory assumes a mean pinning energy only, and therefore does not in its present form account for a range of pinning energies, much less a broadening of the range of pinning energies.

In the study of the frequency dependence of the micromagnetic Barkhausen emissions over narrow frequency ranges, the most significant results were the systematic reduction in amplitude of the signal in each frequency range, and the qualitative change in the spectra from one intensity peak to two intensity peaks as the level of shot peening increased.

The results on specimen E, which had received the highest level of shot peening, indicated a much broader range of critical field strengths arising as a result of shot peening. In this case, the result is obviously apparent simply by comparing the micromagnetic activation "spectra" (M versus H) for the shot peened regions of specimen E with the same "spectra" for the shot peened regions of the other specimens. Since the principal difference between the specimens in this case was the intensity of shot peening, it must be concluded, on the basis of these results, that the shot peening intensity largely determines the broadening of the spectrum.

In addition, the emergence of a double peaked structure in the Barkhausen spectra is most clearly exhibited in specimen E. The two peaks occurred at field strengths of H = 1000-1300 A/m and H = 2900-3200 A/m. The peak at higher field amplitudes seemed to be directly related to the peak in micromagnetic activation intensity in the unpeened material, although shifted to slightly higher field strengths as observed in the other specimens. The low field intensity peak, however, was a new feature which emerged only as a result of shot peening.

The low field peak observed in specimen E as a consequence of shot peening was found to be more prominent at higher frequencies (120-160 kHz) than at lower frequencies (20-50 kHz). This result was found consistently at all four locations. Because of this frequency dependence it is concluded that the low field peak corresponds to a state that is predominantly softer than the bulk material (because of its low value of H_{cm}), which occurs directly as a result of shot peening (because it is clearly not present in the unpeened regions) and which is primarily a surface state (because it is prominent at high frequencies but not low frequencies).

CONCLUSIONS

Surface modification, using techniques such as shot peening, increases the residual compressive surface stress in steels and consequently leads to an increase in the fatigue strength of the material. These mechanical changes in the surface conditions are also responsible for changes in the magnetic properties of the material in the surface. The present work was concerned with the identification of magnetic measurement techniques that can be used to indirectly assess the intensity and extent of shot peening.

Two types of micromagnetic measurements have been used. The first procedure utilized a broad band detection of the micromagnetic emissions and analyzed the detected signal to produce two quantitative parameters: the maximum rate of change of magnetization, M_{max}, and the magnetic field strength at which this occurred, H_{cm}. This last parameter is closely related to the coercivity. In some cases two peaks occur in the rate of change of magnetization and then two values of H_{cm} can be identified which correspond to different critical field strengths in different volumes of the material.

It was found that M_{max} was a useful indicator of the spatial extent and the intensity of shot peening. A step change in M_{max} occurred in all cases at the interface between the shot peened and the unpeened material. In every case the value of M_{max} was substantially lower in the shot peened regions. Therefore a scan of M_{max} could be used to establish whether shot peening had occurred.

The results showing the frequency dependence of micromagnetic activity signals in these materials provided further insight into the effect of shot peening on the material. It is quite clear that a qualitative difference between the unpeened and shot peened states of the material can be detected from the broadening of the micromagnetic activity spectrum $M_{max}(H)$. In addition, the variation of M_{max} and H_{cm} can be used to give a quantitative assessment of the intensity of shot peening. Finally, the nature of the spectrum in the shot peened regions yields further information which demonstrates the emergence of a magnetically and mechanically softer state which is produced primarily in the surface of the specimen when subjected to a shot peening intensity of 0.01 Almens at 50 psi. In this specimen it was found that the effect of shot peening resulted in a homogenization of magnetic properties around the circumference of the material and therefore an equalization of mechanical properties.

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