EVALUATION OF RESIDUAL STRESS IN 300M STEELS USING MAGNETIZATION, BARKHAUSEN EFFECT AND X-RAY DIFFRACTION TECHNIQUES

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INTRODUCTION

This investigation was undertaken to compare the techniques of x-ray diffraction, Barkhausen effect and magnetization measurement as methods of nondestructive evaluation of stress in shot peened 300M steel. In particular we were concerned with the estimation of the level of prevailing applied stress and the compressive overload (plastic deformation) which the samples had been subjected to. The 300M steel used in this study is a constructional material for the landing gears of aircraft, and as these components will eventually experience fatigue failure if not replaced, it was of interest to develop NDE techniques for the assessment of the mechanical condition of landing gears of in-service aircraft.

Landing gears of aircraft are usually shot peened to improve their resistance to fatigue failure. Most fatigue failures begin at the surface and consequently fatigue properties are very sensitive to surface condition[1] shot peening produces a compressively stressed surface layer which inhibits crack initiation since the applied stress needs to overcome the residual compressive stress before cracks can begin.

EXPERIMENTAL PROCEDURE

Specimens used in this investigation were shot peened using standard size shot with a hardness of R_c 53-55 and an intensity of 0.008A resulting in a compressively stressed surface layer with a maximum stress of the order of 100 ksi over a depth of 0.5 mm. X-ray diffraction measurements were made to determine the residual stress in the surface.

The specimens were subjected to a uniaxial stress and Barkhausen emission count rates were recorded as a function of stress. They were then compressively overloaded to different levels of strain as shown in Table I, and the Barkhausen emission count rates were remeasured as a function of stress. Since the specimens had differing amounts of compressive plastic deformation, it was possible to measure the changes in Barkhausen emission response with plastic deformation.

Table I. Compressive overloading of specimens.

Specimen Number	Strain Overload
1	-0.005
2	-0.010
3	-0.015
4	-0.200
5	-0.0025
6	-0.0075
7	-0.0125
8	-0.0175
9	No overload
10	

Specimens were then unloaded and x-ray diffraction measurements were made again to measure the residual stress in the surface after compressive plastic deformation. The results were compared with the initial x-ray data to determine the changes in residual surface stress arising from the compressive overload.

Finally bulk magnetization measurements were made on the unloaded specimens in order to study the changes in magnetic parameters that had arisen as a result of the compressive overload. These measurements had the virtue of measuring the properties throughout the whole of the material and therefore were only slightly affected by the surface condition.

RESULTS

(i) X-ray Diffraction

X-ray diffraction measurements were taken on unloaded specimens before and after compressive overload. This method has been used extensively in the past for nondestructive evaluation of residual stress[2]. The quantity usually measured is the shift in position of an x-ray diffraction line due to lattice strain[3]. Plastic deformation which results in an increase in dislocation density leads to a broadening of diffraction lines[4].

The depth of penetration of x-rays into the material is typically 0.05 to 0.2 mm. Therefore, the diffracted beam originates in a thin surface layer and information on the state of stress obtained from such measurements relates only to this surface layer. In shot peened specimens, the x-ray diffraction technique only measures the stress in the shot peened layer and does not give any indication of the bulk stress in the rest of the material.

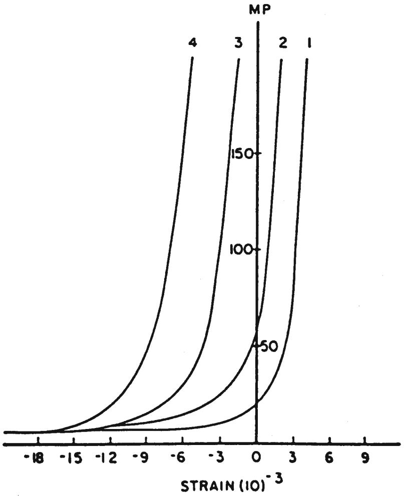
The method used for estimation of stress was the "$\sin^2\psi$" technique described by Prevey[5]. The results both before and after the compressive overload are shown in Table II. It should also be noted in passing that the change in residual surface stress as determined by the x-ray measurement before and after compressive overload was not indicative of the bulk plastic deformation either.

Table II. X-Ray Diffraction Data.

Specimen	Initial (ksi)	After Overload (ksi)
1	-70 ± 10	-95 ± 37
2	-96 ± 13	+16 ± 21
3	-109 ± 17	+37 ± 17
4	-85 ± 13	+3 ± 20
5	-117 ± 54	-80 ± 13
6	-85 ± 34	+48 ± 23
7	-90 ± 27	+21 ± 48
8	-83 ± 27	+11 ± 15
9	-73 ± 19	---
10	-111 ± 7	---

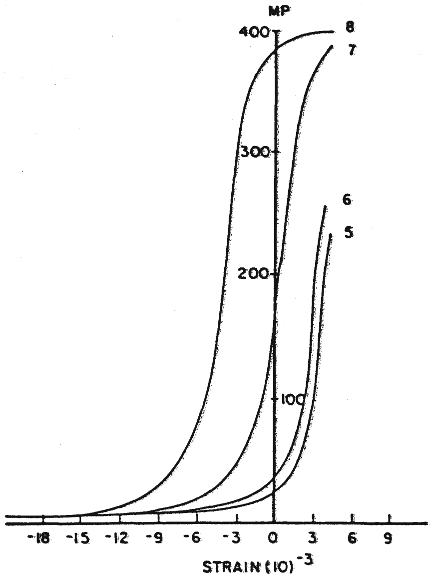
(ii) Barkhausen Emissions

The Barkhausen results were taken as a function of stress under either stress control or strain control, both before and after compressive overload. Measurements were made using a commercial instrument known as the Rollscan[6]. Results under stress control are shown in Fig. 1 and under strain control in Fig. 2, for various levels of compressive overload. The Barkhausen emission signals recorded on the ordinates of these figures are the maximum count rate $(dn/dt)_{max}$. The shape of the curves shown in Figs. 1 and 2 are quite well known, having been reported by, among others Matzkanin et. al.[7], however the reason for the shape remained unknown.



Sample	Compressive Overload dl/l
1	0.005
2	0.010
3	0.015
4	0.020

Fig. 1. Variation of maximum count rate of Barkhausen emission (magnetoelastic parameter MP) with strain, under stress control, for various levels of compressive overload.



Sample	Compressive Overload
5	0.0025
6	0.0075
7	0.0125
8	0.0175

Fig. 2. Variation of maximum count rate of Barkhausen emission (magnetoelastic parameter MP) with strain, under strain control, for various levels of compressive overload.

Our suggestion is that the shapes of these curves can be explained by assuming that for a constant rate of change of field dH/dt the maximum Barkhausen count rate $(dn/dt)_{\max}$ will be proportional to the maximum differential susceptibility $(dM/dH)_{\max}$, which as is known from previous work[8] usually occurs close to the coercive point H_c. As has been shown elsewhere[9] the maximum differential susceptibility and the anhysteretic differential susceptibility are closely related to the stress, σ, and this can be represented by

$$\sigma = A\left(\frac{1}{x'_{\max}(o)} - \frac{1}{x'_{\max}(\sigma)}\right)$$

$$x'_{\max} = \frac{\text{constant}.x'_{\max}(o)}{\text{constant}-\sigma x'_{\max}(o)}$$

where the constant term A contains information about the dependence of magnetostriction λ upon magnetization M[9] and for this kind of material A will have a value of about 300 x 10^9 $A^2.H.m^{-3}$. Hence

$$\left(\frac{dn}{dt}\right)_{\max} \propto x'_{\max}(\sigma)$$

$$\propto \frac{x'_{\max}(o)}{A-\sigma x'_{\max}(o)}$$

This formula is of the same form as the results in Figs. 1 and 2 and will apply in compression ($\sigma < 0$) and most of the tensile ($\sigma > 0$) range, except when the denominator approaches zero. Under these conditions $(dn/dt)_{max}$ does not become infinite but instead reaches a relatively constant level as shown in Fig. 2, specimen 8, due to the saturation magnetization of the material.

Taking the results of specimen 1 of Fig. 1 $dn/dt_{max} = 25\ \text{sec}^{-1}$ at zero stress, $x'_{max}(0) = 500$, and consequently,

$$\left(\frac{dn}{dt}\right)_{max} = \frac{(1.5\times 10^{10})x'_{max}(0)}{3\times 10^{11} - \sigma x'_{max}(0)}\,\text{sec}^{-1}$$

using Hooke's law, $\sigma = \epsilon E$ where ϵ is the strain, E is Young's modulus with a value of $E = 2.0\times 10^{11} Pa$ and substituting in the numerical values,

$$\left(\frac{dn}{dt}\right)_{max} = \frac{75}{3 - 1000\epsilon}\,\text{sec}^{-1}$$

From this, it can be seen that the rapid rise in $(dn/dt)_{max}$ as a function of strain is expected at $\epsilon = 3\times 10^{-3}$ for this specimen which is in excellent agreement with the results.

(iii) Magnetization

Magnetization measurements were made on the specimens in the unloaded but plastically deformed state. These measurements consisted of dc hysteresis curves. The objective was merely to determine correlations between the amount of compressive overload and any of the magnetic parameters such as hysteresis loss and coercivity.

Figs. 3 and 4 show the variation of coercivity and hysteresis loss with compressive overloads of up to 0.02 strain. In both cases, there is a significant decrease amounting to 22% of the undeformed value. Coercivity was reduced from 40 to 31 Oe and hysteresis loss from 1,650 to 1,300 ergs. cm^{-3}. Over the same range of compressive overloads the initial permeability was found to increase from 54 to 72 Gauss.Oe^{-1}.

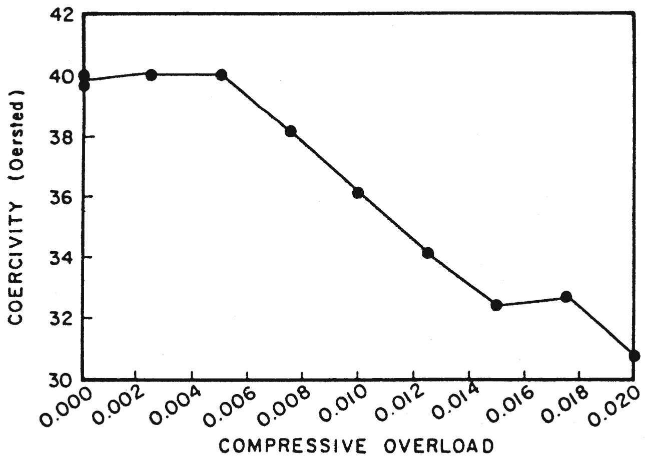


Fig. 3. Variation of coercivity with level of compressive overload.

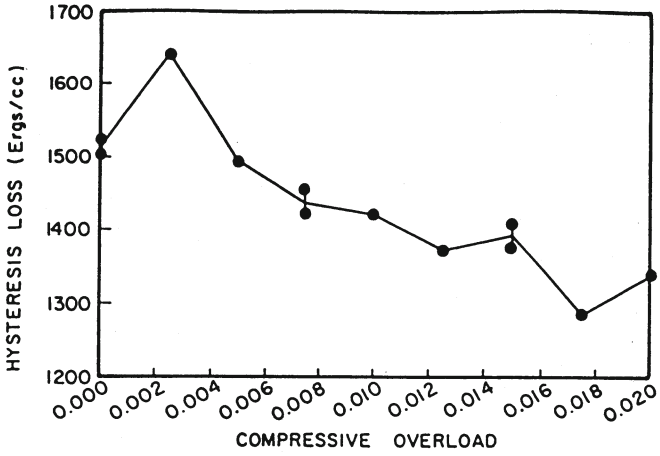


Fig. 4. Variation of hysteresis loss with level of compressive overload.

It is well known that the initial susceptibility increases with decreasing coercivity. Theoretical work by Kronmuller et. al.[10] has even indicated that the product $x'_{in}.H_c$ is constant. The present results seem to confirm this, although recent work by Jiles et. al.[11] has shown that such a relationship is not totally general. In particular, under an applied stress x'_{in} changes quite drastically, whereas H_c is relatively insensitive. Hence the product $x'_{in}.H_c$ does vary with applied stress.

The maximum differential permeability and the anhysteretic differential permeability at the origin were both found to increase after compressive overload. This is indicative of a bulk residual tensile stress as explained by Garikepati et. al.[9].

CONCLUSIONS

It is known from previous work that plastic deformation of ferromagnetic steels leads to changes in coercivity and hysteresis loss, while applied stress changes the differential susceptibilities, both at the coercive point and at the origin of the anhysteretic curve. In this work, changes in all four parameters were observed.

The increases in x'_{an} and x'_{max} were indicative of an increasing tensile residual stress within the bulk of the material as the level of compressive overload increased. The actual level of the bulk residual stress can only be determined from subsequent magnetostriction measurements.

The Barkhausen emission results were capable of evaluating the applied stress only after calibration. Such calibration was also altered by subsequent plastic deformation. The method can unambiguously determine the applied stress, whether in tension or compression after calibration. However the strain sensitivity of the peak Barkhausen count rate decreases at large strains, particularly in compression, as shown in Figs. 1 and 2.

The frequency of the Barkhausen measurements was in the range 70-200 kHz corresponding to a probing depth of 0.02 mm. Therefore, the Barkhausen measurements made in this study were only able to give information about the surface condition of the material. Barkhausen instruments with a wider frequency range have been developed by Theiner and co-workers in Germany[12,13,14] which are capable of probing to greater depths in the material.

The x-ray diffraction results were not convincing as a method of determining the compressive overload in these materials. This was probably due to the shot peening of the surface layer where the x-ray measurements were made. The effect of the compressive overload instead caused changes in the bulk properties of the material which were not detected by the x-ray method. It is not clear how well the x-ray technique would have fared as a measurement of applied stress. We suspect it would have been viable. However, from a practical viewpoint, there are distinct disadvantages of x-ray methods as fieldable stress detection techniques because of the radiation hazard. For this reason, in the inspection of nuclear reactor pressure vessels in Germany, the Barkhausen technique is now supplanting the x-ray technique.

ACKNOWLEDGMENT

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