AN ASSESSMENT OF FACTORS THAT INFLUENCE THE SKIN DEPTH IN A.C.F.M.

CRACK SIZING*

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INTRODUCTION

The a.c. field measurement technique makes use of the skin effect in which an a.c. field applied to a metal is confined to a thin layer at the surface. The surface electric field is then investigated using a voltage-difference probe. A change in the voltage gradient along the surface is interpreted as being due to a change in the path length along a field line between the probe contacts, thus indicating the presence of a crack. The technique has been described previously [1,2], and the development of this work to cover line contacts and sub-surface flaws is described elsewhere in these proceedings [3].

The work described here arose from a study of a.c.f.m. monitoring of fatigue cracks growing along welds in internally stiffened steel cylinders. In order to try to account for small (\(\leq 10\%\)) differences between crack depths measured with the a.c.f.m. technique and those measured using ultrasonics an investigation was mounted into factors that could affect the surface voltage readings. The instrument used for the a.c.f.m., the Crack Microgauge, has a constant current output, thus any change in measured voltage not caused by the presence of a crack must be due to a change in skin depth. The measured voltage is proportional to \((\sigma\delta)^{-1}\) and hence to \((\mu/\sigma)^{\frac{3}{2}}\). For the magnetic materials used in this study, any factor that affects electrical conductivity will have a much greater effect on magnetic permeability. Thus the main theoretical analysis has been confined to the latter. The a.c.f.m. readings on the cylinders are often taken in the presence of a high residual stress. Mechanical stress is a factor known to have an appreciable effect on permeability and consequently the work has centered around this aspect.

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This paper describes the theory behind the effect of stress on the permeability of iron and goes on to give the results of experiments on the effects of stress in both magnetic high strength steels and in a non-magnetic titanium alloy. The effect of anisotropy in the surface of a metal due to rolling or machining is also discussed.

**STRESS EFFECT - THEORY FOR IRON**

Atoms of magnetic material contain uncompensated electron spins which give rise to a net magnetic dipole moment. In addition to the normal electrostatic interaction between atoms that determines the interatomic spacing there is an exchange interaction between the electron spins. In ferromagnetic materials the strength of this interaction is such that the total energy of the system is a minimum when the dipole moments are all aligned parallel to each other, and, in the case of iron, parallel to a [100] crystal plane. In actual specimen, however, if all the spins were aligned in the same direction there would be a large amount of magneto-static energy associated with the magnetic field closure lines. This is reduced because the material is subdivided into magnetic domains. Within each domain the spins are parallel to each other, but the direction of alignment changes from one domain to the next, typically by 180° or 90°.

The presence of inhomogeneity in the crystal lattice structure caused by an applied stress introduces extra terms into the interaction energy. Following Kittel [4], the interaction energy between a magnetic dipole and the surrounding field for a cubic lattice in the presence of a uniaxial applied stress, T, is:

\[
E = K_1 \sin^2 \theta (\cos^2 \phi + \sin^2 \phi \cos^2 \phi) + K_2 \cos^2 \theta \sin^2 \phi \cos^2 \phi
\]

\[+ \frac{1}{2} B_2 T s_{44} [2 \sin \theta (\gamma_1 \gamma_2 \cos \theta \cos \phi + \sin \phi \{\gamma_2 \gamma_3 \sin \phi \cos \theta + \gamma_1 \gamma_3 \cos \phi})
\]

\[\quad - (\gamma_1^2 \cos^2 \theta + \sin^2 \theta (\gamma_2^2 \cos^2 \phi + \gamma_3^2 \sin^2 \phi))]

where \(\theta, \phi\) are the spherical polar coordinates describing the direction of magnetization with respect to one crystal axis, and the \(\gamma_i\)'s are the direction cosines of the applied stress with respect to the three crystal axes. In deriving this equation it was assumed that the two magnetostriction constants for iron are related by

\[\lambda_{100} = -\lambda_{111}\]

The values of the constants in the equation for iron are:

\[K_1 = 4.2 \times 10^4 \text{ Jm}^{-3}\]
\[K_2 = 1.5 \times 10^4 \text{ Jm}^{-3}\]
\[B_2 = 6.4 \times 10^6 \text{ Jm}^{-3}\]
\[s_{44} = 8.9 \times 10^{-12} \text{ m}^3 \text{ J}^{-1}\]

The six minima in \(E\) give the six "easy" directions of magnetization for a given domain. For \(T=0\), these are \(\theta = 0°\) and \(180°\), and \(\theta = 90°, \phi = 0°, 90°, 180°, 270°\) - i.e. along the crystal axes. When a stress is applied the depths of the six minima are changed so that some become "easier" than others, causing some domains to grow at the expense of the rest. For a tensile stress, the domains orientated roughly parallel (or antiparallel) to the stress grow, while a compressive stress causes domains orientated roughly perpendicular to the stress to grow. (Fig.1).
At higher stresses, or in single domains, the energy minima are shifted away from the crystal axes. A numerical solution of the energy equation finds for instance, that a stress of 500 MPa applied at 45° to two crystal axes turns the energy minima through 10°.

Permeability is a measure of how much a material's net magnetization is increased when it is placed in an external magnetic field. The net magnetization is the vector sum of the magnetizations of the individual domains, and in an unmagnetized specimen is zero. When an external field, H, is applied an extra term, $-M\cos X$ is introduced into the interaction energy, where M is the magnetization of each domain and X is the angle between M and H. Domains orientated roughly parallel to H will tend to grow at the expense of domains orientated anti-parallel. The permeability, ($\mu = M/H$), is limited by the fact that to increase net magnetization domain walls have to move past obstacles (dislocations, inclusions etc.) which requires expenditure of energy.

Quantitative predictions of the effect of stress on permeability are difficult because of the essentially random distributions of dislocations, domain wall orientations etc., but the qualitative effect can be illustrated with reference to Figure 2.

For an external field applied parallel to the stress, permeability is increased with tension, because there are then more domain walls favourably orientated, and decreased with compression. The opposite holds when the field is perpendicular to the stress.

STRESS EFFECT - EXPERIMENTAL RESULTS

In general, the a.c.f.m. technique is used in such a way that the surface electric field is parallel to the principal stress axis, so that the associated magnetic field is perpendicular to this stress; the experiments described here were carried out with this arrangement. The Crack Microgauge produces a current of 2A rms at 6kHz. For the specimens used here the surface field strength produced, H, is quite small (around 20 A/m).
Fig. 2. Effect of stress on permeability.

Fig. 3. Effect of elastic stress on Crack Microgauge readings.
A universal hydraulic test machine of 250kN capacity was used with flat plate specimens held by hydraulic grips. The fields used were either impressed (direct contact at the ends of the specimen) or induced into the specimen by a series of parallel current-carrying wires. The results were the same in both cases. The initial series of tests were confined mainly to tensile stresses below yield. Three high strength steels were investigated: Q1(N), HY100 and HY130, with quoted 0.2% proof stresses of 605, 739 and 951 MPa respectively, together with a non-magnetic titanium alloy (proof stress 740MPa). Some typical results from these four specimens are given in Figure 3.

The relationship between Microgauge reading and stress is fairly linear with little noticeable hysteresis and good repeatability. Notice that the titanium alloy shows essentially no effect, indicating that the stress affects permeability much more than conductivity. The percentage changes found are given in Table 1.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Percentage change in Microgauge reading</th>
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</thead>
<tbody>
<tr>
<td>Titanium Alloy</td>
<td>-0.6% for 0 - 375 MPa</td>
</tr>
<tr>
<td>Q1(N)</td>
<td>-8.5% for 0 - 325 MPa</td>
</tr>
<tr>
<td>HY100</td>
<td>-9.2% for 0 - 350 MPa</td>
</tr>
<tr>
<td>HY130</td>
<td>-4.1% for 0 - 270 MPa</td>
</tr>
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Because of the test geometry used the amount of compressive loading available was limited, but for stresses up to around 200 MPa the voltage readings measured were simply an extrapolation of the tensile results. A few tests were carried out with an induced field perpendicular to the applied stress, but because of the small specimen width, geometric effects make the results inconclusive. In general the Microgauge readings increase with tension in this set-up as expected, though the change is not as large as for a parallel field.

More recent experiments using thinner specimens have extended the tensile stress range up to and past the yield point. Figures 4 and 5 show the results for a specimen of HY130 in which the load was ramped up and down slowly in a series of cycles, increasing the specimen's plastic strain each time. The Microgauge readings correlate better with stress than with strain after yielding and are fairly linear in the elastic region. Above the yield point, however, the readings increase dramatically for a while. After a decrease of around 23% from zero load to yield, there is an increase of 6.6% before the readings settle down again at higher plastic strains. Part of this increase is due to the specimen becoming thinner and the electric field strength therefore increasing, but this has been calculated to give an increase of only 0.5%. The bulk of the increase seems to be due to internal microstresses. Plastic deformation leads to most of the cross-section being under compressive residual micro-stress with small regions under high tensile residual micro-stress [5]. The specimen then behaves as if it has an initial compressive stress superposed on any applied stresses.
Fig. 4. Effect of plastic strain on Crack Microgauge readings (Voltage v. stress).

Fig. 5. Effect of plastic strain on Crack Microgauge readings (Voltage v. strain).
EFFECT OF ANISOTROPY

Since the permeability is affected by an applied stress it is likely that rolling or similar process will alter the permeability too. In particular, if the grains are elongated in one direction that direction will become a preferred axis of magnetization. An a.c. field applied in this direction will experience a lower permeability and hence produce a lower surface electric field strength.

An experiment was carried out on a cubic specimen (to eliminate geometric effects) of Q1(N) to investigate the effects of anisotropy in grain orientation. Unfortunately the specimen used had undergone heat treatment after rolling so any anisotropy effects present were likely to be small. Crack Microgauge readings in two perpendicular directions were taken at the centre of each of the six faces, and the pairs of readings were compared. Figure 6a shows a summary of the results for each face. The differences between the two readings on each face were found to be significant, around 4% in each case. However the directions of lower permeability were not consistent with the rolling direction. Instead it was found that the directions of lower permeability were all perpendicular to the direction of machining on each face. It thus appeared that surface conditions had more effect on the Microgauge readings than bulk anisotropy. This would be expected, since the skin depth in steel at 6kHz is only 0.2mm.

Arrows show direction of field input for each reading

![Fig. 6a](image)

**Fig. 6a.** Surface Anisotropy effects on Crack Microgauge readings.

In order to avoid surface machining effects the experiment was repeated at a frequency of 600 Hz (ie. a skin depth of 0.6mm). The results are summarized in Figure 6b. The differences between the pairs of readings on each face were negligible, confirming that the differences found previously were due to surface conditions rather than grain anisotropy.

SUMMARY AND FUTURE WORK

The experiments on the effect of stress on Microgauge readings gave quite consistent results. In the elastic region, the small hysteresis found makes it feasible to invert the experiment and predict surface
stresses from Microgauge readings. In order to get absolute stresses a reference reading will need to be taken on a part of the specimen assumed to have zero stress. Care must be taken to eliminate geometric effects that will lead to a non-uniform field distribution over the specimen. The best way to do this is to use an induced field that is carried around with the voltage probe, so that the probe "sees" the same field strength everywhere. If the region being investigated has undergone plastic strain in the past, however, there is no unique relation between the present stress level and the Microgauge reading. The use of the Microgauge to measure stresses due to welds will therefore be prone to errors at the weld toe but could show the decay of residual stress away from this region.

Future work is planned to use the Microgauge to measure surface residual stresses in a welded plate for comparison with results obtained using the hole-drilling technique. More work is also needed at low frequencies on unannealed specimens to investigate effects due to grain anisotropy.

ACKNOWLEDGEMENTS

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REFERENCES

4. C. Kittel, Rev. Mod. Phys, 21, 541 (1949).