NONDESTRUCTIVE MAGNETIC MEASUREMENT OF BIAXIAL STRESS USING MAGNETIC FIELDS PARALLEL AND PERPENDICULAR TO THE STRESS PLANE

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INTRODUCTION

Many mechanical stress situations tend to be biaxial in character in that two stresses act along axes at 90°. Examples are the stresses found in gas pipeline, oil pipeline, power plant steam pipes, and railroad wheels.

In steel pipes, two principal stresses act axially and circumferentially. From the pressure in the pipe, the circumferential stress can be determined. From magnetic measurements with magnetic field in the stress plane, it has been shown previously [1,2] that the difference σ_1-σ_2 between circumferential and axial stress can be determined. Combining knowledge of the stress difference with knowledge of the circumferential stress enables the axial stress to be determined.

In railroad wheels, the important stresses are radial and circumferential. In this case, measuring the stress difference does not enable each stress to be determined individually. On the other hand, there is a need to know when the circumferential stress is changed from compressive to tensile after many braking actions on the wheel. If circumferential stress becomes tensile, then cracks in the rim can open up and propagate and the wheel can fail. To determine the circumferential stress, more information is needed than just the stress difference.

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This paper studies magnetic effects under biaxial stress with the magnetic field both parallel and perpendicular to the stress plane. It will discuss how one might use these magnetic effects to measure both components of biaxial stress. It will also discuss pitfalls in the measurements and will comment about expected errors in the measurements. The paper will also present a model for magnetic effects due to biaxial stress. The focus of the paper will be on magnetic effects with field perpendicular to the stress plane. The paper will discuss conflicting data that has been published for this situation and how recent measurements have possibly elucidated some of the conflicts.

ANALYSIS

Since the magnetoelastic part of the energy involving external stress depends on linear magnetostriction and not volume magnetostriction, the hydrostatic part of the stress does not contribute to magnetic effects produced by stress. Thus, only the distortional (or deviatoric) parts of the stress [3,4] contribute. This means that the effective stress components tending to interact magnetically in the three principal directions, have the form

$$S_i = \sigma_i - \sigma_0 = \sigma_i - \frac{1}{3}\left(\sigma_i + \sigma_j + \sigma_k\right) = \left(2\sigma_i - \sigma_j - \sigma_k\right)/3 , \qquad (1)$$

where $i \neq j \neq k$ denote the three principal stress directions and where $\sigma_0 = (\sigma_i + \sigma_j + \sigma_k)/3$ is the hydrostatic part of the stress. S_1, S_2, and S_3 are called the normal distortional stress components, [3,4] and each is the effective stress leading to distortion along a principal axis. For biaxial stress, $\sigma_3 = 0$.

Under compression, moments in domains tend to be aligned perpendicular to the field, whereas under tension, moments in domains tend to be aligned parallel to the field. In going from compression to tension, the favored domains change abruptly from perpendicularly-aligned to parallel-aligned. Under biaxial stress, this change in domain behavior affects the magnetic property measurements when field is parallel to a stress axis. Thus, the effective stress contributing to the magnetization behaves differently when the stress axis parallel to the field is compressive rather than tensile. In particular, with $H \| \sigma_1$-axis, the effective stress is

$$\sigma = \begin{cases} S_1 & \text{for } \sigma_1 < 0 \text{ (compressive)}, \\ -S_2 & \text{for } \sigma_1 > 0 \text{ (tensile)} . \end{cases} \qquad (2)$$

Simplifying, one has

$$\sigma = \begin{cases} \left[\left(\sigma_1 - \sigma_2\right) + \sigma_1\right]/3 & \text{for } \sigma_1 < 0 , \\ \left[\left(\sigma_1 - \sigma_2\right) - \sigma_2\right]/3 & \text{for } \sigma_1 > 0 . \end{cases} \qquad (3)$$

For $H \| \sigma_2$-axis, the effective stress is given by (2) and (3), but with indices 1 and 2 interchanged. The flux density due to these effective stresses is computed by substituting these effective stresses into the Schneider-Cannell-Watts model [5], as discussed in earlier papers [2,6].

If the flux density with H$\|\sigma_2$-axis is subtracted from the flux density with H$\|\sigma_1$-axis, the result is approximately the same as if a difference effective stress were acting equal to

$$\Delta\sigma = \begin{cases} [(\sigma_1 - \sigma_2) + \sigma_1]/3 - [(\sigma_2 - \sigma_1) + \sigma_2]/3 & \text{for } \sigma_1, \sigma_2 < 0, \\ [(\sigma_1 - \sigma_2) - \sigma_2]/3 - [(\sigma_2 - \sigma_1) - \sigma_1]/3 & \text{for } \sigma_1, \sigma_2 > 0. \end{cases} \tag{4}$$

Simplifying, we see that

$$\Delta\sigma = \sigma_1 - \sigma_2 \tag{5}$$

for both cases. Hence, by subtracting the flux densities for the field in the two stress directions, one can measure the biaxial stress difference $\sigma_1 - \sigma_2$. Even when $\sigma_1 < 0$, $\sigma_2 > 0$ or $\sigma_1 > 0$, $\sigma_2 < 0$, the proportionality of experimental flux density difference to biaxial stress difference holds to a good approximation. Figures 1(a) and 1(b) show this. Figure 1(a) shows data points computed theoretically after substituting effective stress σ from Equation (3) into the Schneider-Cannell-Watts model [5], and Figure 1(b) shows data points obtained experimentally at SwRI by Kwun and Burkhardt on SAE4130 steel. [7] One notes that both theoretical and experimental plots indicate that stress can be determined to within about ±50 MPa.

For the case of H$\perp$ σ_1-axis and σ_2-axis (viz. H out of the stress plane), the model states that the effective stress contributing magnetically is

$$\sigma = \begin{cases} \mp S_3 & \text{for } \sigma_1 + \sigma_2 < 0, \\ S_3 & \text{for } \sigma_1 + \sigma_2 > 0. \end{cases} \tag{6}$$

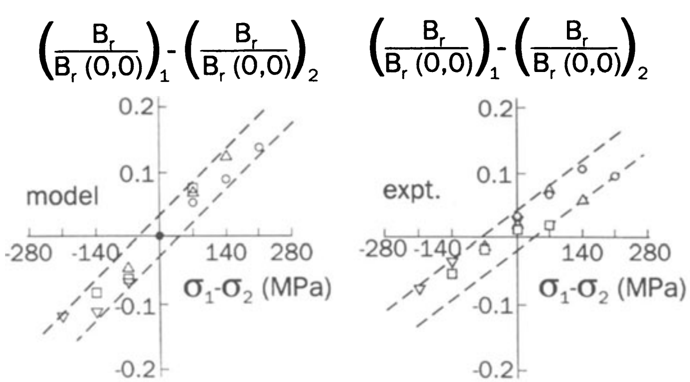

Figure 1. Normalized flux density difference between case with H$\|$ σ_1-axis and case with H$\|$ σ_2-axis, taken as a function of $\sigma_2 - \sigma_1$ for (a) model and (b) experiment.

Simplifying, this is

$$\sigma = \begin{cases} \pm(\sigma_1 + \sigma_2)/3 & \text{for} \quad \sigma_1 + \sigma_2 < 0\,, \\ -(\sigma_1 + \sigma_2)/3 & \text{for} \quad \sigma_1 + \sigma_1 > 0\,. \end{cases} \tag{7}$$

Whether a plus or minus sign was to be used depended on experiment. Experimental results have conflicted. The top sign fits SwRI data by Kwun and Burkhardt on SAE4130 steel [7]. The bottom sign tends to fit Kashiwaya data [8] and Belle and Langman data [9] on mild steel. The key here is that the effective stress (and hence the magnetic property) is proportional to the sum of the two biaxial stresses, which applies for either sign. Thus, in principle, from magnetic property measurements, one can obtain the sum $\sigma_1 + \sigma_2$ and the difference $\sigma_1 - \sigma_2$ of the biaxial stresses, and hence the individual stresses themselves.

For the top sign (i.e. plus sign in equation (7)), the predicted behavior, using Equation (5) and the Schneider model, [5] is given in Figure 2(a). This appears to be corroborated by the experimental results of Kwun and Burkhardt on SAE4130 steel [7] who measured the third harmonic of the flux density, as seen in Figure 2(b).

However, Kashiwaya's data [8] for mild steel indicates under compressive $\sigma_1 + \sigma_2$, that the magnetic property, instead of decreasing, increases very slightly, remaining almost constant as $\sigma_1 + \sigma_2$ varies from zero to negative values up to about -200 MPa. Belle and Langman's data [9], also for mild steel, indicates also a slight increase with a slight peak in the magnetic property under progressively compressive $\sigma_1 + \sigma_2$. Additional work was clearly required because of the conflict between these data and Kwun and Burkhardt's data.

In this paper, we present measurements by Belle and Langman on the same specimen of SAE4130 steel as used by Kwun and Burkhardt. The key feature is that in the

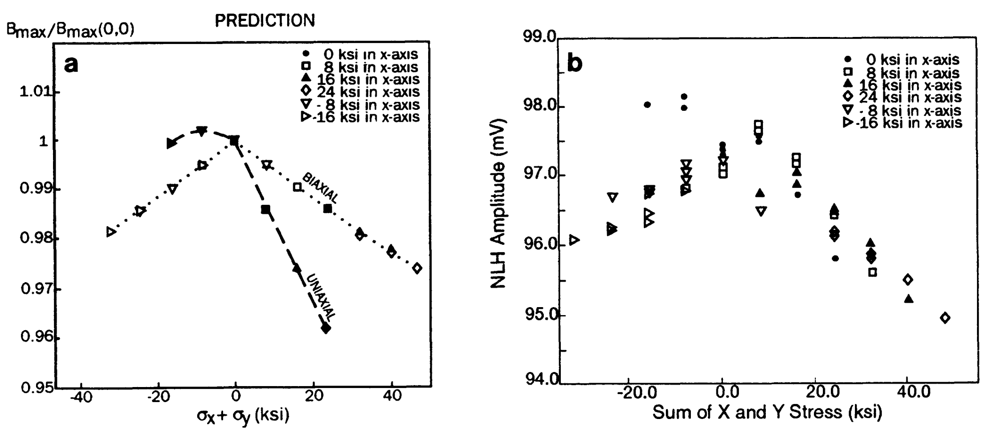

Figure 2. (a) Top sign theoretical prediction for flux density vs. stress sum $\sigma_1 + \sigma_2$, and (b) experimental results of Kwun and Burkhardt on SAE4130 steel for the third harmonic of the flux density vs. $\sigma_1 + \sigma_2$.

present measurements, great care was taken to eliminate bending of the specimen under compression. The stressing apparatus used here gripped the arms of the SAE4130 cruciform-shaped specimen via intermeshing grooves on the cruciform specimen arms and on the apparatus gripping jaws. (This differs from the technique of Kwun and Burkhardt, who used a metal pin, or peg, through each specimen arm to hold the specimen to the stressing apparatus arm.) By using grooved grips and strain gauges on the top and bottom of the specimen in the center area of the cruciform, it was possible to keep watch on the strain gauges and make sure that they agreed and did not indicate bending. When bending was indicated, set screws on the stress apparatus jaws were adjusted to realign the specimen and remove the bending. (Kwun and Burkhardt used only strain gauges on one side and did not check for bending during each stress change.) The result is the data seen in Figure 3(b). With the minus sign in Equation (7), the model predicts the data seen in Figure 3(a). It will be noted that the experiment, to within the confines of experimental data variation, exhibits a magnetic permeability ratio $\mu_{max}/\mu(0, 0)$ with a mean behavior that is negligibly varying under compression but decreases under increasing tension, just as predicted by the Schneider model when the negative sign is used in Equation (7) instead of the positive sign.

DISCUSSION

What happened in the Kwun and Burkhardt measurement in Figure 2(b)? We present here a possible explanation. Suppose the specimen in their case started to bend under compression and the bending went undetected. A small deflection of 0.2 mm in the 75 mm length of the specimen arm, where specimen thickness is 5 mm, would cause

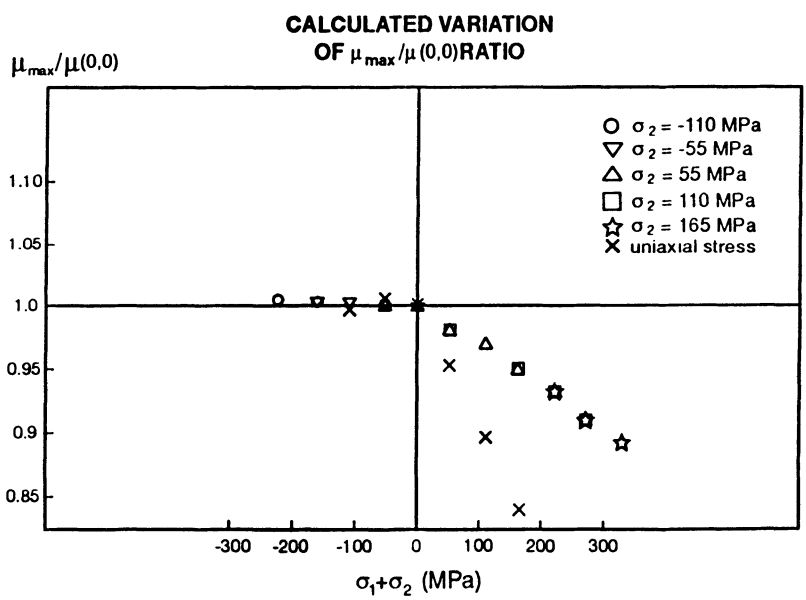

Figure 3(a). Computed variation of the permeability ratio $\mu_{max}/\mu(0, 0)$ vs. stress sum $\sigma_1 + \sigma_2$. μ_{max} is the maximum differential permeability at stresses σ_1 and σ_2, whereas $\mu(0, 0)$ is the maximum differential permeability at $\sigma_1 = \sigma_2 = 0$.

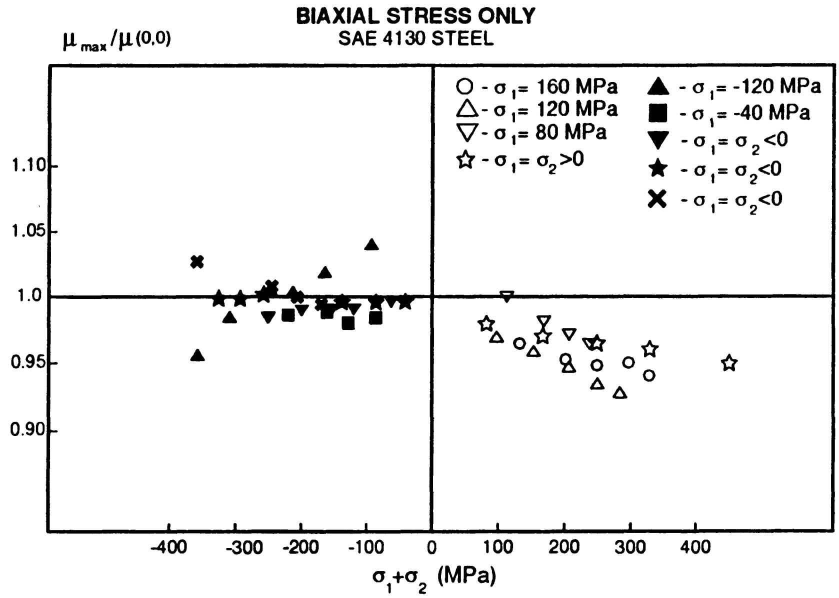

Figure 3(b). Presently measured data for SAE4130 steel, as taken by Langman and Belle, using special precautions so that the specimen did not exhibit effects of bending. For this data, peak flux density = 0.2 T, frequency = 2.0 Hz.

surface stresses of ~140 MPa (20 ksi) on opposite sides of the specimen. Yet, such a small deflection would be hard to spot. Note that a bending stress has an equal part contribution from a tensile stress and a compressive stress. Since the magnetic contribution from the compressive part produces essentially no change in the magnetic property, the bending stress contributes only the magnetic effect of the tensile part, which is to decrease the magnetic property. Thus, Kwun and Burkhardt in their data might have observed a decrease in the magnetic property under compression, <u>owing to the tensile part of the bending stress</u> acting on their specimen. In effect, the tensile data would have been "ghosted" while the stress apparatus was exerting compression (but causing bending). In evaluating this argument, caveats should be noted here because Kwun and Burkhardt's stress apparatus was not the same as Langman and Belle's apparatus, nor was the same magnetic measurement actually made. Thus, further study is needed.

Another point has to do with the flux density that was used. Langman and Belle used a 0.2 T peak. Kashiwaya [8] used an applied field of 1500 A/m on mild steel. If his mild steel was annealed such a field would give a flux density of about 1.4 T; for a cold-rolled specimen, the flux density would be somewhat less. No more details of Kashiwaya's specimen are given. Kwun and Burkhardt [7] do not state what their flux density was. Clearly, since the flux density level determines which domain wall movements dominate and what the stress dependences are for the magnetic properties, it is difficult to compare the three results that presently exist.

Why is there so much scatter in the data of Figure 3(b)? This scatter was observed to be caused in part by a <u>sensitivity to the stress history</u> of the specimen. There is a magnetic hysteresis under stress variation and hence the same residual stress might correspond to a range of values instead of one value of the magnetic property. A discussion of hysteresis under stress variation may be found in the papers by Schneider *et al.* [5] and by Jiles [10]. Further measurements that clarify this have been made recently by Belle and Langman.

Another point has to do with the actual slope of the data for $(\sigma_1 + \sigma_2) > 0$. Small air gap changes in the magnetic circuit can have an effect on the slope of the data obtained for the permeability, and so it is not clear that the data shown in Figure 3(b) is a true measure of the slope of the permeability ratio as a function of tensile stress sum. In fact, the field strength in the specimen will vary in the out-of-stress-plane direction as a result of the "poles" that are formed in the vicinity of the air gaps in the magnetic circuit. This is very difficult to quantify, and further study is needed here as well.

CONCLUSIONS

(1) A magnetic technique in principle appears to be available to obtain both biaxial stresses σ_1 and σ_2, via magnetic determinations of stress sum and stress difference. It has obvious limitations for $(\sigma_1 + \sigma_2) < 0$.

(2) Even for $(\sigma_1 + \sigma_2) > 0$, the technique gives only approximate results, probably to ±10%, depending on stress values. This is because the measurements are affected by the stress history of the sample, as well as by local microstructural and compositional variations.

(3) The case of railroad wheels would be, in practice, difficult to implement. There is usually up to -200 MPa of radial stress in the rim of a wheel.[11] The sum of radial and circumferential stresses in the rim would have to become positive before our proposed method could work, by which time the circumferential stress could have become dangerously tensile.

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