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Effects of stresses on magnetic properties of silicon-iron laminations

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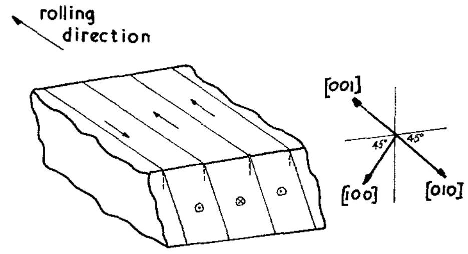
The magnetic properties of grain-oriented 3¼% silicon-iron, as used in laminated transformer cores, are extremely sensitive to mechanical stresses. Power loss and magnetostriction (the cause of core vibration and noise) are most affected by compressive stresses. The theoretical effects of different types of stress on the domain structures of silicon-iron are correlated with measurements made on single laminations and transformer cores. The ways in which stresses can arise in cores and possible methods of avoiding or eliminating them in practice, are discussed.

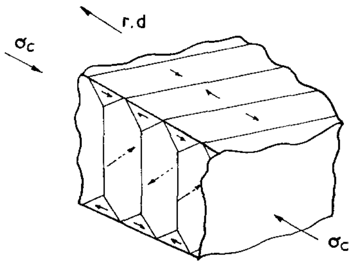
1. Introduction

For many years, grain-oriented 3¼% silicon-iron has been used in transformer cores because of its low cost and good magnetic properties. During the assembly of a core, poor flatness or non-uniformity can cause large stresses to develop and partly as a result, the power loss and magnetostriction (the major source of transformer noise), both increase markedly.

In general, compressive stresses are the main cause of the increased losses and much detailed work has been carried out on the effects of compressive stress acting parallel to the rolling direction of the sheet. However, in a practical core the stresses will be either randomly distributed or isotropic. This paper summarizes the present knowledge of the effects of stress on the magnetic properties of silicon-iron and a simple domain energy theory is used to predict the effects of different types of stress. Once the effects of stress has been established, possible methods of reducing its effect in large cores and the extent to which it is practicable to attempt to eliminate internal stresses are discussed.



(a) unstressed



(b) linear compressive stress

Figure 1 Effect of linear compressive stress on the domain pattern in Goss oriented silicon-iron (a) unstressed, (b) compressive stress σ_c applied along rolling direction.

2. Basic considerations

It has been known for a long time that there is a strong dependence of the magnetic properties of an iron crystal on its state of stress. Internal stress adds magnetoelastic energy to the free energy of a crystal and normally the domain structure will change to minimize the total free energy when a stress is set up.

The bar domain pattern shown in Fig. 1a is common in well-oriented grains of silicon-iron. This structure is easy to magnetize along the rolling direction by simple domain-wall displacement so its power loss is small and the magnetostriction ideally zero.

If an external stress, σ, is applied to a crystal of cubic material, such as silicon-iron, the magnetoelastic energy introduced is given by [1]

$$E = -\frac{3}{2}\lambda_{100}\sigma\left(\alpha_1^2\gamma_1^2 + \alpha_2^2\gamma_2^2 + \alpha_3^2\gamma_3^2 - \frac{1}{3}\right)$$
$$-3\lambda_{111}\sigma(\alpha_1\gamma_1\alpha_2\gamma_2 + \alpha_1\gamma_1\alpha_3\alpha_3 + \alpha_2\gamma_2\alpha_3\gamma_3) \quad (1)$$

where λ_{100} and λ_{111} are the magnetostriction constants, and the direction cosines of the stress and the magnetization are $(\alpha_1\alpha_2\alpha_3)$ and $(\gamma_1\gamma_2\gamma_3)$ with respect to the crystal axes.

If a tensile stress (σ positive) is applied to the structure of Fig. 1a, then $\alpha_1 = 1$, $\alpha_2 = 0$, $\alpha_3 = 0$, and $\gamma_1 = 1$, $\gamma_2 = 0$, $\gamma_3 = 0$ so Equation 1 reduces to

$$E = -\lambda_{100}\sigma. \quad (2)$$

The negative sign in Equation 2 infers that the free energy is reduced by the tension so the domain structure remains basically unaltered. If the stress were compressive, then an increase of free energy occurs. The energy term of Equation 2 is very small compared with other factors (such as the magnetocrystalline energy) at stresses below the elastic limit, but when it reaches about 1 % of the total energy, it causes the static domain pattern to change to that shown in Fig. 1b.

In this pattern, predicted by Corner and Mason [2], the bulk of the domains are magnetized along the [100] and [010] directions. In this case, $\alpha_1 = 1$, $\alpha_2 = 0$, $\alpha_3 = 0$ and $\gamma_1 = 0$, $\gamma_2 = 1$, $\gamma_3 = 0$ so Equation 1 reduces to

$$E = +\frac{\lambda_{100}\sigma}{2}. \quad (3)$$

The positive sign of Equation 3 shows that the [100] and [010] directions are favourable when compression is applied along the [001] rolling direction. Using this approach, the effect of stress applied along the transverse direction can be predicted for the bar configuration of Fig. 1a; the direction cosines are then $\alpha_1 = 0$ $\alpha_2 = 1/\sqrt{2}\,\alpha_3 = 1/\sqrt{2}$, and $\gamma_1 = 1\,\gamma_2 = 0\,\gamma_3 = 0$, from which

$$E = +\frac{\lambda_{100}\sigma}{2}. \quad (4)$$

Comparing Equations 2 and 4 it can be seen that a compression applied along the rolling direction should have the same effect as a tension of twice its magnitude being applied at 90° to the rolling direction. Experimental measurements have shown that the stress sensitivity of magnetostriction varies in this way [3].

3. Longitudinal stress sensitivity

The domain pattern shown in Fig. 1b is more difficult to magnetize along the rolling direction of the steel since the magnetization vectors of the internal domains have to be rotated by 90°. This increases the power loss and magnetostriction.

In an actual sample some grains will be slightly misaligned and others might have internal residual stresses so the switch over from the bar pattern to the stress pattern occurs at different compressive stresses in different grains giving an overall smooth transition as shown in the magnetostriction stress sensitivity curve (Fig. 2). The two curves shown in Fig. 2 represent the extremes of stress sensitivity found in commercial materials at present. In both the domains switch in the region B to A. At very high stresses (beyond point C) a more complex pattern appears [2, 4] which remains stable up to the elastic limit of the material.

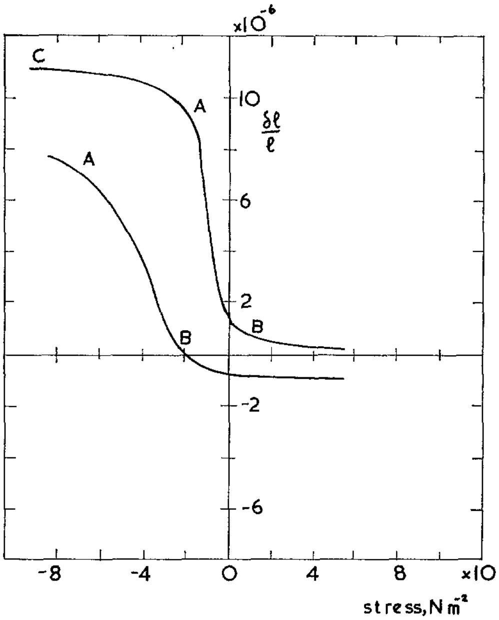


Figure 2 Range of variation of the 100 Hz component of magnetostriction of commercial grain-oriented silicon-iron with stress applied along the rolling direction (at 1.5 T).

The compressive stress also has a serious effect on the power loss in commercial material as shown in Fig. 3. The loss increases rapidly by up to 30 % under medium values of compressive stress and then levels out at very high stresses.

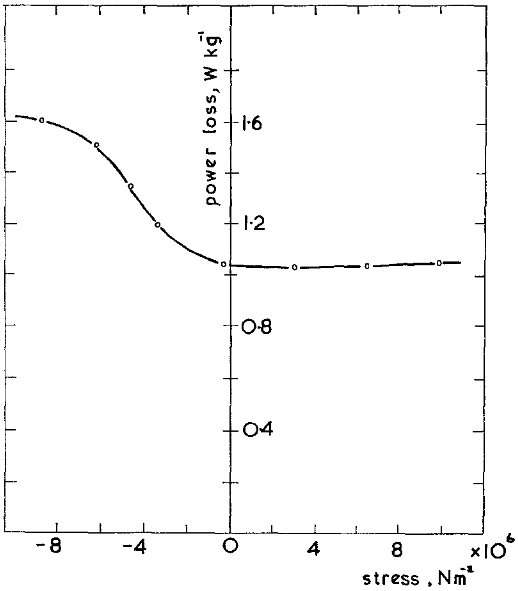


Figure 3 Variation of power loss with stress applied along the rolling direction of $3\frac{1}{4}\%$ Goss oriented silicon-iron (50 Hz, 1.5 T).

In commercial grain-oriented material, many of the slightly misaligned grains have complex closure domains on their surfaces [5]. When tension is applied parallel to the rolling direction, the surface closure domains disappear and as it is increased the domain wall spacing decreases [6, 7]. The decrease in spacing reaches an optimum at about 40 × 10^6 N m^{-2}, all the surface domains being removed before about 7 × 10^6 N m^{-2}. The closer wall spacing implies a lower power loss, but it is sometimes found to increase and a great deal of effort has been put into attempts to explain this [6-8] although its effect is negligible compared with compressive stress.

4. Theoretical effects of other planar stresses

As seen in Section 2, tension applied perpendicular to the rolling direction has half the effect of compression along the rolling direction. Referring again to Equation 1 if a stress is applied to the ideal bar domain pattern at an angle θ to the rolling direction in the plane of the sheet then $\alpha_1 = \cos\theta$ $\alpha_2 = 0$ $\alpha_3 = 0$, and $\gamma_1 = 1$ $\gamma_2 = 0$ $\gamma_3 = 0$, hence

$$E = -\frac{3}{2}\lambda_{100}\sigma\left(\cos^2\theta - \frac{1}{3}\right). \qquad (5)$$

Equation 5 shows that tensile stresses at angles of up to 52° to the rolling direction reduce the magnetoelastic energy and the maximum increase in energy occurs when the stress is applied at 90° to the rolling direction. Sometimes isotropic stresses might be set up in the steel when dimples are present in the sheet. In this case, the magnetoelastic energy can be expressed as

$$E = -\frac{1}{2\pi}\int_0^{2\pi}\frac{3}{2}\lambda_{100}\sigma\left(\cos^2\theta - \frac{1}{3}\right)d\theta \qquad (6)$$

for an isotropic stress acting on a domain oriented parallel to the rolling direction. Solving Equation 6 gives

$$E = -\frac{\lambda_{100}\sigma}{4}. \qquad (7)$$

Hence, an isotropic compression has the same effect as a linear compression of four times its value applied along the rolling direction.

5. The effects of normal stress

Stresses normal to the plane of the laminations often occur in transformer cores although their magnitudes are usually hundreds of times less than any planar stresses present. If a normal stress is applied to the domain configuration in Fig. 1a, then $\alpha_1 = 0$, $\alpha_2 = 1/\sqrt{2}$, $\alpha_3 = 1/\sqrt{2}$ and $\gamma_1 = 1$ $\gamma_2 = 0$ $\gamma_3 = 0$ giving a magnetoelastic energy

$$E = \frac{\lambda_{100}\sigma}{2}. \qquad (8)$$

This is the same magnitude as the energy owing to a transverse stress of equal magnitude but in practical cases the magnitude of this energy term would be very small and only minor changes in domain structure would be expected.

However, Eingorn [9] studied the effects of normal stress on the power loss of laminations magnetized along different directions to the rolling direction and found that the greatest effect occurred when the samples were magnetized along their rolling directions where the power loss increased by about 15% when a stress of 1 × 10^6 N m^{-2} was applied.

This result was confirmed by Joslin *et al* [10], who made measurements on large laminations of different grades of silicon-iron. Their results showed that the better quality material was also the least sensitive to normal stress. In all cases the power loss increased with normal stress and became constant at an increase of about 10%, when the normal stress was greater than 12 × 10^4 N m^{-2}.

The large experimental increases in power loss might be owing to non-flatness which produces additional linear stresses [10] and in some cases the normal stress probably increases the loss in badly oriented grains. For this reason better grades of material, with better grain-orientation have lower normal stress sensitivity.

6. Combined linear and normal stresses

In many cases linear and normal stresses might occur together in practice. The effects of combined normal stress and linear stress parallel to the rolling direction on the magnetostriction of silicon-iron samples has been investigated by Holt and Robey [11]. They found that the magnetostriction rose as normal stress was applied, but when combined with compressive stress applied along the rolling direction, a point was reached (at about 4×10^6 N m^{-2} compression) where the normal stress caused the magnetostriction to drop.

Similar measurements of the stress sensitivity of power loss were made by Joslin *et al* [10] who found that the normal stress caused the power loss to be reduced when compressive stresses greater than 5×10^6 N m^{-2} were applied parallel to the rolling direction of large samples of various grades of material. They explained the measurements in terms of the interaction of the magnetoelastic energies of the normal and linear stresses and the effect of normal stress on non-flat laminations.

7. Causes of stress in transformer cores

Measurements have shown that stresses up to 7×10^6 N m^{-2} may be present in large transformer cores [3]. These stresses can be induced in several ways, the three most important factors being: (1) clamping stresses; (2) wavy laminations; (3) temperature gradients.

7.1. Clamping stresses

Stresses caused by clamping are probably not so important now as transformers are constructed with few, if any, bolt holes in the cores themselves. When bolt holes are used to hold yoke clamping plates in position, they set up high localized normal and planar stresses in the steel as well as producing flux direction. Bolted cores undoubtedly have a higher noise and loss than taped ones, but the contributing factors of localized stress and non-uniform flux have not been separated.

When bolts are used to attach clamping plates to large cores now it is common practice to have the bolt holes outside the core itself, to ensure a more uniform and smaller clamping stress.

Some cores are built in which the laminations are entirely held together using resin impregnated fibre glass tape. However, even using this method of clamping an average flattening stress of about 0.15×10^6 N m^{-2} is required to give a good stacking factor.

7.2. Wavy laminations

The use of non-flat laminations can set up the greatest stresses in large transformers. Waviness in the sheets has been reduced to a large extent by careful heat-treatment [12], but it has not been eliminated. Even though a sheet might appear metallurgically flat, slight waviness can cause large stresses to be induced when the sheet is flattened in a core either by its own weight, or by pressure from adjacent laminations. Such flattening produces a compressive stress on one side of the lamination and a tensile stress on the other, but because of the larger effect of the compressive stress, an increase in loss occurs. The waviness in laminations is small, but even a wave of amplitude 0.3 cm in a length of 1.0 m would set up stresses of $\pm 2 \times 10^6$ N m^{-2} on the sheet surfaces along the rolling direction. Similar stresses can be set up by small variations of lamination thickness in a core.

It is important to realize that a surface stress of 2×10^6 N m^{-2} in a bent lamination does not have such a large effect as a linear compressive stress of the same size. Cole [13] found an increase of loss of only about 8 % in laminations artificially bent to produce this surface stress and Moses and Pegler [14] only found a shift of 0.1×10^6 N m^{-2} in the linear stress sensitivity curves of such laminations.

7.3. Temperature gradients

Even in an efficiently cooled transformer temperature differences occur between the inside and the outside of the core. Localized hot spots owing to rotating flux or over-fluxing in the corner regions can produce large thermal gradients. If a temperature difference of 20°C existed between the inside and outside of a large transformer limb, a stress of 1×10^6 N m^{-2} would be set up.

7.4. Effect of stresses on overall properties

Although high stresses are set up in laminated cores they tend to occur in small isolated regions; nevertheless, their accumulative effect can be large. If an area is stressed, owing to an external stress, its permeability drops slightly and an uneven flux distribution and hence higher loss occurs even in the surrounding material.

It is difficult to assess to what extent stressed laminations effect the overall magnetic properties of the core, but probably the best attempt was made by Wilkins and Thompson [12], who built similar cores from commercial material and specially selected flat material. They found the noise level of a 15 MVA core built using flat material was 72 dB (at 1.6 T) and for two similar cores built using the commercial material were 78 and 83 dB. No corresponding loss figures were published but it would be expected that similar improvements would have occurred.

The harmonics of magnetostriction are an important contribution to transformer noise and they also appear to be stress sensitive although little detailed work has been published. Holt [15] computed the level of harmonic noise output from silicon-iron and found a wide variation of stress sensitivity. In highly stress sensitive material the higher harmonics become the predominant feature of the noise spectrum with increasing compressive stress.

8. Methods of reducing the effects of stress

The stress level in a laminated core can be minimized either by ensuring that clamping stresses and temperature gradients are controlled or by reducing the stress sensitivity of the basic material. The stress sensitivity of present-day material is low because of the beneficial action of the insulating coatings applied at a high temperature during production. The coating has a lower coefficient of expansion than steel and so as the steel cools to ambient temperature an isotropic tensile stress is set up in it. This shifts the stress sensitivity curve of Fig. 2 by up to 3.5×10^6 N m^{-2} if a suitable coating is used [16]. A coating should be applied with as low a coefficient of expansion as possible and its thickness should be sufficient to overcome the major proportion of the core stresses.

Much work has been done on the possible effects of the coatings [3, 11, 16, 17] but greater improvements are possible by combining a suitable heat-treatment under tension with the coating process. Annealing with a tension applied along the rolling direction can produce significant improvements in stress sensitivity as shown in Fig. 4, even when the coating is already applied owing to a residual tensile stress being set up in the steel [18]. Indeed, it has been shown that the role of the phosphate coating in improving the magnetic properties of the material is dependent upon tensile stress being set up in the steel at the same time [19].

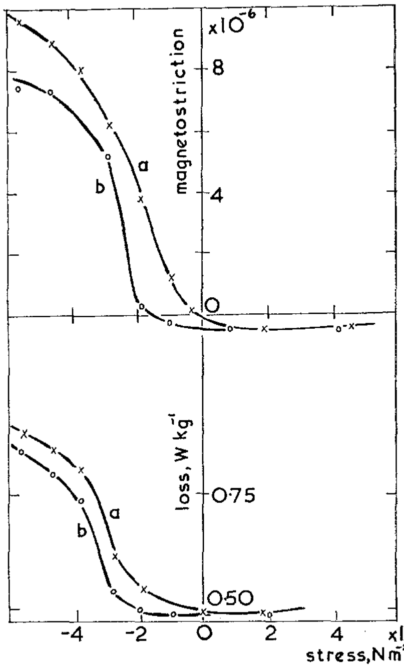


Figure 4 Change in stress sensitivity of power loss and magnetostriction of an Epstein strip of $3\frac{1}{4}$% Goss oriented silicon-iron caused by annealing under a stress of 5.25×10^6 N m^{-2}.

Possible methods of pre-stressing stacks of laminations before being built into a core should be investigated. Cores built with laminations bonded together in this way could be quieter and more efficient [20].

Another approach to the problem is to consider the possible application of material with a slightly different texture to the Goss orientation. Goss material magnetized at about 30° to its rolling direction for instance has a higher basic loss and magnetostriction, but it is not stress sensitive. There might be a suitable texture close to the Goss texture which may have a lower average loss and magnetostriction over the stress range occurring in present transformers.

9. Conclusions

Unavoidable stresses occur in all laminated cores and although the overall stress level is usually low, in localized areas the stress might cause increases of 30% in power loss.

The greatest degradation in properties is caused by compressive stress acting along the rolling direction, transverse tensile stress has half the effect and isotropic compression has one quarter of the effect.

The overall effect of stress on a complete core might be reduced by careful design to avoid clamping stresses and temperature gradients. The basic stress sensitivity of grain-oriented silicon-iron might be further improved by the development of different insulating coatings and suitable heat-treatments. This, coupled with efforts to improve sheet flatness even further, could lead to more efficient transformers.

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