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Effects of temperature on a.c. magnetostriction in grain-oriented silicon-iron

E. C. PIKE
Department of Electrical and Electronic Engineering, University of Wales Institute of Science and Technology, Cardiff, UK

A. J. MOSES
Department of Electrical and Electronic Engineering, Wolfson Centre for Magnetics Technology, University College, Cardiff, UK

The a.c. magnetostriction of conventional grain-oriented 3¼% silicon–iron and more highly oriented silicon–iron has been measured from room temperature up to the Curie point using high temperature strain gauges. Curves of magnetostriction plotted against flux density showed that a definite change in the magnetization process occurred at about 300° C extending to 400° C for both types of material. This was considered to be due to the onset of magnetic annealing, considerably modified by the effect of the coating on the materials. From the experimental results the magnetostriction constant λ_{100} has been calculated using a predicted domain structure and was found to agree well with single crystal values apart from within the 300 to 400° C region.

1. Introduction

Magnetostriction in grain-oriented silicon–iron is important particularly with respect to its influence on noise and vibration in magnetic devices. It is also a sensitive structure-dependent property which can be measured easily at room temperature and which can be used to indicate changes in domain structure and magnetization processes.

Grain-oriented silicon–iron is operated at temperatures as high as 200° C or more in some components so it is important to know the magnetostriction characteristics over such an operating range. Also, because of its structure sensitivity, it is desirable to measure the magnetostriction at higher temperatures to study some effects of heat-treatment on the material.

Some measurements of magnetostriction in single crystals of silicon–iron at high temperatures have been made previously [1, 2], but no measurements of its dependence on flux density at high temperatures have been reported in the literature. It was considered that an investigation of the behaviour of polycrystalline material at elevated temperatures would yield further information on the performance of this material when used in modern machines operating under elevated temperature conditions.

2. Experimental apparatus

Epstein samples were cut from standard 3¼% grain-oriented silicon–iron and from highly oriented material, both materials having been covered with a phosphate coating during the manufacturing process. The samples were cut perpendicular to the rolling direction, since the magnetostriction in the transverse direction is most sensitive to heat-treatment.

All heat-treatment was done in a horizontal, resistively heated, tube furnace in an atmosphere of argon. The furnace heating coil was non-inductively wound and an extra magnetizing winding was fitted to provide a controlled magnetic field in the hot zone over the full length of the sample when required. The furnace temperature was controlled manually by adjusting the voltage applied to the heating coil since the only controller available employed burst firing of thyristors which caused excessive noise in measuring instruments. Manual control, although less convenient, was found to give temperature stability to better than ± 1° C, which was adequate.

Before being placed in the furnace a small (3.2 mm x 1.6 mm) high temperature strain gauge was attached to each sample to measure magnetostriction along its length, perpendicular to the rolling direction. The gauges were fixed by first coating a small area of the sample with ceramic cement and then transferring the free grid gauge from its carrier onto the prepared surface. The whole gauge was then coated with cement and the cement cured by raising the temperature at a controlled rate to 400° C, and cooling slowly. The installation was completed by spot-welding nichrome leads to the gauge tags.

To check on the installation and performance of the high temperature gauges, conventional metal-foil strain gauges of the same size were mounted with shellac on the opposite face of the sample. The performances were then compared at room temperature when the sample was magnetized in a single strip tester described elsewhere [3]. The magnetostriction was found to vary by less than 10% using this technique and the mean value was within 10% of that measured on the same samples using a crystal transducer technique.

When the sample was magnetized in the furnace at 50 Hz, the strain gauge output was monitored using a carrier frequency bridge and the demodulated output signal was fed into a frequency analyser to obtain the 100 Hz component. This was recorded on a calibrated multi-channel ultraviolet recorder, together with the d.c. component of magnetostriction obtained directly from the bridge and the dB/dt waveform in the sample. Thus, at any temperature, magnetostriction at a range of flux densities could be obtained by scanning through the full range of magnetizing current available over a period of 20 to 30 sec, which overcame the drift problems inherent in high temperature measurements.

The magnetizing winding could produce a flux density in the cross-cut samples of up to 1.1 T

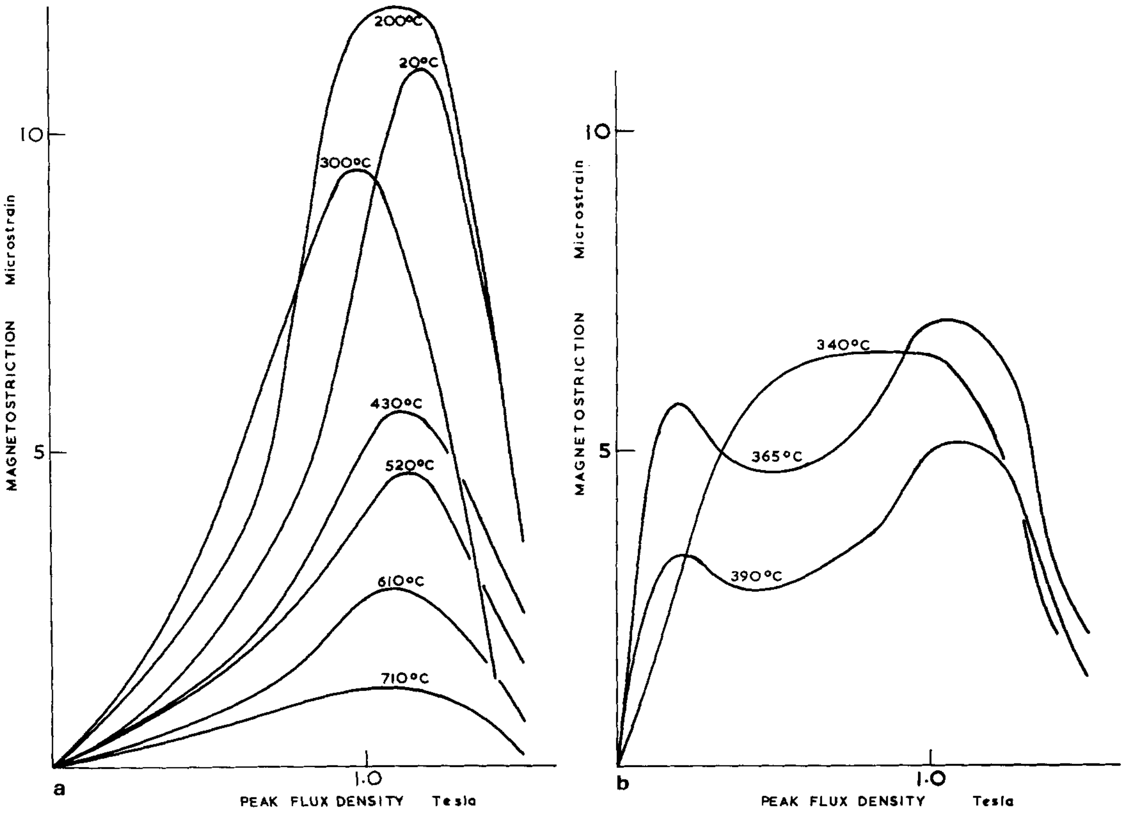

Figure 1(a) Fundamental (100 Hz) magnetostriction as a function of flux density for type A material. (b) In the temperature range 300 to 400° C.

with less than 5% distortion. Samples cut parallel to the rolling direction could be magnetized up to 1.5 T with less than 5% distortion. For the experiments described a.c. magnetization at 50 Hz only was employed. Flux density was monitored with a single turn search coil wound around the sample and the dB/dt waveform fed into the ultraviolet recorder via a buffer amplifier. After some experimenting, it was found that an oxide-coated, 0.004 in. diameter, high temperature thermocouple wire, T2 alloy, would withstand 750° C without the insulation breaking down and so this was adopted for the search coil.

3. Experimental results

The two types of grain-oriented silicon–iron used for the experiments, one with the conventional degree of orientation and the other very highly orientated, are referred to as types A and B respectively. The nominal losses of the samples were about 1.1 and 0.92 $\mathrm{W\,kg^{-1}}$ at 1.5 T, 50 Hz respectively. The results presented here are the mean values of measurements obtained when heating and cooling the samples and the maximum deviation from the curves was within 10% unless otherwise stated. In each case the sample was slowly heated to 750° C and measurements taken of magnetostriction over the largest range of flux densities obtainable at a variety of temperatures, and the same procedure was adopted during cooling.

Fig. 1 shows the a.c. magnetostriction (100 Hz component) of the A type material perpendicular to the rolling direction plotted against flux density in the temperature range 20 to 700° C. At flux densities beyond the peaks of the curves, flux distortion has occurred and magnetostriction under sinusoidal conditions was no longer being measured. At temperatures up to about 300° C the magnetostriction rises steadily with flux density in a fashion which is approximately linear up to 1.0 T. Between 300 and 400° C the shape of the curves changes drastically–the linear approximation up to 1.0 T clearly is no longer valid, and the maximum magnetostriction occurs at low flux densities. Fig. 1a shows that above 400° C the curves again follow the form of the low temperature characteristics, and that the magnetostriction falls off rapidly as the Curie point is approached.

Fig. 2 shows representative characteristics for type B material over the temperature range 20 to 750° C. Again, a change is observed in the region 300 to 400° C, but the transitions are less pronounced.

The discontinuity in the curves is further illustrated in Fig. 3 which shows the variation of magnetostriction with temperature at two flux densities in the type A and type B materials.

4. Discussion

In order to discuss the results adequately, it is first necessary to consider the magnetization process in the material. For a single grain with a misorientation θ in the plane of the sheet (with respect to the perfect (1 1 0) [0 0 1] structure) it can be shown [4] that the a.c. magnetostriction λ is given approximately by:

$$\lambda = \frac{3}{\sqrt{2}}\lambda_{100}\frac{B}{M_s}\sin\theta\left(\sin^2\frac{\theta}{2}-\cos^2\theta\right) \tag{1}$$

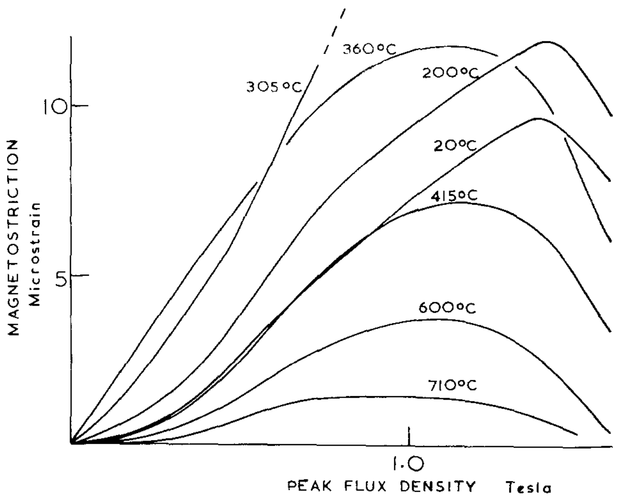

Figure 2 Fundamental (100 Hz) magnetostriction as a function of flux density for type B material.

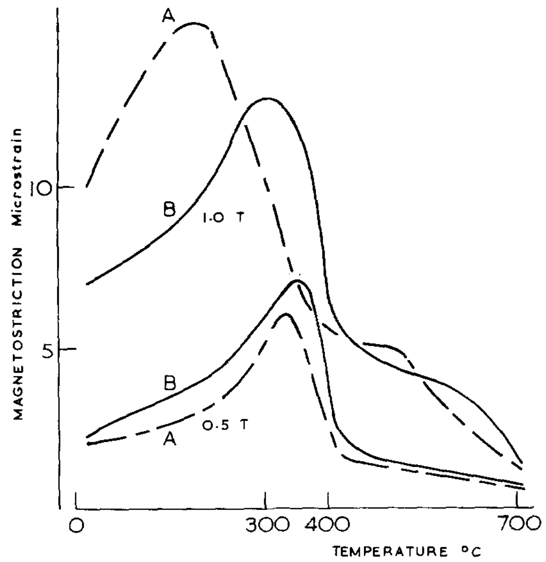

Figure 3 Fundamental (100 Hz) magnetostriction as a function of temperature for two flux densities, using type A and B materials.

where λ_{100} is the saturation magnetostriction in the [0 0 1] direction, M_s is the saturation magnetization and B the flux density. This equation is valid for values of flux density up to about 1.1 T. For perfectly oriented grains, in the [0 1 1] direction $\theta = 90°$ and Equation 1 becomes

$$\lambda = \frac{3}{2\sqrt{2}}\lambda_{100}\frac{B}{M_s}\ . \qquad (2)$$

This shows that the magnetostriction is proportional to the flux density in this range and provides a method of calculating λ_{100} at different temperatures. This can be done by considering the linear portion of each curve where one can assume that Equation 2 is valid. Taking into account the fall in M_s with temperature the curves shown in Fig. 4 are obtained. The calculated curves are compared with values obtained by Takaki [1] and Tatsumoto and Okamoto [2], who used single crystals of 3.8% silicon–iron and different measuring techniques. In the region 20 to 200° C there is good agreement between the three curves; between 250 and 400° C the equation is not valid showing that the magnetization process has changed.

The temperature range 300 to 400° C is the region in which magnetic annealing might start to occur. Efforts were made to induce magnetic annealing in this temperature region using the two grain-oriented materials, but no evidence was noted at room temperature after annealing although some previous authors have shown it should occur at these temperatures [5–7]. However, present work by the authors shows that the phosphate coating applied to the laminations has a pronounced effect on the susceptibility to magnetic annealing. When the samples were held in a field temperature between 300 and 400° C, some change in magnetostriction with time was observed, but on cooling to room temperature the coating plays a major role and masks any other effects.

It appears, therefore, that magnetic annealing occurs which affects the domain structure in the 300 to 400° C region so invalidating Equation 2. The magnetic annealing tends to occur during the measuring process, i.e. during the time in which the sample is magnetized, but work by Helms [5] suggests that in this temperature range magnetic annealing times are in terms of hours rather than the minutes for which the magnetizing field was applied to scan the magnetostriction/flux density relationship. Hence, complete magnetic annealing was not achieved but since the time dependence for completion is exponential a significant degree of annealing was obtained. The process cannot be said to be pure magnetic annealing since there is a considerable interaction effect from the coating.

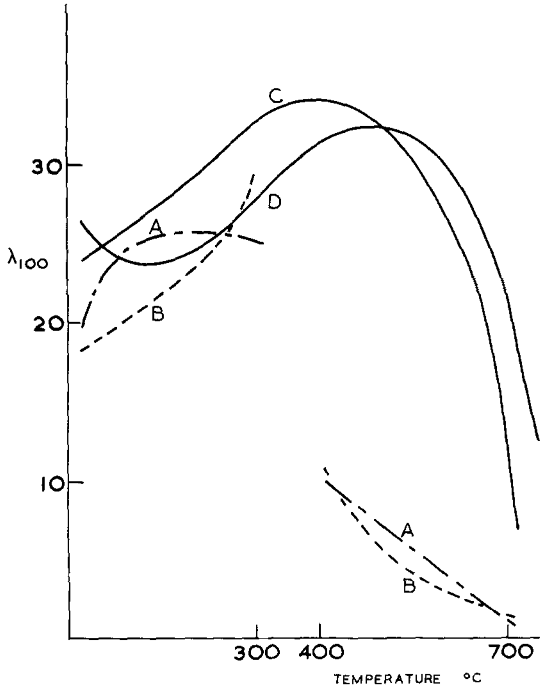

Figure 4 Calculated magnetostriction constant (λ_{100}) as a function of temperature. (A) Material type A, (B) material type B, (C) single crystal [2], (D) single crystal [1].

The probable influence of the coating is as follows. At room temperature the coating holds the steel in a state of tension set up by a differential contraction mechanism after the coating is applied at a high temperature and cooled down. When the sample is heated, this tension in the steel, which has a pronounced effect on the magnetostriction, drops as the steel expands. Tension applied to a sample at high temperature tends to have the same effect as magnetic annealing [8], so as the tension due to the coating drops, the magnetostriction increases as if a magnetic anneal had been carried out and its effect is being removed. Thus, the coating tends to produce an effect opposite to magnetic annealing as the sample is heated.

The difference in characteristics between the highly oriented and conventional samples is due mainly to the fact that the highly oriented material acts more like a single crystal and Equation 2 is more valid since the spread of misorientation is lower. Its average grain size was also very much larger and considerably elongated in the rolling direction but this would produce a secondary effect, although again differences in coatings could cause a significant effect.

5. Conclusions

Experimental measurements of magnetostriction over the range from 20 to 710° C using high temperature strain gauges show that the magnetostriction initially rises and then falls with increasing temperature apart from in the temperature region 300 to 400° C where the magnetostriction versus flux density characteristic alters considerably. This was found with two different types of grain-oriented silicon–iron, (the magnetostriction reaches a peak in the region 250 to 300° C in both cases). The effect is thought to be due to magnetic annealing effects during the heat-treatment and interaction occurring with the stresses set up by the coating. Calculation of the magnetostriction constant λ_{100} agrees well with the previous results on single crystals over the valid temperature range.

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