Mallett P
Cardiff University
School of Engineering

Anderson P
Cardiff University
School of Engineering

Harrison C
Cardiff University
School of Engineering

SUSTAINABLE ENERGY

Measuring the Coupled Effect of Heat and Stress on the Magnetic Properties of Electrical Steel

The coupled effect of heat and stress on the magnetic properties of electrical steel laminations is measured using a novel single-strip tester (SST) that applies uniaxial stress and localised heating to a sample. Magnetic characteristics, such as hysteresis curves, power losses and permeability, are produced as a function of stress, whose effect varies with temperature. The proposed system improves on existing systems by removing the need for a furnace, ring samples and large stressing apparatus.

Keywords:
Magnetic properties, electrical steel, heat, stress.

Corresponding author:
MallettP@cardiff.ac.uk

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INTRODUCTION

Electrical or silicon steel is widely used in the construction of electric motors as magnetic material via excitation coils where permanent magnets are not suitable; hence the magnetic properties of this material are a very important aspect of motor efficiency. Stressing silicon streel affects magnetisation due to imposed restriction on domain movement through the Villari effect [1]; increasing the temperature has a complex effect on this behaviour, not only affecting electrical resistivity but also magnetisation and mechanical properties [2]. Therefore an environment, such as an electric motor in an automotive drive system, that applies both stress and temperature conditions to silicon steel changes the nominal magnetic performance of the material. This effect is largely not considered by motor designers when selecting a grade of electrical steel since this type of measurement is not conducted by manufacturers who market their material based on international standards that exclude variable temperature and stress.

The coupled effect of heat and stress on the magnetic properties of electrical laminations can be investigated using the novel apparatus presented here that applies localised heating to a uniaxially-stressed lamination. Magnetic property data are recorded during the measurement to enable stress- and temperature-dependent power loss and permeability analysis of the material, which is essential when designing or considering materials for automotive applications. Existing methods to conduct this type of measurement have used of ultra-high-pressure containers or furnaces [3], which are considerably more complex and larger than the proposed system shown in Fig. 1, which offers greater measurement repeatability and usability.

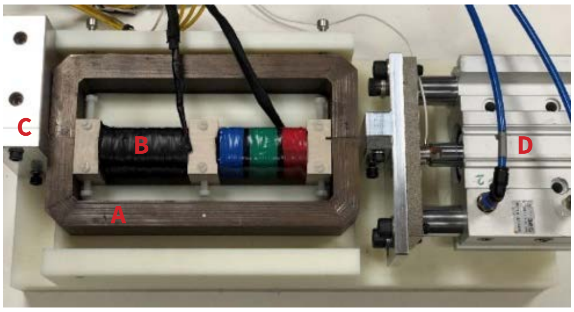

Fig. 1. SST apparatus to apply heat and stress while recording magnetic data; A = iron yoke, B = coil windings, C = aluminium grip, D = piston.

METHODOLOGY

An SST was designed and built to apply uniaxial stress and localised heating to a silicon steel Epstein lamination (30mm x 305mm) while magnetic measurements are conducted. A piston applies either tensile or compressive stress to one end of the clamped sample while a thin silicone heater strip is affixed to its surface as it lies inside coil windings that magnetise and measure the subsequent magnetic flux density. Different temperatures (from room temperature to 150°C) can be set while varying stresses (+/-100MPa) are imparted, during which inductions from 0.1-1.8T are measured at 5-1500Hz.

Stress application

The Epstein sample lies vertically between horizontal iron yokes to remove the compression applied by the top yoke in the conventional SST set up. This is essential for applying the intended stress condition which cannot be effectively administered if a yoke lay atop the Epstein sample. Another issue with stress applications arises from inadequate gripping of the sample, leading to non-uniform stress distribution; this has been addressed by sintering the aluminium clamp faces that grip the ends of the sample. Additionally, the sample is sandwiched between the wall of the coil housing and a ceramic spacer which is held in place with screws to prevent sample buckling. A feedback system measures the pressure exerted on the load cell in the piston and adjusts the pressure in the piston accordingly to apply the desired stress to the sample.

Heat Application

Embedded into the spacer is a silicone heater strip whose temperature is set by a thermal controller using a thermocouple in contact with the sample. The resistive windings inside the strip are arranged so as not to interfere with the magnetic field in the sample.

RESULTS AND DISCUSSION

For the below measurements, data from magnetic measurements of 1.5T at 400Hz are presented in the tensile stress range of 0-35MPa and temperature range of 50-150°C. The stress range selected is to explore the effects of the Villari region at different temperatures, which typically occurs within the 1-25MPa boundary [4]. The material exhibited is a 3.3% silicon B32 0.5mm grade of non-oriented electrical steel.

Different stress inductions create different loss temperature profiles within the Villari region, as seen in Fig. 2, where the profiles with the most change are likely Villari boundaries for this material since the loss-temperature response is more consistent above 10MPa.

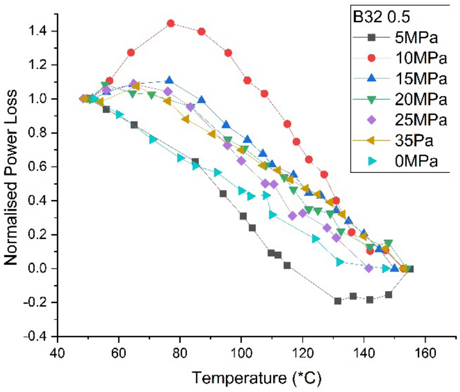

Fig. 2. Power losses at 1.5T, 400Hz due to different temperatures. Power losses normalised to lowest temperature recorded in each stress profile.

Figure 3 shows Fig. 2's data from the perspective of the loss-stress profile to contrast the small effect that large increases in temperature have on the loss-stress profile. Given the contribution of Eddy currents at 400Hz, increases in temperature will decrease power losses through increasing electrical resistance; however, this effect is marginal compared to the effects of stress. Figure 4 further demonstrates the dominance of stress over temperature effects with the increase in coercivity between stressed and unstressed states while temperature has a negligible effect on this. Moreover, the BH loop distortion is dominated by stress.

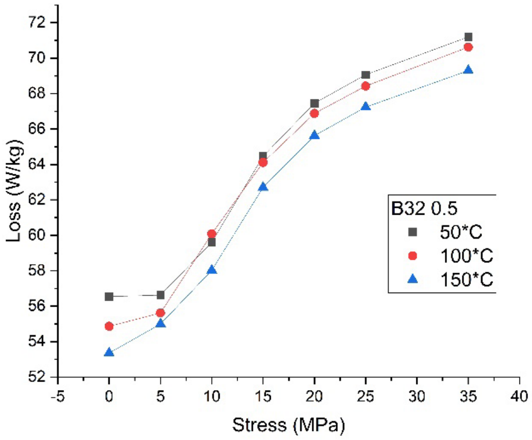

Fig. 3. Power losses due to stress at 1.5T, 400Hz and different temperatures.

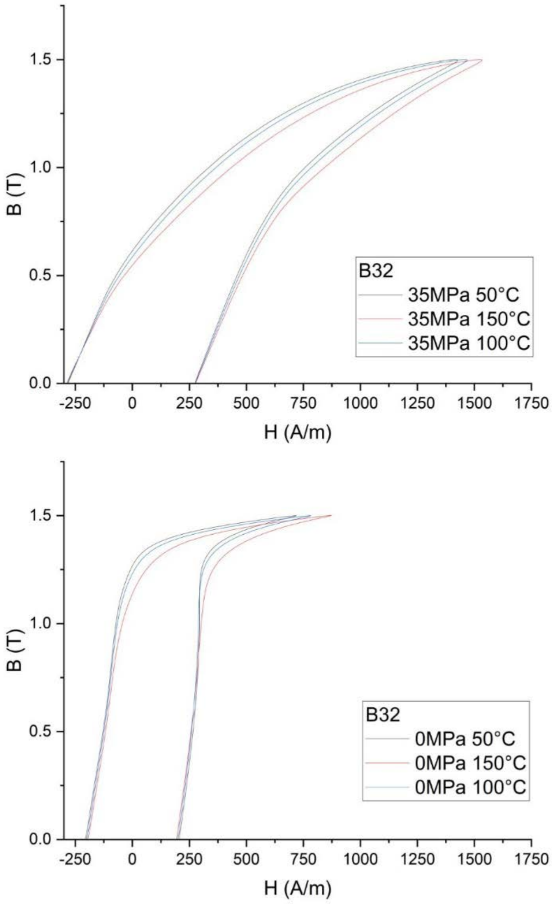

Fig.4. Magnetic hysteresis at 1.5T, 400Hz due to different temperatures in a stress (top) and unstressed (bottom) state.

CONCLUSIONS

The novel test jig presented is capable of measuring the magnetic properties of electrical steel laminations at different stresses and temperatures in conjunction, and could be used further to characterise the dependence of heat and stress effects on material factors that govern hysteresis.

Increases in both stress and temperature negatively impact magnetic permeability; however, within the operational environment of an electric motor the stress effects are dominant and increase power losses by ~30% at 35MPa, while temperatures of 150°C can reduce power losses by ~3% for the same stress due to Eddy current reduction.

Stress-dependent models could implement a temperature coefficient similarly.

Conflicts of interest
The authors declare no conflict of interest.

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