Thermal expansion and magnetostriction of $Nd_{16}Fe_{76}B_8$ alloy

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The spontaneous magnetization variation in the temperature range from room temperature to 500 °C was examined by correlation with thermal expansion measurement. Unaligned and aligned sintered specimens were examined to study the temperature dependencies of their dimensions resulting from spontaneous magnetostriction and thermal expansion. Above the Curie temperature (315 °C) all specimens showed the same normal thermal expansion, whilst below this temperature their thermal expansions were quite different and anomalous.

1. Introduction

Despite the many applications and the extensive studies that have been made of NdFeB compounds, thermo-magnetic dependencies of these materials have been little investigated. In general, the variation of the dimensions of ferromagnetic materials with temperature arises from thermal expansion and the change in spontaneous magnetostriction with temperature. Thermal expansion is caused by an increased amplitude of atomic thermal oscillation which results in an increased mean interatomic spacing, while the spontaneous magnetostriction is related to interactions between electrons and the atomic lattice of the crystal, the spin-orbit interaction.

As proposed by many authors [1–3] the relative importance of lattice thermal oscillation and ferromagnetic coupling in determining thermal expansion depends upon the Curie temperature. Above the Curie temperature only normal thermal expansion occurs because of the absence of ferromagnetic coupling. In the present study the temperature dependencies of the spontaneous magnetostriction of $Nd_{16}Fe_{76}B_8$ were studied through thermal expansion measurements from room temperature to approximately 500 °C. This temperature range includes both the ferromagnetically ordered and the paramagnetic states of the compound.

2. Experimental procedure

The sintered materials were produced by sintering powder made by the hydrogen decrepitation (HD) process, and were sectioned parallel and perpendicular to the magnetic alignment axis, and hence to the *c*-axis, using a diamond saw. The dimensions of the specimens were approximately 5 mm × 5 mm × 10 mm. The specimens were heated to 500 °C at a heating rate of 5 °C min^{-1} in an argon atmosphere. Two kinds of specimens were examined, namely, aligned specimens, produced by the normal route, and unaligned specimens, fabricated in the same way except that they were not aligned prior to compaction. The dimensional changes were observed using a thermomechanical analyser TMA-790.

3. Results and discussion

It is well known that for tetragonal $Nd_2Fe_{14}B$ the easy direction of magnetization is the *c*-axis, while the hard direction is the *a*-axis. Figs 1 and 2 show the temperature variation in dimensions, parallel and perpendicular to the magnetic alignment direction, that is parallel and perpendicular to the easy *c*-axis. It is evident that there is a temperature of about 315 °C, which divides both curves into two parts with quite different slopes, and shape. The relative variation in dimension parallel to the easy direction, $\alpha_{||}$, increases with increasing temperature up to 250 °C, after which it decreases up to 315 °C. The relative variation in dimensions perpendicular to the easy direction, $\alpha_{\perp}$, is slightly different. It monotonically decreases with increasing temperature from room temperature to 315 °C. Above this temperature both curves have essentially the same shape and exhibit normal thermal expansion. This behaviour above 315 °C is also almost the same for the unaligned specimen, as shown in Fig. 3. From these observations it is concluded that the thermal expansion above approximately 315 °C is isotropic and as expected for paramagnetic specimens. Therefore, 315 °C corresponds to the Curie temperature. This interpretation is confirmed by DTA experiments [4] and is supported by Cheng *et al.* [5, 6].

The Curie temperature is the critical temperature between normal thermal expansion which arises from lattice thermal vibration and thermal expansion which is affected by ferromagnetic coupling, which is related to exchange interaction between magnetic ions. These two competing factors oppose each other. Below this temperature strong ferromagnetic coupling is dominant and above it normal thermal expansion is dominant and ferromagnetism disappears. Obviously below the Curie temperature the variation in dimensions arises from the sum of changes in spontaneous magnetostriction and normal thermal expansion. The broken lines in the figures show the contribution of the normal thermal expansion below the Curie temperature. They are determined by extrapolating from the paramagnetic region (above the Curie temperature) to

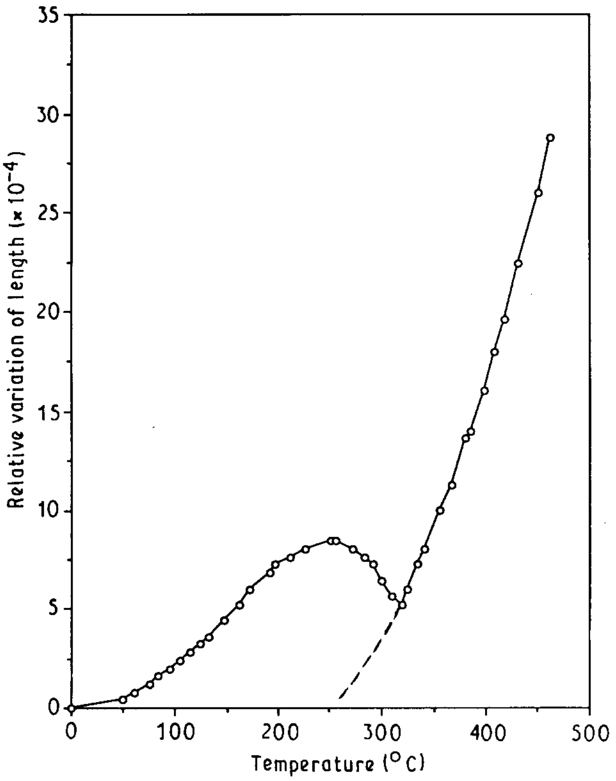

Figure 1 Temperature variation in dimensions parallel to the easy direction.

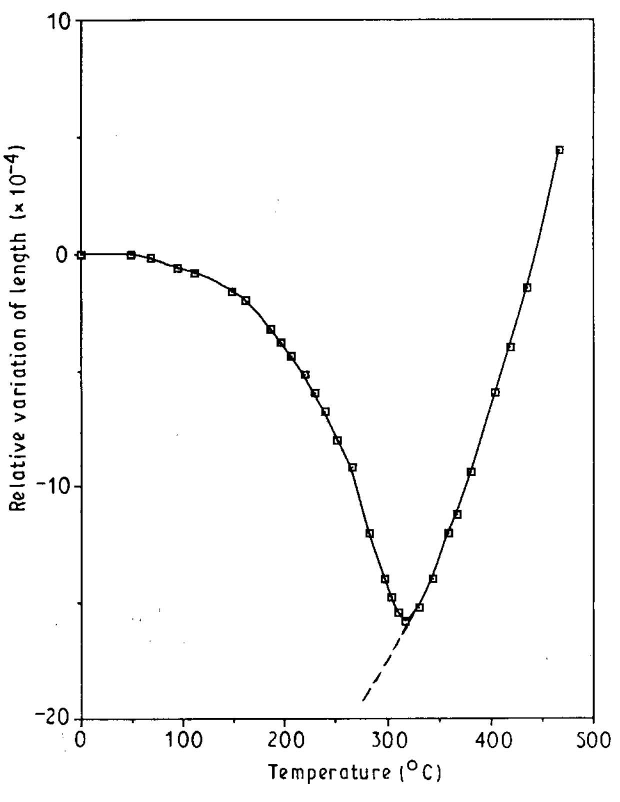

Figure 2 Temperature variation in dimensions perpendicular to the easy direction.

the ferromagnetically ordered regions. The spontaneous magnetostriction effect can be obtained by subtracting the contribution of normal thermal expansion from the measured curves. A comparison between the curves shown in Figs 1 and 2 indicates that at room temperature $\alpha_{\parallel}$ increases with temperature very gently, while $\alpha_{\perp}$ decreases. It is concluded that this

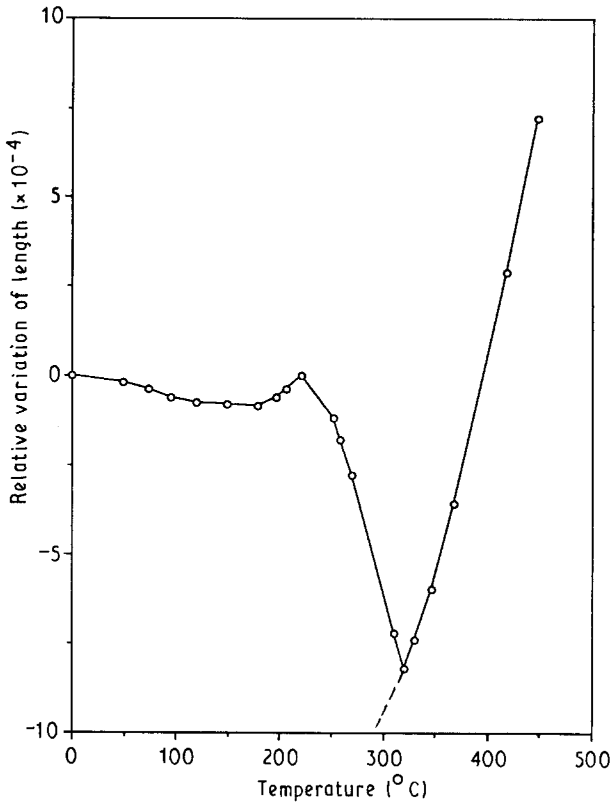

Figure 3 Temperature variation in dimensions for the unaligned specimen.

different behaviour is almost certainly related to the very anisotropic nature of NdFeB alloys.

4. Conclusion

The temperature-dependence of changes in dimension of unaligned and aligned specimens showed that above the Curie temperature all specimens had almost the same thermal expansion coefficient, whilst below this temperature their thermal expansions were quite different and anomalous. At room temperature the relative dimensional change parallel to the easy direction, $\alpha_{\parallel}$, increases with increasing temperature, whilst perpendicular to the easy direction, it decreases with increasing temperature. This behaviour is a consequence of the large uniaxial magnetocrystalline anisotropy of NdFeB alloys.

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Received 27 February
and accepted 30 March 1992