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MAGNETIZATION AND MAGNETOSTRICTION OF TERBIUM-SCANDIUM ALLOYS

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Abstract. — Lattice parameters, magnetization, thermal expansion and magnetostriction of a series of single crystal and polycrystalline specimens of Tb-Sc alloys have been measured. The various experimental observations are examined in terms of the single ion theory of Callen & Callen and the magnetoelastic energy evaluated for the various compositions.

I. Introduction. — Scandium forms solid solutions with the heavy rare earths which have been studied by the Oak Ridge group using neutron diffraction techniques. The Gd-Sc series has also been examined magnetically [2]. Scandium stabilises the helical antiferromagnetic state and depresses both Néel and Curie points. We have studied the Tb-Sc series in greater detail.

II. Experimental details. — Measurements of magnetization, thermal expansion and magnetostriction along the principal crystallographic directions have been made on single crystal discs of Tb,Sc, where x = 0.89, 0.825 and 0.695. These were produced by Metals Research Ltd. by annealing the alloy at ~ 1300 °C and spark machining the ingot to give discs of diameter ~ 5 mm and thickness ~ 1 mm. Offcuts were used for analysis. Measurements were also made on polycrystalline samples with x = 0.5 and 0.25, prepared by repeated argon arc melting of weighed quantities of material.

Lattice parameters at room temperature were determined by the X-ray powder method with Cohen's corrections for systematic errors. Density was determined w. r. t. C,H,Br. Homogeneity was checked by X-ray fluorescence spectrometry. This method and conventional spectroscopy were used to check the purity. Absorption spectroscopy gave better estimates of composition in certain samples. Alloy compositions are accurate to within ± 0.5 atomic % and homogeneity was good. The sample purity was of the order 4 N, excluding dissolved gases.

A Foner type magnetometer, calibrated against pure Iron using the data of Weiss and Forrer [4], was used for magnetization measurements between 4.2 °K and 300 °K. Thermal expansion and magnetostriction were measured using strain gauges in a D. C. bridge with a photoelectric galvanometer amplifier as null detector. The strain measurements were checked against the thermal expansion data of Nix and MacNair [5] for Copper. Strains of order 5 × 10⁻⁷ were detectable.

III. Results and discussion. — The alloys have h. c. p. structure. As seen in figure 1, the a-axis parameters follow Vegard's Law within experimental accuracy. The c-axis parameter, however, shows a negative deviation, while the pycnometric density exhibits a corresponding positive deviation. The pycnometric and X-ray densities agree within experimental error.

Two discs of Tb,Sc, alloy were used, one with the basal plane in the plane of the disc and the other with the c-axis and one of the b-axes in the plane. Magnetization was measured as a function of applied fields (up to 9 kOe) over the temperature range along a, b and c directions, the former being the easy direction and the c-axis very hard. Saturation
magnetization at 4.2°K was found by extrapolating the \( \sigma \) versus \( H^{-1} \) curve to \( H = \infty \). To estimate the ferromagnetic Curie point \( \theta_c \), the linear portion of the \( \sigma^2 \) versus \( T \) curve was extrapolated to \( \sigma^2 = 0 \). The value of \( T \) so obtained was plotted against \( H \) and extrapolation to \( H = 0 \) gave \( \theta_c \). The \( T \) versus \( H \) plot showed the variation with temperature of the critical field required to switch from helical antiferromagnetism to ferromagnetism. The Néel point is also field dependent. Above this the susceptibility follows a Curie-Weiss law. From the linear \( \chi^{-1} \) versus \( T \) plots, the paramagnetic Curie temperature \( \theta_p \) and the effective moment \( \mu_{\text{eff}} \) have been estimated. The basal plane and the c-axis values of \( \theta_p \) differ indicating high anisotropy. The polycrystalline \( \theta_p \) is well represented by \( \frac{1}{3} \theta_p \) (c-axis) + \( \frac{2}{3} \theta_p \) (basal). The variation of critical field with temperature and some representative magnetization data are shown in figure 2.

The \( \text{Tb}_{0.825}\text{Sc}_{0.175} \) crystals showed similar behaviour to the previous alloy, but with different values of the parameters. The other alloys do not show ferromagnetism, but have a characteristic Néel point except for \( \text{Tb}_{0.22}\text{Sc}_{0.78} \), which shows no ordering. The various parameters measured are summarised in Table I.

Thermal expansion measurements on \( \text{Tb}_{0.89}\text{Sc}_{0.11} \) single crystals show that the a-axis contracts from 300°K down to \( \theta_c \) with a change of gradient around \( T_N \). At \( \theta_c \) there is a sharp contraction and in the ferromagnetic state the contraction continues. The c-axis contracts down to \( T_N \) after which expansion starts under the influence of inter-layer magnetic forces. A sharp change is observed at \( \theta_c \). Application of a magnetic field in the basal plane causes magnetostrictive deformation along the a-axis. The experimental observations are shown in figure 3. Below \( \theta_c \) satisfactory measurements of magnetostriction along the c-axis could not be made. From the magnetostriction data, the term \( \lambda^{-2} \) of Callen and Callen's [6] theory was estimated; it follows the single ion theory well with \( \lambda^{-2}(T = 0) = (7.0 \pm 0.4) \times 10^{-3} \). \( \text{Tb}_{0.825}\text{Sc}_{0.175} \) crystals show similar behaviour.

Scandium alloys do not obey the \( G^{2/3} \) law (\( G = \text{de Gennes Factor} \)) like the Yttrium alloys. Using available data and our measurements it appears that \( T_N \) varies as \( G^{2/3} \) while \( \theta_c \) varies approximately as \( G^2 \). From the room temperature magnetization, the

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|c|c|}
\hline
Alloy & basal & \( \theta_c \) °K & \( T_N \) °K & \( \theta_c \) °K & \( \mu_{\text{eff}} \)/Tb ion & \( \mu_{\text{eff}} \)/(Tb atom) Bohr magnetons \\
\hline
\text{Tb}_{0.89}\text{Sc}_{0.11} & 195 ± 1 & 180 ± 2 & 190 ± 2 & 197 ± 1 & 136 ± 1 & 10.2 ± 0.2 & 9.6 ± 0.2 \\
\text{Tb}_{0.825}\text{Sc}_{0.175} & 186 ± 1 & 135 ± 2 & 170 ± 2 & 188 ± 1 & 75 ± 2 & 9.9 ± 0.2 & 9.4 ± 0.2 \\
\text{Tb}_{0.60}\text{Sc}_{0.40} & — & — & 150 ± 2 & 152 ± 2 & — & 9.7 ± 0.2 & — \\
\text{Tb}_{0.32}\text{Sc}_{0.68} & — & — & 63 ± 2 & — & — & 10.5 ± 0.2 & — \\
\text{Tb}_{0.22}\text{Sc}_{0.78} & — & — & 15 ± 2 & — & — & 10.1 ± 0.2 & — \\
\hline
\end{tabular}
\caption{Table 1}
\end{table}
No data exists for the elastic constants of these alloys and those for pure rare earths are not complete. We have tried to estimate the elastic constants from those of the elements. A crude estimate has been made of the constant \( C' = 2(C_{11} - C_{12}) \). Using the relation \( F_{ms} = -C'(\lambda^2)/8 \) (Cooper [8]), the magnetostrictive energy at 0 °K is about 1.25 °K/atom for Tb\textsubscript{0.89}Sc\textsubscript{0.11} and 0.8 °K/atom for Tb\textsubscript{0.825}Sc\textsubscript{0.175} indicating a rapid fall from the value of 2 °K/atom estimated for pure Tb. This rapid fall seems to account for the absence of any driving force for the transition to ferromagnetism even at high Tb concentration. From the experimental data, estimates of interplanar exchange constants and their variation with temperature have also been made. Wollan [9] discussed the effect of the smaller atomic volume of Scandium on the magnetic ordering. Our results are in line with Wollan’s analysis indicating that the magnetism is dominated by the reduction in size due to alloying with Scandium.

References