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MAGNETIC PROPERTIES OF NICKEL-COPPER AND NICKEL-COBALT ALLOYS

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Abstract. – This paper reports on the effects of alloy composition and applied stress on the magnetic properties of nickel, nickel-copper and nickel-cobalt alloys. The reduction in saturation magnetization on addition of copper to nickel was greater than expected on the basis of a simple rigid band approximation, however the effects of adding cobalt to nickel were very close to expectations. The saturation magnetostriction λs of the copper-nickel alloys was reduced by the addition of copper, however the rate of change of magnetostriction with magnetization, dλs/dM, was increased on addition of copper. The change in anhysteretic and maximum differential susceptibility with stress was found to be consistent with recent theoretical models only at stress amplitudes below 25 MPa.

Introduction

The magnetic properties of the 3d transition metal series are of theoretical importance because their behavior can be interpreted on the basis of a simple rigid band theory [1, 2]. The addition of cobalt to nickel has the effect of subtracting one electron from the 3d band for each cobalt atom added. The 3d band of nickel is nearly full and so this results in a reduced magnetic moment per atom. Conversely the addition of copper has the effect of adding an electron, and this results in a reduction of magnetic moment per atom.

In the nickel rich region of both the Ni-Cu and Ni-Co phase diagrams the alloys form a single phase solid solution, which in the case of Ni-Cu extends over the entire composition range, while in Ni-Co it extends to compositions of up to 67 % Co. This means that in these alloys the magnetic properties can be studied without the interference of microstructural effects such as occur in the presence of a second phase. They provide an ideal system for making fundamental measurements of the complex effects of stress on the properties of ferromagnetic materials.

Recent work on this alloy system has been performed by Akopov et al. [3] and by Ali and Said [4-6] who investigated the effects of residual stresses associated with dislocations on structure sensitive magnetic properties such as coercivity and initial susceptibility.

Sample preparation

The specimens were produced from 99.99 % pure nickel and either 99.99 % pure cobalt or copper by arc melting in a magnesium oxide crucible under an inert argon atmosphere. Following this the specimens were rod rolled to a diameter of 2 cm and then annealed at 700 °C for 3 hours to remove any residual stresses associated with dislocations within the material.

Results

The dependence of the saturation magnetization, and hence the average magnetic moment per atom, on composition is shown in figure 1. The semi empirical model based on the rigid band approximation [7], predicts the magnetic moment per atom of these alloys as

$$\mu = (0.6 \pm 2) \mu_B$$  

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where \( x \) is the fraction of copper or cobalt present in the alloy. (The positive sign is used for cobalt and the negative sign for copper.) Compared with this the present results on Ni-Cu show significant deviations which follow more closely the relation \( \mu = (0.6 - 1.6x) \mu_B \). The results for Ni-Co alloys however followed more closely the expected relation.

The maximum differential susceptibility, which in these specimens occurred at the coercive point, has been shown elsewhere to be closely related to the ideal or anhysteretic susceptibility at the origin \([8]\). In the present work comparison of these two properties showed them to be identical to well within experimental error. The value of \( x'_{\text{max}} \equiv \chi_{\text{an}} \) was found to vary with alloy composition in such a way that under zero stress it was proportional to the average magnetic moment per atom.

The variation of \( x'_{\text{max}} \) with stress was the most significant result however. According to previous theory \([9]\) based on stress induced uniaxial anisotropy predicts that the anhysteretic susceptibility \( \chi_{\text{an}} \) should be

\[
\chi'_{\text{an}} = \frac{\mu_0 M_s^2}{3\sigma \chi_x}
\]

where \( \sigma \) is the stress, \( \chi_x \) the saturation magnetostriction and \( M_s \) the saturation magnetization.

If the magnetization process is principally a domain wall motion process, then an alternative theory which has recently been devised by Sablik \textit{et al.} \([10]\) and Garikepati \textit{et al.} \([11]\) leads to a different prediction for the stress dependence,

\[
\sigma = \frac{\mu_0 M^2}{3\lambda} \left( \frac{1}{\chi'_{\text{an}} (0)} - \frac{1}{\chi'_{\text{an}} (\sigma)} \right)
\]

where \( M \) is the magnetization and \( \lambda \) is the bulk magnetostriction, \( \chi'_{\text{an}} (0) \) and \( \chi'_{\text{an}} (\sigma) \) are the anhysteretic differential susceptibilities at the origin under zero stress and a stress of \( \sigma \) Pa.

Experimental results taken in this work are shown in figure 2. These indicate that the variation of \( \frac{1}{x'_{\text{max}}} \) with stress is not linear as predicted by both theories, but is instead closer to a quadratic relationship.

At low stresses the dependence of \( \frac{1}{x'_{\text{max}}} \) on \( \sigma \) is linear to a first approximation and it is reasonable therefore to consider whether the theories given above are usable in the low stress limit.

The result based on the domain rotational model is a little closer to observed stress in this case, but it is not significantly better than the more recent model.

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Fig. 2. – Dependence of \( 1/x'_{\text{max}} \) on applied tensile stress.