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MAGNETIC PROPERTIES OF METASTABLE 304 STAINLESS STEEL WITH BCC STRUCTURE

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Abstract. – Ordinary 304 stainless steel has a fcc structure and is non-magnetic at room temperature. By using a vapor quenching method, we have fabricated single-phase metastable bcc 304 stainless steel which is strongly ferromagnetic with a magnetization of 130 emu/g and a Curie temperature in excess of 550 °C. Upon subsequent annealing above 550 °C, the metastable bcc state transforms back into the usual non-magnetic fcc phase. The changes in the magnetic properties and the structure of these films during the transformation are examined.

1. Introduction

The structural dependence of the magnetic properties of Fe-based alloys is one of the most interesting aspects of magnetism [1]. For example, ordinary bcc (body-centered cubic) α-Fe is strongly ferromagnetic, whereas the fcc (face-centered cubic) γ-Fe is not. An interesting case in point is 304 stainless steel (SS). Ordinary 304 SS, with a nominal composition of 72 w.% Fe, 18 w.% Cr, 8 w.% Ni and 2 w.% Mn, normally appears in the fcc phase, which is non-magnetic. However, the metastable bcc phase of 304 SS, as obtained by vapor quenching methods, is strongly ferromagnetic [2, 3]. Hence it is possible to examine the magnetic properties of 304 SS in two distinct crystalline states, a stable fcc state and a metastable bcc state, and study the transformation from bcc to fcc.

2. Results

Thin films of 304 SS were obtained using a high-rate DC magnetron sputtering system. Films a few microns in thickness were deposited on mica and Al₂O₃ substrates kept at room temperature. X-ray diffraction shows that the 304 SS target is essentially fcc as expected. However, the as-sputtered 304 SS is single-phase bcc with no evidence of the fcc phase. The transformation from the metastable bcc state to fcc state was investigated by annealing the as-sputtered samples at elevated temperatures; each at a specific temperature for 20 minutes. The X-ray diffraction pattern was then recorded at room temperature. To quantitatively characterize the transformation kinetics, the normalized sum of the bcc [110] and bcc [200] peaks and the sum of the fcc [111] and fcc [200] peaks are plotted as a function of the annealing temperature as shown in figure 1. It is found that the transformation begins slowly near 500 °C, with a 5 % yield, and quickly reaches 50 % near 550 °C. The transformation is completed near 800 °C.

The magnetic properties of the films were determined with a vibrating sample magnetometer. The fcc phase is essentially non-magnetic; the magnetization of the 304 SS target material is about 1 emu/g under an external field of 14 kOe. The bcc phase of the as-sputtered 304 SS, however, is strongly ferromagnetic with a spontaneous magnetization of 130 emu/g. Measurements with the applied field perpendicular and parallel to the sample plane show that the magnetic easy axis is in the plane (Fig. 2). The anisotropy field, where M∥ and M⊥ intersect, is slightly higher than the maximum applied field available. By extrapolation, the anisotropy field is estimated to be 19 kG. The bcc 304 SS is magnetically soft with a coercivity of about 50 Oe.

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2 Present address: AT & T Bell Labs, Murray Hill, NJ 07974, U.S.A.
Since the magnetic properties of 304 SS depend critically on the structure being bcc or fcc, the structural transformation can be directly related to the resulting magnetic properties. The spontaneous magnetization of the sputtered 304 SS sample was measured at progressively higher annealing temperatures ($T_A$) with the sample in a flowing Ar atmosphere. Each measurement of about 10 min at $T_A$ was always followed by a measurement at 30 °C, before heating the sample to the next higher $T_A$. The spontaneous magnetization at 30 °C of 130 emu/g is maintained up to $T_A = 550$ °C. Above 550 °C, the magnetization at 30 °C decreases rapidly, signaling the structural transformation. The sample annealed at 800 °C is essentially non-magnetic at 30 °C with a magnetization of about 1 emu/g under a field of 14 kOe. The Curie temperature of the metastable bcc phase is at least 550 °C.

The distinct magnetic properties of the fcc and bcc states of 304 SS have also been fruitfully investigated by Mössbauer spectroscopy. In the non-magnetic state of the starting fcc 304 SS, the Mössbauer spectrum exhibits a single peak as expected (Fig. 3a). In the as-sputtered sample of bcc 304 SS, one instead observes a six-line spectrum with a hyperfine field of about 255 kOe (Fig. 3b). If we use the magnetic hyperfine field to gauge the Fe moment, the moment in bcc 304 SS is about 1.7 $\mu_B$. Since 304 SS has 72 % of Fe, this accounts very well for the observed magnetization of 130 emu/g. Hence it can be concluded that in the bcc 304 SS, only the Fe atoms contribute significantly to the magnetization. After the bcc 304 SS has transformed completely to the fcc state, the resulting spectrum is once again a single line (Fig. 3c).

### 3. Conclusions

We have obtained single-phase bcc thin films of 304 stainless steel by DC magnetron sputtering. The samples are strongly ferromagnetic with the magnetic easy axis oriented in the plane, and only the Fe atoms contribute to the magnetization. The bcc phase begins to transform to the fcc state at 550 °C, and the transformation is completed after 20 min at 800 °C. During the transformation the magnetization is directly proportional to the amount of bcc phase present.