ADP012303

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TITLE: Applications of Ferromagnetic and Optical Materials, Storage and Magnetoelectronics: Symposia Held in San Francisco, California, U.S.A. on April 16-20, 2001

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Mat. Res. Soc. Symp. Proc. Vol. 674 © 2001 Materials Research Society

High Strength Soft Magnetic Composites

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ABSTRACT

There has been an increasing demand for high temperature soft magnetic materials with mechanical properties better than those of existing commercial materials such as FeCo alloys. We have designed new magnetic composites by reinforcing FeCo alloys with high strength tungsten fibers. The composite materials were fabricated by electrodeposition. In general, the as-deposited composites have a relatively high coercivity H_c and low magnetic permeability μ, because of induced strain during fabrication. After appropriate thermal annealing, the composites have good soft magnetic properties, comparable to commercial bulk alloys. However, the saturation induction is reduced due to the non-magnetic inclusions. The composites also show significant enhancements in yield strength and tensile strength that increases linearly with fiber volume fraction as seen in other common composite materials. In addition, near zero creep is observed at 600 °C under a stress of 600 Mpa. The mechanical properties can be further improved by co-depositing soft magnetic material and Al_2O_3 onto the fibers. An approximately linear relationship was observed between the coercivity and volume fraction of Al_2O_3 particles. The square-root relationship was observed between the hardness and the Al_2O_3 concentration.

INTRODUCTION

There is an increasing demand for high-performance soft magnetic materials in the design of high-speed motors and generators for high temperature operation [1-5]. The mechanical strength of these materials at high temperatures is a crucial parameter in such applications. Fe-Co alloys exhibit high saturation magnetization M_s and high Curie temperatures T_c ($T_c \approx 900$ °C) that make them potential candidates. The ordered Fe-Co alloys are excellent soft magnetic materials with negligible magneto-crystalline anisotropy K_1 [6]. However, equiatomic Fe-Co alloys are extremely brittle and other elements such as V are usually added to obtain workable materials. These additions however, significantly deteriorate the soft magnetic properties, due to the precipitation of a second phase [7-9]. Therefore, mechanical strength is achieved at the expense of magnetic performance.

We have developed new magnetic composites by reinforcing Fe-Co materials with tungsten fibers and Al_2O_3 particles. In the case of FeCo-fiber composites, the contributions to magnetic and mechanical properties come from two nearly independent entities, i.e. the FeCo matrix and fiber network, respectively. One immediate advantage of such materials is that one can optimize magnetic and mechanical properties in each entity independently, and thus no comprise between the magnetic and mechanical properties is necessitated. For further improvement in mechanical properties, hard fine particles of Al_2O_3 were dispersed in the matrix, to inhibit recrystallization and grain growth at elevated temperatures.

EXPERIMENTAL

Fiber and dispersion reinforced magnetic composites were fabricated by the electrochemical deposition of the alloys onto W fibres. An aqueous bath containing $CoSO_4 \bullet H_2O$, $FeSO_4 \bullet H_2O$, HBO_3, and saccharine [10] was used. The Al_2O_3 particles of diameter $d<0.1$ μm were mixed directly into the solution. Sulfuric acid was added to the bath to adjust the pH value to about 2.0.

Toroidal and long stripe samples were used to measure magnetic properties using a magnetic loop tracer, with a maximum field of 150 Oe. The magnetic measurements were made parallel to the long axis of the fibres. Grain sizes and precipitates were characterized by optical microscopy, SEM and TEM. The Vicker microhardness (HV) of the magnetic composites was measured using a load of 50 g for 10 s. Tensile tests were performed using an Instron mechanical tester.

RESULTS AND DISCUSSION

Room temperature magnetic hysteresis loops for the as-deposited and annealed $Fe_{50}Co_{50}$-W composites are shown in figure1. The sample diameter was 50 μm and the diameter of the fiber was about 12 μm. In the as-deposited state, the samples are not magnetically soft and have low magnetic permeabilities and coercivities of about 16 Oe, whereas the annealed samples have good soft magnetic properties. The improvement of soft magnetic properties is related to a micro structural change during thermal annealing. First, the grain sizes increase from about 50 nm to 200 nm after heat-treatment, which reduces coercivity [11]. In addition, thermal annealing relieves the internal stress induced during the electrodeposition process. This internal stress, which causes a radial dependence of permeability, results in giant impedance effects in the as-deposited sample [12]. There are also other micro structural changes such as an increase in the structural order parameter and a decrease in the number of defects, which further enhance the soft magnetic properties.

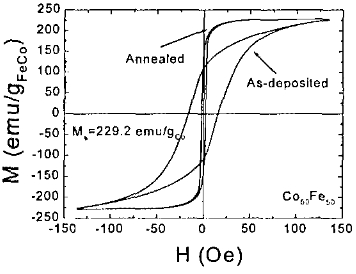

Figure 1. Magnetic hysteresis loops for the as-deposited and annealed Fe20Co80-W samples

A significant improvement of mechanical properties has been observed in these composites. In figure 2 the mechanical strength is presented as a function of the W fiber volume percent for the annealed $Fe_{50}Co_{50}$-W samples. Both yield strength and tensile strength increase linearly with fiber volume percent as seen in other common composite materials [13]. In our sample geometry, the stress is applied on the matrix material and transferred to the W-fibers through the interface. The observation of such a composite behavior suggests good adhesion between deposited materials and W fibers. Magnetic measurements illustrated that FeCo thickness does not significantly alter the magnetic properties of the samples. More significantly, as shown in figure 3, the high temperature (600 °C) creep was found to be negligible in the FeCo-W composites. This is in contrast with commercial FeCo-based alloys, in which substantial creep takes place after about 50 hours, causing detrimental failures at high operating temperatures.

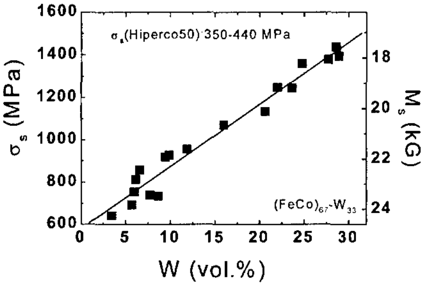

Figure 2. Mechanical strength vs. W fiber volume fraction, for annealed $Fe_{20}Co_{80}$-W composites

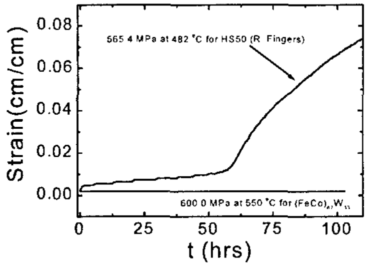

Figure 3. High temperature creep for FeCo composites in comparison with commercial FeCo bulk alloy [*]

To further enhance the mechanical properties of the soft magnetic materials, fine Al_2O_3 particles were uniformly dispersed in FeCo alloys during deposition. Figure 4 shows the dependence of H_c on the volume percent of Al_2O_3 particles of diameter of 37 nm for as-deposited and annealed FeCo(Al_2O_3)-W samples. A reduction in coercivity H_c is seen after thermal annealing, but the heat treatment does not influence the trend of coercivity H_c as a function of the Al_2O_3 content.

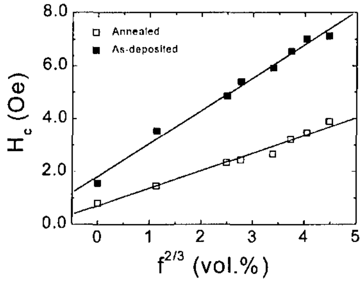

Figure 4. Coercivity vs. Al_2O_3 content in the as-deposited and annealed Fe50Co50-W samples

Kersten [14] developed a theory to explain the effect of inclusions on the magnetic properties. In his model, he assumed that spherical nonmagnetic particles of average radius r were uniformly imbedded at the corners of unit cells of an adopted simple cubic lattice with lattice constant a. In addition, the size of inclusions is assumed to be comparable to the domain wall thickness. The coercivity H_c can be expressed as:

$$H_C = 2.4\frac{\delta_W K_1}{M_S \mu_0 r} f^{2/3} \qquad (1)$$

where f is the volume percent of the inclusions. This linear relationship between H_c and $f^{2/3}$ has indeed been observed as shown in Fig. 4. Using $\delta_W \approx \sqrt{k_B T_C / a K_1}$, where k_B is the Boltzmann constant, we estimated the domain wall thickness for $Fe_{50}Co_{50}$ alloy to be about $\delta_W \approx 0.26$ μm, which is comparable to the Al_2O_3 particle size.

Figure 5 shows the Vicker hardness of FeCo-Al_2O_3 composites as a function of Al_2O_3 content. The increase in hardness was found to be about a 100% for FeCo samples with 12 vol.% Al_2O_3 particles when compared with a pure a FeCo sample. A reduction of the hardness in the annealed samples is due to the increase in grain size and the relief of internal stress. A roughly linear relationship between the hardness and the cube root of the volume percent of the dispersed Al_2O_3 phase has been observed for both as-prepared and annealed samples. Dispersion hardening commonly follows the Orowen-Ashby model [15]. For the case of non-coherent spherical particles of size r, Orowen [15] proposed the mechanism where the yield stress is determined by the shear stress required to bow a dislocation line between two particles separated by a distance λ. The increase in yield stress is given by:

$$\Delta\sigma = \frac{0.13Gb}{\lambda}\ln\frac{r}{b} \qquad (2)$$

where G is elastic modulus, b is Buger vector of a dislocation. For dispersion reinforced composites, the spacing λ between particles can be estimated using: $\lambda \propto (16/f)^{1/3}r$. The hardness as a function of $f^{1/3}$ is shown in Fig. 5. The linear relationship between hardness and $f^{1/3}$ suggests that the dispersion hardenning in our samples follows the Orowen-Ashby model.

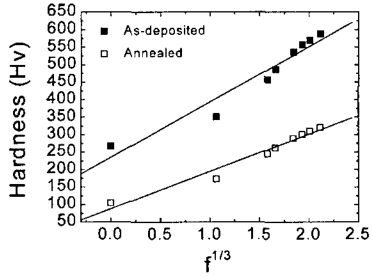

Figure 5. Vicker hardness vs. the square root of the volume fraction of Al_2O_3 content for the as-deposited and annealed $Fe_{50}Co_{50}$-W samples

CONCLUSIONS

To significantly improve the mechanical properties without significantly sacrificing the magnetic properties, we have designed and fabricated fiber and ceramic particle reinforced soft magnetic composites. Excellent mechanical properties including high yield strength and negligible creep rate at 600°C have been observed in the fabricated fiber composites. The dispersion hardness in the ceramic particle reinforced composites increases in accordance with the Orowen-Ashby model.

ACKNOWLEDGEMENT

This work was supported by the AFOSR under grant number MURI F49620-96-1-0434.We are indebted to Dr. L. Li and S. Masteller of Carpenter Technology for providing us the FeCo alloys.

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