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Hiperco® 50 alloy heat treated between 450 and 650 °C exhibits superior mechanical properties. We report the measurements of the ac core loss at various frequencies up to 4500 Hz of the Hiperco® 50 alloy samples annealed at 450 and 650 °C. The 650 °C annealed specimens have lower ac core loss than that of the 450 °C annealed ones. The total core loss, consisting of contributions from hysteresis core loss and eddy-current core loss, depends on frequency f as $af+bf^2$. The eddy-current loss of a single laminate is minor compared to the hysteresis loss. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1557308]

I. INTRODUCTION

Soft magnetic alloys with superior magnetic and mechanical properties are used in magnetic bearing rotors, thrust disks, auxiliary power units, and other applications. Depending on the specific applications, the operating temperature varies from near ambient to 550 °C. These materials must exhibit high Curie temperature, high magnetization, and low ac core loss, but also high yield strength, low creep rate, and other essential mechanical properties. The intermetallic FeCo alloy with a B2 structure is one alloy system that can meet the demanding requirement of a combination of mechanical, magnetic, and high-temperature properties.[1–3]

It is well known that the mechanical properties of an alloy depend sensitively on grain sizes in the alloy and the processing methods with which the specimen has been fabricated and deformed.[4–7] In the FeCo-based alloys, the desire to retain the B2 phase often resorts to heat treatments of the specimens at high temperatures (e.g., 750 °C) with slow cooling after processing.[8] The magnetic and mechanical properties reported in the literature are mostly those after high-temperature annealing.[4–8]

Recently, we have developed ultrahigh strength FeCo alloys with a unique combination of high yield strength (as much as a factor of 3 higher) and excellent ductility by controlling the grain size.[9] This unprecedented enhancement of yield strength would greatly expand the realm of the applications of FeCo alloys. In this work, we report the magnetic ac core loss of ultrahigh strength FeCo-based alloys using the commercially available Hiperco® 50 alloys.

II. EXPERIMENT

Commercially available Hiperco® 50 alloy in the form of cold-rolled 0.006 in. ($\sim$152 μm) thick laminates from Carpenter Technology Corporation has been used in this study. The alloy has a nominal composition of 49% Fe, 49% Co, 1.9% V, with small amounts of Mn, Nb, and Si. The specimens for magnetic core loss measurements are in the shape of circular rings with outer and inner diameter of 1.50 in. (3.81 cm) and 1.25 in. (3.175 cm), respectively. The ring specimens were heat treated in a dry hydrogen atmosphere at 650 and 450 °C for 4 h and cooled to room temperature at a rate of 60 °C/h. These annealing conditions were designed to limit grain growth to small sizes. We used a commercially available ac B–H loop tracer (Walker Scientific Inc. Model AMH-401) to measure the ac hysteresis loops of the specimens.

Room temperature tensile tests were performed on specimens along the original rolling direction using an Instron-5582 instrument. The specimens for mechanical properties were annealed in dry hydrogen atmosphere for 4 h at 450, 500, and 650 °C. The details of the measurements will be described elsewhere.[9]

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TABLE I. The values of 0.2% yield strength and elongation in percent of the Hiperco® 50 alloy samples annealed at different temperatures. The values listed at 760 and 843 °C are from the data sheet of Carpenter Technology Corporation.

Annealing temperature (°C)	0.2% yield strength		Elongation (%)
	(ksi)	(MPa)	
450	226	1559	7.6
500	217	1497	9.4
650	160	1105	16.1
760[a]	65	448	8
843[a]	57	393	9

[a]Data sheet from Carpenter Technology Corporation.

III. RESULTS AND DISCUSSION

The heavy mechanical deformation during the cold rolling process results in highly dislocated and atomic disordered microstructure in the as-rolled Hiperco® 50 sheets. The annealing process is necessary to reorder and recrystallize the as-rolled alloys. The mechanical properties of the cold-rolled Hiperco® 50 alloy specimens depend sensitively on the subsequent heat treatments. The grain sizes of the alloys are controlled by the subsequent heat treatments. Preliminary transmission electron microscopy indicates that the grain sizes are about 0.1–0.3 μm and about 0.5 μm in the specimens annealed at 450 and 650 °C, respectively. The values of the 0.2% yield strength in ksi and MPa, and elongation in % of the Hiperco® 50 alloy samples annealed at different temperatures are shown in Table I. Also listed are the values for the samples annealed at 760 and 843 °C obtained from the data sheets of the manufacturer. It is clear from Table I that the Hiperco® 50 alloy specimens with annealing temperature below 650 °C have much higher yield strength than those annealed at 760 °C and higher. In particular, the specimen annealed at 450 °C shows the largest yield strength of 1559 MPa, which is *three* times the value of 448 MPa for the 760 °C annealed specimen. The ductility of the Hiperco® alloy 50 specimens annealed at 650 °C is also much higher with elongation as much as 16.1%. The primary reason for the ultrahigh strength is the small grain sizes of about 0.5 μm for the sample annealed at 650 °C, and smaller for samples annealed at lower temperatures. In contrast, heat treatments at 760 °C and higher result in grain sizes of several μm. Thus by judiciously choosing the heat treatment conditions, we have realized an ultrahigh strength Hiperco® 50 alloy.

Magnetic properties are also important for applications. The frequency range of interest for most applications of magnetic generators is about several kHz. The ac hysteresis loops and core loss of the as-rolled, 450 °C annealed, and 650 °C annealed Hiperco® 50 alloy specimens using a single sheet have been measured at frequencies up to 4500 Hz. Figure 1(a) shows the hysteresis loops of the as-rolled, 450 °C annealed, and 650 °C annealed specimens at a typical frequency of 1 kHz. The as-rolled specimens have a slanted hysteresis loop with high saturation field and low remanence, which is undesired for applications requiring soft magnetic materials. The heat treatment improves the soft magnetic characteristics of the as-rolled specimen by decreasing the saturation field and increasing the remanence. The heat treatment of the heavily deformed cold-rolled Hiperco® 50 alloy stimulates a series of dynamic process involving recovery, reordering, and recrystallization, which leads to the retaining of the ordered B2 structure and reduction in the residual stress, resulting in the improvement in magnetic properties.

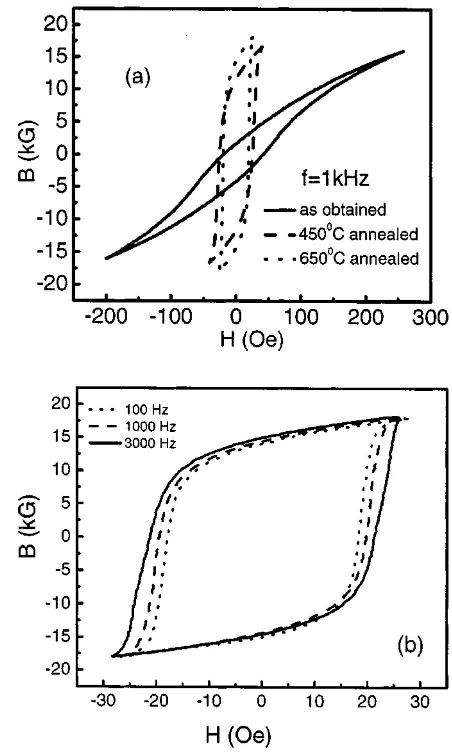

FIG. 1. (a) B–H loops of as-rolled, 450 °C annealed, and 650 °C annealed Hiperco® 50 alloy specimens at 1 kHz. (b) B–H loops at 100, 1000, and 3000 Hz of Hiperco® 50 alloy annealed at 650 °C.

The influence of the frequency on the hysteresis loop is illustrated in Fig. 1(b), where the ac hysteresis loops of the Hiperco® 50 alloy specimen annealed at 650 °C measured at 100, 1000, and 3000 Hz are shown. As the frequency in-

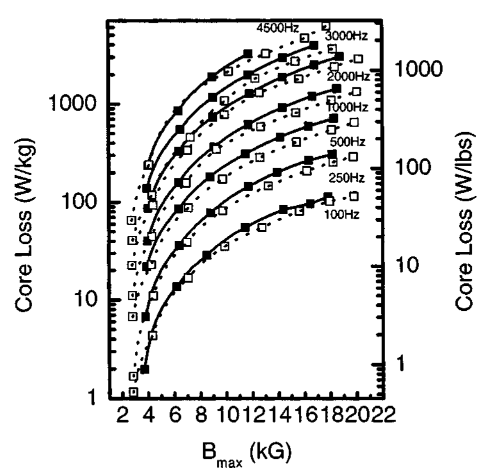

FIG. 2. ac core loss as a function of maximum magnetic induction $B_{\max}$ of the Hiperco® 50 alloy specimens annealed at 650 and 450 °C shown as open and closed symbols, respectively.

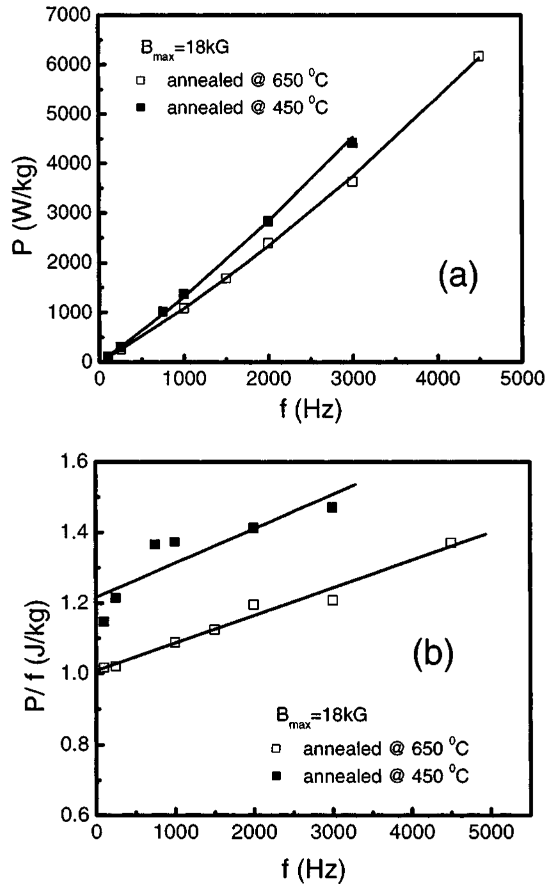

FIG. 3. Frequency dependence of ac core loss power P and energy P/f for the 450 and 650 °C annealed specimens at $B_{\max}=18$ kG.

creases, the value of coercivity increases from 18.0 Oe at 100 Hz to 21.3 Oe at 3000 Hz, and the hysteresis loop becomes wider due to the eddy current contribution.

The ac core loss at frequencies up to 4500 Hz, measured at different values of maximum magnetic induction $B_{\max}$ of the Hiperco® 50 alloy specimens annealed at 450 and 650 °C is shown in Fig. 2. As expected, the core loss increases with frequency, and the 650 °C annealed specimen has smaller core loss than the 450 °C annealed one.

The frequency dependence of power P and energy P/f of total ac core loss for the 450 and 650 °C annealed specimens at $B_{\max}=18$ kG are shown in Fig. 3. The ac core loss power P varies with frequency f as $af+bf^2$. The f and the f^2 terms are the contributions due to hysteresis loss and eddy-current loss, respectively. The total ac core loss energy P/f depends on frequency f as $a+bf$, as shown in Fig. 3(b). From the frequency dependence of P/f, we have obtained $a=1.22$ J/kg and $b=9.72\times10^{-5}$ J/kg Hz for the 450 °C annealed sample, and $a=1.01$ J/kg, $b=7.84\times10^{-5}$ J/kg Hz for the 650 °C annealed sample.

The small values of b indicate that within the measured frequency range, the major contribution of the core loss is from the hysteresis loss and the eddy-current loss is minor, which can be explained by the small specimen thickness of only 0.006 in.[10] This suggests that in the applications where large volume of soft magnetic materials is required, instead of using thick material, stacks of thin sheets with proper insulation are preferred so that the eddy-current loss can be kept at a minimum.

IV. CONCLUSIONS

The ac core loss of Hiperco® 50 alloy annealed at 450 and 650 °C, which exhibits exceptionally superior mechanical properties because of the small grain sizes, have been measured up to 4500 Hz. The annealing process improves the soft magnetic properties of the as-rolled Hiperco® 50 alloy. The total core loss has a frequency dependence of $af+bf^2$, where the linear and the quadratic frequency terms are contributions from hysteresis core loss and eddy-current core loss, respectively. The 650 °C annealed sample has a lower core loss than the 450 °C annealed one. In the present measurements using a single sheet, the eddy-current loss is minor compared to the hysteresis loss.

ACKNOWLEDGMENT

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