Giant coercive force and certain features in the magnetization reversal of bulky single crystals of the intermetallic compounds $Sm(Co_{1-x}Ni_x)_5$

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It was observed that in certain ferromagnetic $Sm(Co_{1-x}Ni_x)_5$ compounds the domain walls remain frozen at low temperatures up to very high values of the constant magnetic field. An anomalous anisotropy of the magnetic susceptibility and an anomalously high coercive force, exceeding 83 kOe was observed in bulky single crystals at 4.2 °K.

Intermetallic ferromagnetic compounds of rare-earth metals have as a rule a very high anisotropy energy, comparable in magnitude with the exchange energy and even larger. The thickness of the domain wall, determined by the ratio of these energies, is quite small in these compounds and in the limiting case can be equal to one interatomic distance. Such walls should remain frozen-in until magnetic fields comparable with the anisotropy field are applied.[1–3] Such an effect was indeed observed in a number of compounds,[2–5] although the wall-displacement fields turned out to be much lower than the theoretical estimates. In the compound series $Sm(Co_{1-x}Ni_x)_5$ investigated by us, the effects connected with the freezing-in of the boundaries are specially strongly pronounced, and in particular the coercive force reaches unprecedented high values.

We investigated 11 alloys, uniformly covering the entire interval $0 \leq x \leq 1$. They were smelted in an induction furnace, in an argon atmosphere. The initial components were Sm (99.9%) and electrolytic Co and Ni (99.99% pure). After smelting, the ingots were homogenized at 1150 °C for 6 hours, and subsequently quenched in water. Metallographic and x-ray diffraction analysis showed that the alloys were essentially single-phase with hexagonal structure of the $CaZn_5$ type; in individual cases, traces of the $Sm_2(Co,Ni)_7$ phase were observed. The large grains of the alloys were used to prepare single-crystal samples in the form of spheres of 2–3 mm diameter. The magnetic properties were measured by a ballistic method in a superconducting solenoid with maximum field 83 kOe. The Curie point was determined by measuring the initial susceptibility in an alternating magnetic field.

All the alloys had an easy-magnetization axis coinciding with the *c* axis of the crystal. The magnetization curves plotted along this axis were used to determine the saturation magnetic moment σ_s of the alloys. The anisotropy constant K_1 was determined from the slope of the initial section of the magnetization curve, plotted in a direction perpendicular to the *c* axis. These characteristics for 4.2 °K, as well as the Curie points of the alloys, are shown in Fig. 1. We see that the Curie point decreases monotonically with increasing x, whereas K_1 has a maximum near $x \approx 0.35$.

The reversal of magnetization of samples with $0 \leq x \leq 0.4$ along the *c* axis is jumplike, owing to the difficulty of formation and growth of the nuclei of the reversed phase.[6] The coercive force increases smoothly with increasing x. However, starting with $x = 0.5$, the samples were practically not magnetized in an 83-kOe field at 4.2 °K. They could be magnetized only by cooling them from room temperature in the presence of a magnetic field. Subsequently they were not demagnetized even in an inverse field of 83 kOe. Thus, their coercive force exceeded 83 kOe. It was possible, by varying the value of the field during the cooling, to obtain also intermediate states between demagnetized and magnetized to saturation; these states were also preserved when a field ± 83 kOe was applied. It is therefore clear that we are dealing with a domain structure with frozen-in walls. It is interesting that such samples have in the demagnetized state, like antiferromagnets, a larger susceptibility along the difficult-magnetization direction (owing to the rotation processes) than along the *c* axis. If they are placed in a magnetic field freely, then they orient themselves with the easy-magnetization axis perpendicular to the field.

At $x = 0.9$, the coercive force decreases and can be measured. The magnetization curve and the hysteresis loop of this alloy are shown in Fig. 2. The magnetization process on the gently sloping part of the curve is

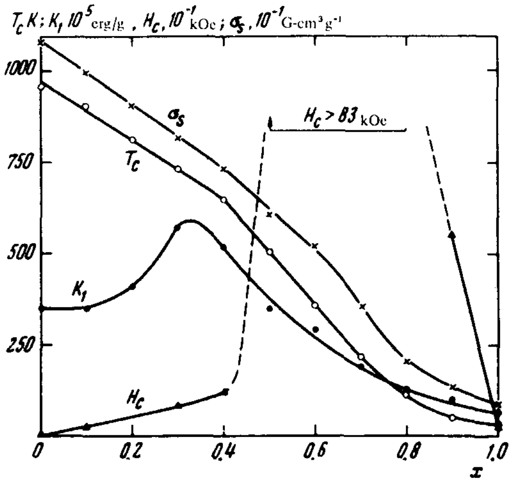

FIG. 1. Concentration dependences of the spontaneous magnetization σ_s, of the anisotropy constant K_1, and of the coercive force H_c, measured at 4.2 °K, and also of the Curie point T_c of the compound $Sm(Co_{1-x}Ni_x)_5$.

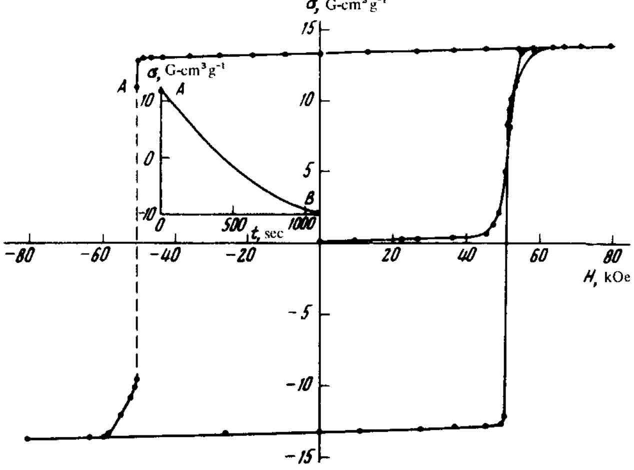

FIG. 2. Magnetization curve and hysteresis loop of the compound $SmCo_{0.5}Ni_{4.5}$ at 4.2°K.

reversible, but is irreversible on the steep part, with a strongly pronounced aftereffect. The latter is observed also when the sample magnetization is reversed. The insert in the hysteresis loop shows a time sweep of the magnetization reversal from the point A to the point B, at a fixed external field. The aftereffects are responsible also for the intersection of the magnetization curve with the ascending branch of the hysteresis loop.

The value of H_c of $SmNi_5$ is 2500 Oe at 4.2°K, and the magnetization-reversal processes in this compound do not exhibit the peculiarities described above.

The main regularities of the magnetization reversal of alloys with $0.5 \leqslant x \leqslant 0.9$ can be understood from the point of view of the model of the frozen-in thin domain walls, which was developed in[1-3]. Indeed, as the cobalt becomes replaced with nickel, the T_c of the compounds decreases much faster than K_1 (the latter even increases up to $x \approx 0.35$). The ratio of the anisotropy energy to the exchange energy then increases, and the thickness of the domain walls decreases. It is possible that at $x = 0.5$ the walls become so thin that they turn out, in accordance with the aforementioned model, to be frozen-in up to relatively high magnetic fields. The decrease of H_c at x close to unity can be due to the decrease of K_1 and to the fact that the measurement temperature (4.2°K) approaches the Curie points of the alloys.

It should be noted, however, that the large jump in the coercive force on going from $x = 0.4$ to $x = 0.5$ is difficult to explain from the point of view of the model of frozen-in domain walls, since the main characteristics of the alloys experience no noticeable changes in this range of compositions. It is possible that the abrupt increase of H_c is due to still unknown features of the crystal or magnetic structure, which become manifest in the alloys starting with $x = 0.5$.

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