May 2000

Magnetic and structural properties of SmCo$_{7-x}$Cu$_x$ alloys

I.A. Al-Omari  
*University of Nebraska - Lincoln*

Y. Yeshurun  
*Institute of Superconductivity and Department of Physics, Bar-Ilan University, Ramat Gan S2900, Israel*

Jian Zhou  
*University of Nebraska - Lincoln*

David J. Sellmyer  
*University of Nebraska-Lincoln, dsellmyer@unl.edu*

Follow this and additional works at: [http://digitalcommons.unl.edu/physicssellmyer](http://digitalcommons.unl.edu/physicssellmyer)

*Part of the [Physics Commons](http://digitalcommons.unl.edu/physicssellmyer)*
Magnetic and structural properties of SmCo$_{7-x}$Cu$_x$ alloys

I. A. Al-OMari$^{a}$
Behlen Laboratory of Physics and Center for Materials Research and Analysis, University of Nebraska, Lincoln, Nebraska 68588-0111

Y. Yeshurun
Institute of Superconductivity and Department of Physics, Bar-Ilan University, Ramat Gan 52900, Israel

J. Zhou and D. J. Sellmyer
Behlen Laboratory of Physics and Center for Materials Research and Analysis, University of Nebraska, Lincoln, Nebraska 68588-0111

We report the structural and magnetic properties of SmCo$_{7-x}$Cu$_x$, where \( x = 0, 0.1, 0.2, 0.3, 0.4, 0.5, \) and 0.7. X-ray diffraction shows that these alloys from the disordered hexagonal TbCu$_7$-type structure. For large values of \( x (~ 0.8) \) the hexagonal TbCu$_7$-type structure cannot be formed. X-ray diffraction on magnetically aligned samples show that these samples have uniaxial anisotropy. The lattice parameters \((a \text{ and } c)\) are dependent on the Cu concentration, and the unit cell volume is found to increase with \( x \). The saturation magnetization decreases with \( x \) at both room temperature and 25 K. The Curie temperature increases with \( x \) for small values of \( x \) while it decreases with \( x \) for large values of \( x \). A maximum value of \( T_C = 852 \text{ }^\circ \text{C} \) is found in these alloys.

© 2000 American Institute of Physics. [S0021-8979(00)95108-9]

I. INTRODUCTION

In the last 30 years, there has been an intensive search for new iron-rich or cobalt-rich rare-earth intermetallic compounds for magnetic applications including materials for room temperature permanent magnets, high temperature permanent magnets, magnetic recording, etc. The compounds \((R,Fe,Cu)\) include materials with atomic ratios of rare-earth to iron and cobalt 1:5, 1:7, 1:12, and 2:17 with different types of structure. Most of the R–Fe compounds have low Curie temperature \((T_C)\), relatively low saturation magnetization \((M_s)\), small magnetic anisotropy, in-plane anisotropy, and are unstable at high temperature which lowers their potential as materials for high temperature applications.\(^1\)–\(^7\) The disordered TbCu$_7$-type or so-called 1:7 structure shows interesting magnetic properties when Co or other elements are substituted for Fe.

The metastable TbCu$_7$-type structure of Sm(Fe, Ti)$_7$, or Sm(Fe, V)$_7$, can be formed under certain preparation conditions. Saito et al.\(^8\) studied SmFe$_{11}$Ti alloy ribbons and found that the structure changes from a tetragonal ThMn$_{12}$-type structure to a hexagonal TbCu$_7$-type structure by changing the rolling velocity. They also found that ribbons with a ThMn$_{12}$-type structure give the maximum hard magnetic properties. Xiao et al.\(^9\) studied the Sm–Fe–Ti system and found that this system crystallizes in the metastable TbCu$_7$-type structure with an easy in-plane magnetization and has a \( T_C \) of 243 \text{ }^\circ \text{C}. The metastable TbCu$_7$-type structure transforms to a ThMn$_{12}$ structure (with \( T_C = 305 \text{ }^\circ \text{C} \) and easy in-plane magnetization) at an annealing temperature higher than 740 \text{ }^\circ \text{C}. Katter et al.\(^10\) studied Sm–Fe–N and found that Sm$_{10.6}$Fe$_{89.4}$N$_4$ forms the TbCu$_7$-type structure with a coercivity of 6.0 kOe, a remanence of 684 emu/cm$^3$, and an energy product \((BH)_{\text{max}} \) of 8.74 MGOe, while Sm$_{12}$Fe$_{88}$ crystallizes in the rhombohedral Th$_2$Zn$_{17}$ structure. This study also showed that \( T_C \) and \( M_s \) change from 200 \text{ }^\circ \text{C} and 987 emu/cm$^3$ for Sm$_{10.6}$Fe$_{89.4}$ to 470 \text{ }^\circ \text{C} and 1114 emu/cm$^3$ for Sm$_{10.6}$Fe$_{89.4}$N$_4$. A study of R–Cu compounds by Buschow and Van Der Gast\(^11\) showed that for R=Gd, Tb, Dy, and Y a compound of the approximate composition RCu$_7$ can be formed with the TbCu$_7$ structure and these compounds decompose with annealing at low temperatures into RCu$_5$ and elementary Cu. They also found that \( c/a \) is about 0.84 for RCu$_7$ compounds while it is about 0.80 for RCu$_5$ compounds. Huang et al.\(^12\) found \( c/a \) ratios of 0.82–0.83 for Sm(Co, Zr)$_7$ alloys and also found the same ratios in our Sm(Co, Ti)$_7$ alloys.\(^13\) Suzuki et al.\(^14\) studied Sm$_{10}$Fe, V)$_90$N$_y$ and found that the substitution of vanadium for iron in Sm$_{10}$Fe, V)$_90$ alloys gives a great range of stability in the TbCu$_7$-type structure, where this structure can be formed for $5 < V < 10$. They also found that nitrogenation of the samples improves the magnetic properties including a \((BH)_{\text{max}} \) value of 8.0 MGOe and a \( T_C \) value of 477 \text{ }^\circ \text{C} for Sm$_{10}$Fe$_{82.5}$V$_{7.5}$N$_4$. Chen et al.\(^15\) studied SmCo$_x$ alloys by melt spinning and found that the alloys exhibit a single phase SmCo$_5$ and Sm$_2$Co$_{17}$ structure for $x = 5.0$ and $x = 8.8$, respectively, while a three-phase structure (Sm$_5$Co$_{17}$, SmCo$_5$, SmCo$_3$) appears for $5.0 < x < 8.5$. Recently, studies by Lefever et al.\(^16,17\) and by Huang et al.\(^12\) showed that a small amount of Zr substitution could contribute to the stabilization of the hexagonal TbCu$_7$ structure and improve the magnetic anisotropy in Sm–Co–Zr compounds. An anisotropy field \((H_A)\) of 180 kOe and a \( T_C \) value of 750 \text{ }^\circ \text{C} for SmCo$_5$Zr$_{0.5}$ have been reported by Huang et al.\(^12\) The TbCu$_7$-type structure could be indexed according to the CuCu$_5$-type structure with significant deviation of the lattice constants and x-ray peaks' intensities.
we are interested in alloys with the TbCu₇-type structure; showed the TbCu₇-type structure except for therefore, we present the results for the samples with 1:7 ducting quantum interference device.

FIG. 1. Typical x-ray diffraction pattern for a SmCo₆.7 Cu₀.3 alloy. The inset shows a typical x-ray diffraction pattern for the same sample after it has been magnetically aligned.

The aim of this article is to study the effect of Cu substitution for Co on the magnetic and structure properties of SmCo₇₋₄Cuₓ alloys.

II. EXPERIMENTAL PROCEDURE

Bulk samples of SmCo₄₋₄Coₓ alloys, where δ is between 0 and 2 and x = 0, 0.1, 0.2, 0.3, 0.4, 0.5, and 0.7, were prepared by arc melting the elements of at least 99.9% purity in a water-cooled copper boat in a flowing-argon gas atmosphere. The alloys were melted four to five times to insure homogeneity. The phase purity for all the samples was determined by x-ray diffraction using Cu Kα radiation. The magnetization of the alloys was measured by a superconducting quantum interference device (SQUID) magnetometer in the temperature range 25–300 K and in fields from 0 to 50 kOe. High temperature magnetic measurements were done by a vibrating sample magnetometer (VSM) in the temperature range 300–1273 K.

III. RESULTS AND DISCUSSION

Figure 1 shows a typical x-ray diffraction pattern for a SmCo₆₋₄Cu₀.₃ alloy. From Fig. 1 we see that the sample crystallizes in the hexagonal TbCu₇-type structure. Samples with different Sm to (Co, Cu) atomic ratios showed different structures. For example, if the Sm-to-(Co, Cu) atomic ratios are more than (1/7) a hexagonal CaCu₅-type structure formed and if the atomic ratio is less than (1/7) a hexagonal Tb₆Ni₁₇-type structure formed. This is in agreement with other observations by Khan for RCo₅₋₄. In this article we are interested in alloys with the TbCu₇-type structure; therefore, we present the results for the samples with 1:7 composition. All the samples with the 1:7 composition showed the TbCu₇-type structure except for x = 0 where a minor 2:17-type structure appears. X-ray diffraction shows that there is a shift in the peaks with increasing Cu concentration, which is due to the difference in the atomic volume. Table I summarizes the lattice parameters a and c obtained from the x-ray diffraction patterns for different concentrations. It can be seen that there is a small increase in a and c. The c/a ratio for these compounds is about 0.81–0.82 which is in agreement with other values of 0.82–0.83 by Huang et al. for Sm(Co, Zr)₇ alloys and our same values for Sm(Co, Ti)₇ alloys. The unit cell volume V obtained from the lattice parameters a and c are listed in Table I. It can be seen from the table that there is a volume expansion by substituting Cu for Co; this expansion is due to the larger atomic volume of Cu, which is in agreement with our observations for other alloys. Samples for magnetic anisotropy studies were prepared by mixing a fine powder of diameter <38 μm with 5-min epoxy on a glass sample holder and then aligning in a magnetic field of 20 kOe for about 1 h. The inset of Fig. 1 shows a typical x-ray diffraction pattern for the SmCo₆₋₄Cu₀.₃ alloy. From this figure we see that the sample, after alignment, shows the (002) peak only indicating a uniaxial magnetocrystalline anisotropy. X-ray diffraction measurements on other aligned samples showed the same results. Magnetic measurements on aligned samples showed that the magnetization in the direction parallel to the aligning field is much higher than that along the direction perpendicular to the aligning field. Figure 2 shows a typical initial magnetization curve for SmCo₆₋₄Cu₀.₃ measured at a temperature of 25 K using the SQUID magnetometer. This figure indicates that the sample is magnetically ordered. Magnetic measurements for other samples showed that all the samples studied are magnetically ordered and the magnetization depends on the Cu concentration. We find the saturation magnetization by using the law of approach to saturation, by plotting M versus 1/H and extrapolating M to (1/H) = 0. The saturation magnetization values for the samples measured at 300 and 25 K are listed in Table I. It is clear from the table that the saturation magnetization decreases with increasing Cu concentration, (x), which is due to the replacement of magnetic element (Co) by a nonmagnetic element (Cu). The deviation of the dependence of Mₛ on x from linear dependence can be due to experimental error and/or the estimation of Mₛ by extrapolation. The magnetization as a function of temperature is measured with a VSM under an applied field of 3 kOe for all the samples. Table I also gives the dependence of T_C on Cu concentration. The Curie temperature increases with x reaching a maximum at x = 0.2 (T_C

<table>
<thead>
<tr>
<th>X</th>
<th>a (Å)</th>
<th>c (Å)</th>
<th>V (Å³)</th>
<th>Mₛ (emu/g) T=300 K</th>
<th>Mₛ (emu/g) T=25 K</th>
<th>T_C (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>4.935</td>
<td>4.010</td>
<td>84.576</td>
<td>102</td>
<td>103</td>
<td>770</td>
</tr>
<tr>
<td>0.1</td>
<td>4.967</td>
<td>4.003</td>
<td>85.538</td>
<td>85</td>
<td>86</td>
<td>850</td>
</tr>
<tr>
<td>0.2</td>
<td>4.968</td>
<td>4.060</td>
<td>85.606</td>
<td>84</td>
<td>84</td>
<td>852</td>
</tr>
<tr>
<td>0.3</td>
<td>4.974</td>
<td>4.060</td>
<td>85.817</td>
<td>82</td>
<td>83</td>
<td>828</td>
</tr>
<tr>
<td>0.4</td>
<td>4.975</td>
<td>4.009</td>
<td>85.939</td>
<td>71</td>
<td>72</td>
<td>769</td>
</tr>
<tr>
<td>0.5</td>
<td>4.978</td>
<td>4.010</td>
<td>86.045</td>
<td>64</td>
<td>63</td>
<td>758</td>
</tr>
<tr>
<td>0.7</td>
<td>4.981</td>
<td>4.001</td>
<td>86.150</td>
<td>57</td>
<td>58</td>
<td>760</td>
</tr>
</tbody>
</table>
at room temperature and at a temperature of 25 K. We find that Curie temperature increases with $x$ reaching a peak at $x = 0.2$ ($T_C = 852^\circ C$) then decreases with $x$. These properties are promising for high temperature permanent-magnet applications.

IV. CONCLUSIONS

Samples of the form of $\text{SmCo}_{7-x}\text{Cu}_x$ ($x = 0, 0.1, 0.2, 0.3, 0.4, 0.5$, and $0.7$) have been prepared and studied. X-ray diffraction shows that these alloys form the hexagonal TbCu$_7$-type structure. We find that the hexagonal TbCu$_7$-type structure cannot be formed at large values of $x$ ($x > 0.8$). X-ray diffraction on magnetically aligned samples show that these samples have uniaxial anisotropy. The lattice parameters ($a$ and $c$) are dependent on the Cu concentration. The unit cell volume is found to increase with $x$. We find that the saturation magnetization decreases with $x$ at room temperature and at a temperature of 25 K.

ACKNOWLEDGMENTS

The authors would like to thank Jordan University of Science and Technology, the US Department of Energy, DARPA, US Air Force Office of Scientific Research, and the Israeli Ministry of Infrastructure for financial support.