Journal of Alloys and Compounds 509 (2011) 1607–1614

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Electrical, magnetic, and Hall properties of $Al_xCoCrFeNi$ high-entropy alloys

Yih-Farn Kao[a], Swe-Kai Chen[b,c,*], Ting-Jie Chen[a], Po-Chou Chu[a], Jien-Wei Yeh[a,c], Su-Jien Lin[a,c]

[a] Department of Materials Science and Engineering, National Tsing Hua University, 101 Kuang Fu Road Sec. 2, Hsinchu 30013, Taiwan, ROC
[b] Center for Nanotechnology, Materials Science, and Microsystems (CNMM), National Tsing Hua University, 101 Kuang Fu Road Sec. 2, Hsinchu 30013, Taiwan, ROC
[c] High-entropy Alloys Lab., National Tsing Hua University, 101 Kuang Fu Road Sec. 2, Hsinchu 30013, Taiwan, ROC

ARTICLE INFO

Article history:
Received 4 October 2010
Received in revised form 25 October 2010
Accepted 28 October 2010
Available online 10 November 2010

Keywords:
Bulk $Al_xCoCrFeNi$ alloys
Cast
Homogenization
Plastic deformation
Melt-spinning
Electrical resistivity
Hall effect
Carrier density
Carrier mobility
Magnetic property
Kondo-like effect
Lattice defects

ABSTRACT

This investigation explores the electrical and magnetic properties of as-cast, -homogenized, and -deformed $Al_xCoCrFeNi$ (C-*x*, H-*x*, and D-*x*, respectively) alloys at various temperatures from 4.2 to 300 K. Experimental results reveal that carrier density of the alloys is of 10^{22-23} cm^{-3}. H-*x* has a carrier mobility of 0.40–2.61 $cm^2\,V^{-1}\,s^{-1}$. The residual electrical resistivity of the alloys varies from 100 to 220 $\mu\Omega$ cm. The temperature coefficient of resistivity (TCR) of H-2.00 is small (82.5 ppm/K). Therefore, defects in the lattice dominate electrical transportation. Some compositions exhibit Kondo-like behavior. At 300 K, H-0.50, H-1.25, and H-2.00 are ferromagnetic, while H-0.00, H-0.25, and H-0.75 are paramagnetic. Al and AlNi-rich phases reduce the ferromagnetism of single FCC and single BCC H-*x*, respectively. Spin glass behavior of some compositions is also observed. Alloys H-*x* are of the hole-like carrier type, and ferromagnetic H-*x* exhibits an anomalous Hall effect (AHE).

1. Introduction

The first study on high-entropy alloys (HEAs) was published in 1996 [1]. Today, research into HEAs addresses their mechanical, anticorrosion, hydrogen storage [2], and thermophysical [3] properties, among others. Relevant results demonstrate that HEAs have simple microstructures in the form of a solid solution of multiple elements [4–6], a favorable capacity to form nano-scale precipitates [5,7], high thermal stability [8], superior extensive or compressive properties [9], extremely high hardness [10], excellent anticorrosive properties [11,12], and special thermophysical and magnetic properties [3]. The crystallinity of HEAs is commonly simple, even though they are comprised more than five elements. The simple crystal lattices exhibit both the individual characteristics of their constituents and collective characteristics. For example, they exhibit the collective mechanical and thermal properties of a solid solution, but the anticorrosion performance of its individual constituent elements.

Understanding the physical properties, including electrical, magnetic, and thermal properties, of HEAs can help in understanding their lattice. The magnetic property of $CoCrCuFeNiTi_x$ alloys [13] has been studied. The FCC solid solutions that comprise in CoCrCuFeNi and $CoCrCuFeNiTi_{0.5}$ alloys exhibit typical paramagnetism, whereas $CoCrCuFeNiTi_{0.8}$ and CoCrCuFeNiTi alloys exhibit superparamagnetism, which is attributable to the embedding of nanoparticle assemblies in the amorphous phase with the addition of Ti. $Al_xCoCrFeNi$ alloys have been widely studied to elucidate their microstructural and mechanical [4], anticorrosive [11], and thermally expansive [3] properties. However, their electrical and magnetic properties are still not fully understood. This investigation, which extends another, [4], aims to study the electrical and magnetic properties of $Al_xCoCrFeNi$ alloys by measuring resistivity, magnetization, and the Hall effect. The values of the relevant parameters obtained using these three methods will be compared with each other, to provide insight into the physical properties of $Al_xCoCrFeNi$ alloys.

2. Experimental details

A total of 40–50 g of Al, Co, Cr, Fe, and Ni with purities of greater than 99.5% was used to prepare $Al_xCoCrFeNi$ ($0 \le x \le 2$) alloys using a vacuum arc-remelter. After the alloys were re-melted, they were turned over and the process was repeated at least three times to ensure that the alloys were completely mixed. As-cast alloys were

* Corresponding author at: Center for Nanotechnology, Materials Science, and Microsystems (CNMM), National Tsing Hua University, 101 Kuang Fu Road Sec. 2, Hsinchu 30013, Taiwan, ROC. Tel.: +886 3 574 2569; fax: +886 3 571 3113.
E-mail address: skchen@mx.nthu.edu.tw (S.-K. Chen).

0925-8388/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jallcom.2010.10.210

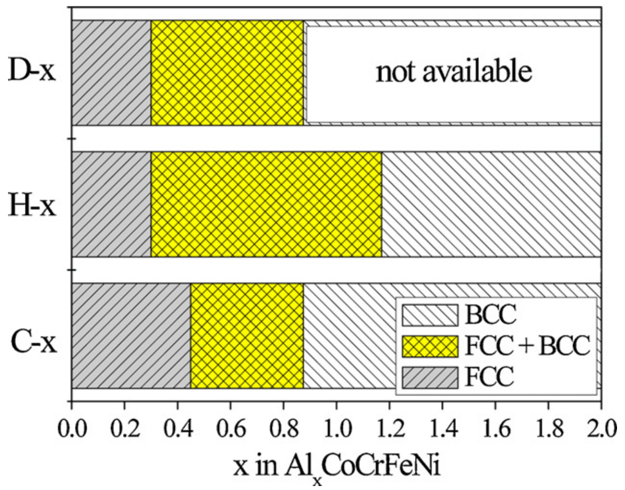

Fig. 1. Drawing for the x interval associated with phase boundary for alloys C-*x*, H-*x*, and D-*x*.

heated to 1100 °C at 20 °C per min and held at that temperature for 24 h. The samples were then quenched in water. These heated and quenched samples are called as-homogenized ones herein, except where otherwise specified. The as-homogenized samples were cold-deformed by a DBR250 two-high rolling mill to reduce their thickness by 75%. Cracks appeared in the samples with molar ratios of Al of more than 0.875 ($x > 0.875$) because they had high hardness. Therefore, the as-deformed samples were those with $0 \leq x \leq 0.875$ in this investigation. Here, C-*x*, H-*x*, and D-*x* represent as-cast, -homogenized, and -deformed $Al_xCoCrFeNi$ ($0 \leq x \leq 2$) alloys, respectively. Melt-spun samples with $x = 0.25$, M-0.25, were also prepared and their resistivity was measured and compared. The samples were cut using a diamond cutter into pieces with a thickness of 2 mm, and then ground to a thickness of less than 500 μm, using smaller-number sandpaper, to enable their resistivity to be measured. An EG & G Model 5210 Dual Phase Lock-in Amplifier was used to measure the resistance by the four-point probe method. To measure the resistivity of the samples at low temperatures, the samples were gradually sunk into liquid helium in a Dewar flask, and their resistance was continuously measured between 300 and 4.2 K. A superconducting quantum interference device magnetometer MPMS5 (SQUID), from American Quantum Design, was used to measure the magnetic properties of the samples, including the hysteresis loop (*M*–*H* curve) and the magnetization vs. temperature curve (*M*–*T* curve). The two states in which the *M*–*T* curves were measured were the zero-field cooling (ZFC) and field cooling (FC) ones. The hysteresis loops were measured at 300, 50, and 5 K. The *M*–*T* curves of 5–150 K were measured in a magnetic field of 100 Oe. The manipulating current that was used to measure the Hall effect was 10 mA; the applied magnetic field was up to ±9 T, and the temperature range was 5–300 K.

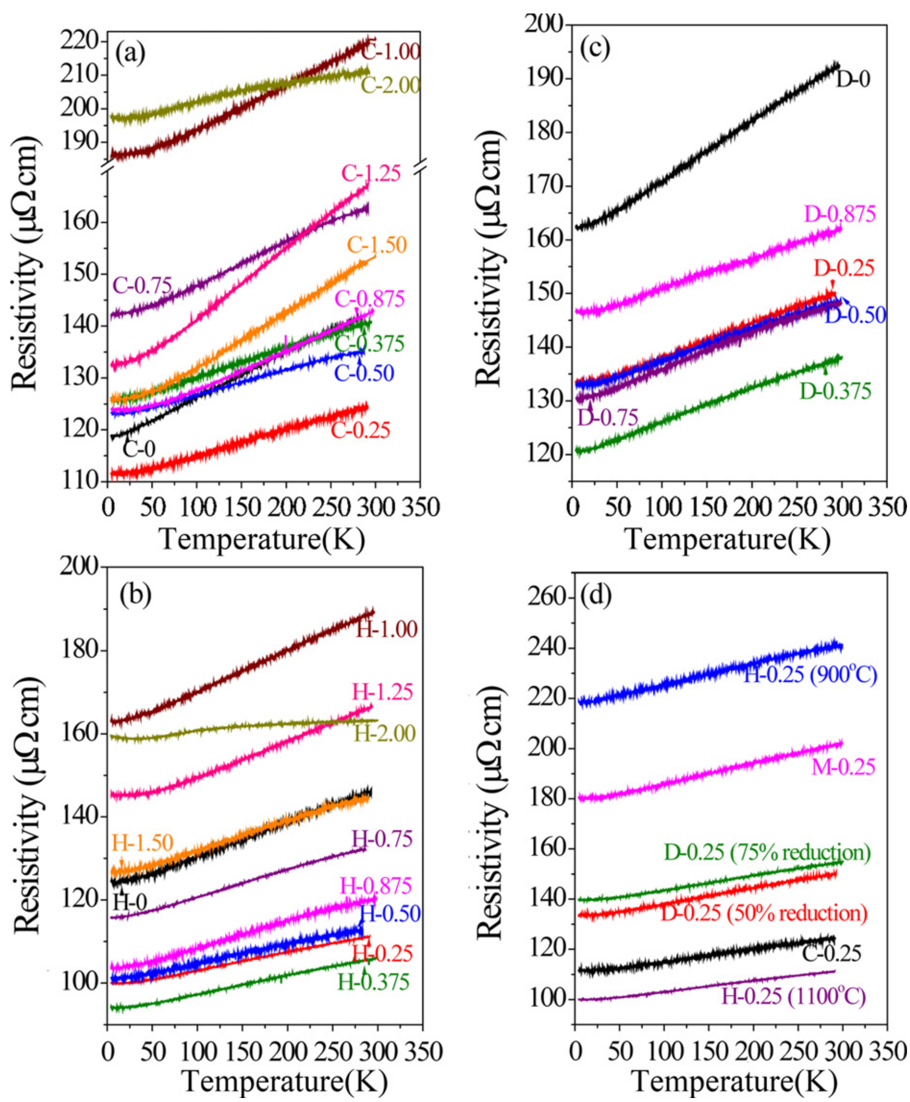

Fig. 2. (a) Experimental data of $\rho(T)$ for alloys C-*x*, (b) alloys H-*x*, and (c) alloys D-*x*, and (d) alloy $Al_{0.25}CoCrFeNi$ at various conditions.