Materials Science and Engineering A 495 (2008) 244–248

MATERIALS SCIENCE & ENGINEERING A

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Diffusion layer growth at Zn/Cu interface under uniform and gradient high magnetic fields

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Received 21 March 2007; received in revised form 24 September 2007; accepted 10 October 2007

Abstract

As a common phenomenon occurring in many material processes, diffusion may induce significant changes in composition and microstructure near the interface. In the present study, liquid/solid (Zn/Cu) interface diffusion experiments in high magnetic fields (up to 12 T) were conducted and the thickness changes of diffusion layer under different magnetic field conditions were examined. It was found that there were no noticeable effects of high magnetic fields on the formation of intermetallic phases at the interface. However, the magnetic flux density exerted a non-linear influence on the diffusion layer thickness. This phenomenon should be attributed to the effect of magnetic fields suppressing natural convection and inducing thermo-electromagnetic convection. In addition, the diffusion of Zn into Cu could be retarded by a magnetic field gradient. These results indicate that both the strength and the gradient of high magnetic fields can be used to control the diffusion behavior.

Keywords: Diffusion; Liquid/solid; Interface; Convection; High magnetic fields

1. Introduction

Diffusion, which often occurs in the vicinity of the interface of a binary alloy system in many material processes, usually results in great changes of alloy composition and microstructure. Additionally, some diffusion-related behaviors may lead to the formation of some layer-pattern compounds at the interface, either useful or harmful for material properties. Therefore, the control of diffusion process is one of the effective measures to improve material properties. With the recent development of high magnetic field technology, some researchers paid more attention to the diffusion control by high magnetic fields [1,2]. Many experiments indicated that high magnetic fields can change the movement of active atoms and vacancies by an intensive Lorentz force or magnetic force. Khine et al. [3] reported that the convection could be significantly suppressed by the Lorentz force during self-diffusion experiments of liquid germanium in the case of 3 T magnetic field. Miyake et al. [4] discussed that under a static magnetic field, the obtained diffusion coefficient in liquid metal was of the same order of magnitude with the data measured in microgravity environment, in which there is not almost any convection. Nakamichi et al. [5] found that the diffusion of carbon in γ-iron was retarded by application of a 6 T uniform magnetic field, but it was enhanced by a negative magnetic field gradient, which means that carbon atoms move towards the direction with a higher magnetic field strength. However, Nakajima et al. [6] reported that a magnetic field had no obvious effect on the diffusion of nickel in titanium. There were some ambiguity about the effects of high magnetic fields on diffusion, so it is necessary to have a deep insight into the mechanism how uniform and gradient high magnetic fields play roles in diffusion process for fundamental as well as practical reasons. Earlier work on diffusion under high magnetic fields was related to a solid/solid diffusion couple. But in industrial application, interdiffusion in a liquid/solid system is the key issue for solidification process, hot-dip coating process, diffusion welding, etc. Since it is easier for a high magnetic field to control the movement of atoms in liquid phase than in solid phase, a liquid

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doi:10.1016/j.msea.2007.10.096

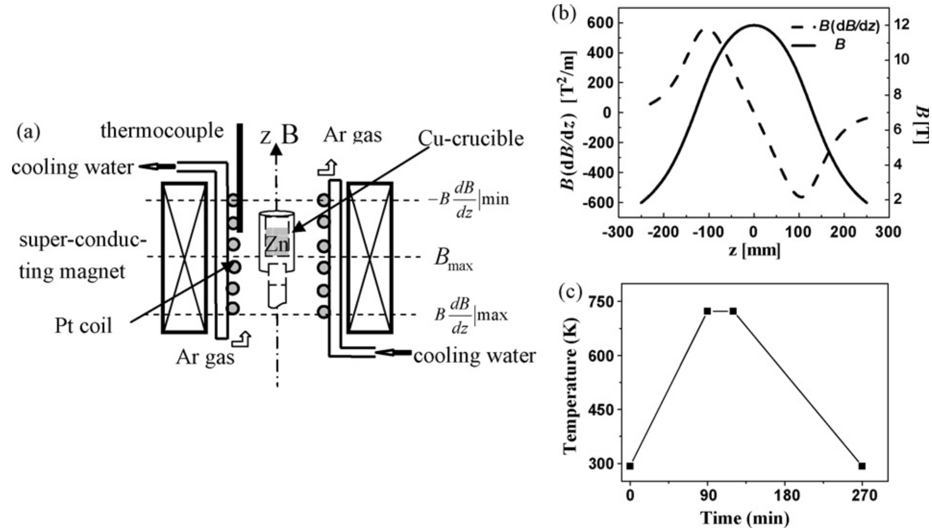

Fig. 1. (a) Schematic view of the superconducting magnetic field heat treatment system, (b) distribution of the magnetic field along the bore axis and (c) the temperature profile of the heating treatment process.

Zn/solid Cu diffusion couple is used to study the diffusion layer growth at the interface under different magnetic field conditions in the current paper.

2. Experimental procedure

Experimental materials were composed of 99.99 wt.% pure copper cold rolled rods and 99.99 wt.% pure zinc granules. Every diffusion couple was produced by filling 5.5 g of zinc granules into a cylindrical copper crucible with an inner diameter of 10 mm. The inner surface of the Cu crucibles was mechanically polished (by a velocity-controlled flat-drill coated with a polishing cloth) to form a clean and smooth interface between Cu and Zn. The zinc granules were cleaned with HCl 3 vol.% before the experiments in order to limit the layer of zinc oxides. The experimental apparatus is based on a superconducting magnet (JMTD-12 T100, JASTEC, Japan) with a bore of 100 mm diameter, in which a resistance furnace (i.d. 33 mm) was installed for melting and solidifying the specimens (Fig. 1(a)). An axial magnetic field with a maximum magnetic flux density (B) of 12 T at the centre of the bore and the maximum value of $B\,dB/dz$ of $\pm 564\,T^2/m$ at ± 105 mm from the centre of the bore was applied upward along the cylindrical crucible axis. Fig. 1(b) shows the distribution of the magnetic field along the bore axis. The influence of the uniform magnetic field was examined with magnetic flux density of 4.5, 8, 8.8, 10.5 and 12 T, respectively. The magnetic field gradients $[B(dB/dz) = \pm 166\,T^2\,m^{-1}$ with $B = 8.8\,T]$ were applied by placing the samples apart from the uniform magnetic field region for ± 45 mm. The magnetic field was applied during all the heating treatment process. Temperature was controlled by means of a programming thermometer with an R-type thermocouple (the precision of ± 0.1 K). The samples were heated up to 723 K (the melting point of pure zinc is 692.5 K) and kept at this temperature for 30 min, then they were cooled down to room temperature (Fig. 1(c)) under a protective atmosphere of high purity argon with a flow rate of 40 ml/min. Thereafter, the 24 samples (3 samples used for each experimental condition) were cut lengthwise with a linear cutting machine, mechanically polished and buff-finished using SiC suspension with a diameter of 3 μm to a mirror surface. The microstructure of the diffusion layers at the bottom of the crucible was observed with LEICA metallographic microscope. Furthermore, the average thickness of the diffusion layers was measured carefully (at least nine regions in each sample) using optical microscopy. The concentration distribution of Cu and Zn across the layers along the diffusion direction

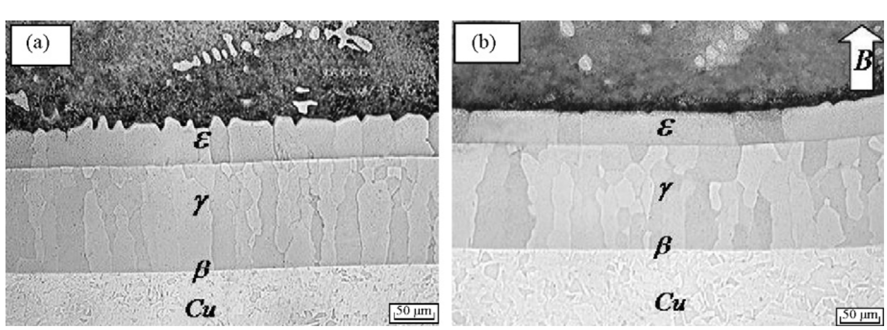

Fig. 2. Micrograph of the intermediate layers (a) without a magnetic field and (b) with a magnetic field of 8.8 T. The bright-colored islands on the top of the micrographs are also ε phase.