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Reaction diffusion in Ni–Al diffusion couples in steady magnetic fields

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ABSTRACT

The effect of a steady magnetic field on reactive diffusion in Ni–Al diffusion couples was investigated. The diffusion couples prepared by the electrodeposition technique were annealed in the temperature range of 530–590 °C with and without the magnetic field of 6 T. Regardless of the magnetic field, two intermetallic compounds, i.e., Ni_2Al_3 and $NiAl_3$, were present in the product layers of diffusion couples. $NiAl_3$ phase shows island-like structures at relatively lower temperatures while the Ni_2Al_3 phase forms a typical layered structure. The growth of Ni_2Al_3 layer was found to be parabolic. When the diffusion direction was perpendicular to the direction of the magnetic field, the external magnetic field reduced the growth rate of the Ni_2Al_3 phase. Whereas the magnetic field had no obvious effect on the growth rate of Ni_2Al_3 layers in the diffusion configuration of mutually parallel directions. The magnetic field intensity and direction dependence of growth rate of Ni_2Al_3 intermetallic layers can be attributed to the change in number of collision of an atom with neighbors during diffusion due to spiral motion under the action of the Lorentz force, which leads to change the frequency factor, not activation energy, for layer growth.

1. Introduction

Diffusion plays a crucial role in many cases [1]. Some examples of good aspects of diffusion include protective coatings like aluminizing, elimination of microsegregation. Diffusion may be bad as well, for example, it can lead to degradation of properties of a deposit at the metal interface due to the formation of brittle intermetallic phases. In the Ni-based superalloy, on one hand, diffusion in a solid markedly affects the formation and degradation of aluminide coatings usually consisting of intermetallic compounds, e.g., $NiAl_3$, Ni_2Al_3, NiAl. On the other hand, diffusion plays an important role on homogeneity and precipitates of superalloy products in subsequent thermal treatments. Therefore, it is necessary for theoretical studies and practical application to apply reasonable methods like external fields and thermal treatment to control the diffusion behavior of atoms in order to achieve desired properties and structures of materials. Much attempt has been made in this respect. Diffusion in external fields such as electric and magnetic fields therein has attracted many investigators. For an example, Garay et al. applied the current effects to enhance the growth of intermetallic phases in the Ni–Ti system [2].

In recent decades, the application of the steady magnetic field to materials processing has been paid much attention to because of various magnetic effects and the contactless interaction between the magnetic field and materials [3]. Among those studies, diffusion in the magnetic field is a subject of great interest. Some experimental findings showed that the magnetic field inhibited diffusion rates of atoms in solid phases [4,5] whereas others demonstrated that the magnetic field accelerated the diffusion process [6,7]. There were reports showing that the magnetic field had no effect on diffusion rates as well [8,9]. Therefore, the effect of the magnetic field on atom diffusion in different materials seems to be different. Moreover, there is argument concerning the nature of atom diffusion in the magnetic field. Some researchers thought the frequency factor for diffusion was modified while the others believed the activation energy for diffusion was changed by the magnetic field. It follows that the atom diffusion in the magnetic field is an open question up to now.

In this work, we aim to investigate the formation of intermetallic phases and their growth kinetics in Ni–Al diffusion couples in the magnetic field in view of wide application of the Ni–Al system. Further, the reason concerning the change in growth kinetics of intermetallic phases in the magnetic field was discussed.

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2. Experiment details

In consideration of various shortcomings of diffusion couples prepared by conventional methods like mechanically coupling under pressure, friction welding and diffusion bonding, the electrodeposition method was employed to prepare diffusion couples in order to avoid defects such as void, cracks and oxides at the interface.

Ni–Al diffusion couples were prepared according to the following processes. The cast ingot of pure Al (99.99%) was cut into bars with dimension of 6 mm × 6 mm × 50 mm. The bars were ground, mechanically polished and electrolytically polished in order to keep the surface flat and clean. They were cleaned with acetone and distilled water successively and then dried. The surface of well-polished bars were activated with mixed solution of HNO_3 and HF. The watt nickel solution was used to electroplate a layer of Ni on the surface of Al bars. The electroplating parameters were determined as following: the current was 0.1A, the temperature of solution was 30 °C and the time was 24 h. The thickness of the plating layer could reach about 420 μm. The well-electroplated samples were cut into small bars of 7 mm in length, which became samples of Ni–Al diffusion couples. In order to avoid the interface from cracking due to internal stress at elevating temperature, all the samples were annealed for 2 h at the low temperature of 150 °C. Fig. 1 shows interface morphology of Ni–Al diffusion couples obtained by the electrodeposition technique and subsequently annealing at the low temperature, from which it is seen that the interface between Ni and Al layers is bonded well. It is noted that no new phase formed at the interface when the couple was annealed for 2 h at 150 °C.

The diffusion couples were annealed for 8–32 h at temperatures from 530 °C to 590 °C with and without the magnetic field of 6 T. The K-type thermocouple was used to monitor the temperature of the samples and its accuracy was ±1 °C. The steady magnetic field was produced by the superconducting magnet and its maximum intensity is up to 6 T. The experimental apparatus is illustrated in Fig. 2(a). The diffusion couple was annealed in the zone of both the homogeneous temperature and magnetic field. The diffusion interface was set to be parallel and perpendicular to the direction of the magnetic field as shown in Fig. 2(b) in order to observe whether or not the magnetic-field direction influences on diffusion rates of atoms.

The diffusion couples after annealing were ground and polished. The interface morphology and the layer composition were examined using scanning electronic microscopy (SEM) and energy dispersive spectrum (EDS), respectively. The thickness of intermetallic layers was measured using image pro-plus software at different positions of the same interface. The average value of thickness data more than 8 sets was used as the thickness of layers in diffusion couples.

3. Results and discussion

3.1. Structures and growth kinetics without the magnetic field

The diffusion couple made up of two metals frequently is used to determine the number of intermetallic phases in equilibrium phase diagram. All phases in the binary system should occur after annealing for a long time at a given temperature. Fig. 3 shows morphology of product layers in Ni–Al diffusion couples annealed at 530 °C for various times. There are only two intermetallic compounds, i.e., Ni_2Al_3 and $NiAl_3$, in reactive diffusion zone, which does not respond to all the intermetallic phases present in equilibrium phase diagram. The results are because that the diffusion temperature was lower and the diffusion time was short. As Castleman et al. pointed out, the conditions that all thermodynamically stable phases form in the diffusion couple are that the diffusion temperature should be high enough and time should be long enough to permit the nucleation of all equilibrium phases [10]. This phenomena

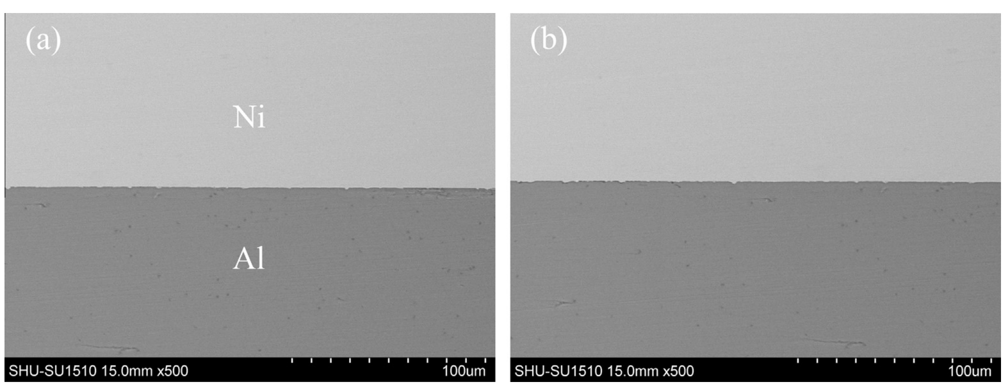

Fig. 1. Interface morphology of Ni–Al diffusion couples obtained by electrodeposition technique (a) and subsequently annealing for 2 h at 150 °C (b).

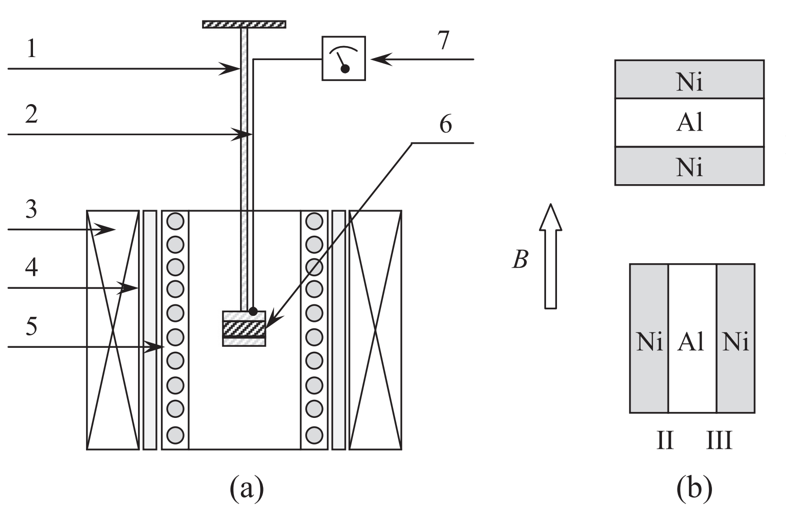

Fig. 2. Schematic diagram of experimental apparatus for diffusion in the magnetic field (a) and the three diffusion configurations: interface I is perpendicular to the magnetic field and interfaces II and III are parallel to the magnetic field (b). (1) Support rod, (2) thermocouple, (3) superconducting magnet, (4) water-cooling jacket, (5) furnace, (6) diffusion couple, (7) temperature controller.