Influence of a magnetic field on microstructure formation in L1₀-type ferromagnetic intermetallics

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Abstract. The influence of a magnetic field on microstructure formation through a disorder-order transformation has been investigated in Co-Pt and Fe-Pd alloys. Single crystals of disordered Co-50Pt(at%) and Fe-55Pd(at%) were subjected to an ordering heat-treatment under a magnetic field. When the ordering heat-treatment is performed without applying a magnetic field, three equivalent variants are formed. On the other hand, when the ordering heat-treatment is performed under a magnetic field of 0.5 T (in CoPt) - 4 T (in Fe-55Pd) and higher as applied along the [001] direction of the disordered phase, a single variant with an easy axis along the field direction is obtained. The induced anisotropy energy of the ordered phase under a magnetic field of 1 T was 4.1 kJ·m⁻³ at 773 K for CoPt and 45.3 kJ·m⁻³ at 673 K for Fe-55Pd.

1. Introduction

Control of microstructure through solid-solid phase transformation under a magnetic field is a promising method to improve the properties and design of new materials. In fact, many studies on the effect of a magnetic field have been done, especially on diffusionless transformation (martensitic transformation) [1-3]. Diffusional transformation, however, has not been studied much.

Disorder-order transformation (A₁-type → L₁₀-type) in ferromagnetic intermetallics such as Co-Pt and Fe-Pd alloys is a representative diffusional transformation. Microstructure formation is expected to be influenced by a magnetic field because the ordered phase (L₁₀-type, tetragonal) consists of three equivalent variants with an “easy” c-axis [4-6], and this is shown in figure 1. Under the influence of a magnetic field a difference exists in the magnetocrystalline anisotropy energy among these three variants. The consequence of this is that only a preferred variant for energy can grow under the field’s influence.

In this study, therefore, the effect of a magnetic field on microstructure formation during the disorder-order transformation was investigated using single crystals of Co-50at%Pt and Fe-55at%Pd alloys. To determine the influence of a magnetic field on microstructure formation we carried out a two-step ordering heat-treatment. The first step of ordering was done under a magnetic field of up to 10 T and applied to the [001]ₐₐ direction to initiate the ordering under the effect of the magnetic field. This was followed by a second step of ordering without using a magnetic field that would result in a disorder-order transformation. We found that a single variant of both alloys was obtained when a magnetic field of 0.5 T or higher was used for CoPt and when 4 T or higher was used for Fe-55Pd if applied at an early stage of the ordering.
2. Experimental procedure

Ingots of Co-50Pt(at%) and Fe-55Pd(at%) were prepared by arc melting. We selected Fe-55at%Pd alloy instead of Fe-50at%Pd alloy to obtain the single L1₀-phase considering the phase diagram [7]. A single crystal of each alloy was grown by a floating zone method using purified argon gas flow. Homogenization was carried out at 1273 K for 168 h followed by ice-water quenching. Cubic and rectangular specimens with each edge parallel to the <001>\textsubscript{\textit{A}1} direction were cut. After cutting, the specimens were heat-treated at 1273 K (CoPt) and 1173 K (Fe-55Pd) for 1 h followed by ice-water quenching to obtain the disordered phase.

Ordering heat-treatments under a magnetic field were made by using a furnace inserted into a superconducting magnet. The specimen was located at the centre of the hot zone which is also the centre of the magnetic field. A two-step ordering heat-treatment was done: the first step of ordering was under a magnetic field of up to 10 T applied to the [001]\textsubscript{\textit{A}1} direction of the disordered cubic specimen. The second step was an ordering at an elevated temperature without a magnetic field.

3. Results

Characteristic temperatures of CoPt and Fe-55Pd such as the Curie temperature and the disorder-order transformation temperature have been determined by resistivity measurements in disordered and ordered specimens. These characteristic temperatures are summarized in table 1.

|          | \(T_{c}^{(d)}\) | \(T_{c}^{(o)}\) | \(T^{(d-o)}\) | \(T^{(o-d)}\) |
|----------|-----------------|-----------------|---------------|---------------|
| CoPt     | 850 K           | 730 K           | 1045 K        | 1095 K        |
| Fe-55Pd  | 740 K           | 670 K           | 955 K         | 1025 K        |

Considering these characteristics, the temperature conditions of the two-step ordering heat-treatment were: the first step of ordering was at 773 K for 0.5 h (CoPt) and 673 K for 1 h (Fe-55Pd) under a magnetic field of up to 10 T. The second step of ordering was at 1023 K for 3 h (CoPt) and 773 K for 24 h (Fe-55Pd). Magnetization curves were measured at 300 K along the X, Y and Z-directions after the first and the second step of ordering for CoPt as well as Fe-55Pd and are shown in figures 2 and 3, respectively. It is noted from figures 2(a) and 3(a) (measured after the first step under a magnetic field of 10 T) that the Z-direction is slightly easier to magnetize. This implies that the fraction of the variant whose easy axis lies in the Z-direction (bold curve) is slightly larger than that of the X- and Y-variants (dotted and dashed curves). Figures 2(b) and 3(b) clearly show that a single variant of both alloys is certainly obtained after the second step of ordering without the influence of a
magnetic field. These results suggest that the magnetic field is especially effective during the early stage of ordering for the selective formation of a preferred variant.

Figure 2. Magnetization curves of CoPt after (a) ordering at 773 K for 0.5 h under a magnetic field of 10 T and (b) successive ordering at 1023 K for 3 h.

Figure 3. Magnetization curves of Fe-55Pd after (a) ordering at 673 K for 1 h under a magnetic field of 10 T and (b) successive ordering at 773 K for 24 h.

We also investigated the effect of magnetic field-strength on the selective formation of a preferred variant. That is, the first step of ordering was carried out under different magnetic field-strengths of up to 10 T. Figure 4 shows the fraction of the Z-variant \( f_z \) after the second step of ordering as a function of magnetic field as applied in the first step for CoPt (open circles) and Fe-55Pd (open squares). The figure clearly shows that \( f_z \) increases with increasing magnetic field and reaches 100% at about 0.5 T for CoPt and 4 T for Fe-55Pd. We notice from the figure that there is an increase in the \( f_z \) at about 0.3 T for CoPt and 3 T for Fe-55Pd which indicates the existence of a critical magnetic field to obtain a single variant for both alloys.

Figure 4. The fraction of Z-variant \( f_z \) after the second step of ordering as a function of magnetic field for CoPt and Fe-55Pd.

Results from resistivity measurements, as summarized in table 1, indicate that the ordering temperature in the first step of 773 K for CoPt and 673 K for Fe-55Pd is higher than the Curie temperature of the ordered phase and less than the Curie temperature of the disordered phase. This means that the ordered phase is paramagnetic and the disordered phase is ferromagnetic at these temperatures. To obtain the induced magnetocrystalline anisotropy energy at the ordering temperature of the first step the magnetization curves were measured along the easy and hard axes of the single variant up to a magnetic field of 1.8 T. Figures 4 and 5 show magnetization curves of CoPt and Fe-55Pd as measured along the easy axis, \( c \)-axis (bold curve) and hard axis as well as the \( a \)-axis (dashed curve). From the enclosed area between the easy and hard axes up to a magnetic field of 1 T the induced magnetocrystalline anisotropy energies were 4.1 and 45.3 kJ·m\(^{-3}\) for CoPt and for Fe-55Pd, respectively. The induced anisotropy energies calculated here are a thousand times smaller than the
uniaxial magnetocrystalline anisotropy constant of CoPt at 298 K, $K_u = 4.5 \times 10^7$ erg·cm$^{-3}$ [8] and Fe-55Pd at 4.2 K, $K_u \sim 1.7 \times 10^7$ erg·cm$^{-3}$ [9].

Figure 5. Magnetization curves of the single variant CoPt measured at 773 K along the easy and hard axes.

Figure 6. Magnetization curves of the single variant Fe-55Pd measured at 673 K along the easy and hard axes.

4. Conclusions
A single variant of Co-50at%Pt and Fe-55at%Pd alloys was obtained by a two-step ordering heat-treatment. A magnetic field was applied in the first step of ordering while the second step was done without a magnetic field. The results suggest that the magnetic field is especially effective during the early stage of ordering for the selective formation of a preferred variant. The magnetic field-strength dependence of single variant formation indicates that there seems to be a critical magnetic field value required to obtain a single variant for both alloys. The induced anisotropy energy of the ordered phase under a magnetic field of 1 T is 4.1 kJ·m$^{-3}$ at 773 K for CoPt and 45.3 kJ·m$^{-3}$ at 673 K for Fe-55Pd.

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