Electron Microscopy Study of Eutectic Structure in Nb-Ti-X and Nb-Zr-X (X = Co, Ni) Hydrogen Permeation Alloys

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The morphology and crystallography of eutectic structures in several niobium-bearing hydrogen permeation alloys such as Nb₂₀Ti₄₀Ni₄₀, Nb₃₀Ti₃₅Co₃₅, Nb₁₃Zr₄₃Ni₄₄, and Nb₂₅Zr₃₅Co₄₀ have been investigated by means of transmission electron microscopy. The alloys Nb₂₀Ti₄₀Ni₄₀, Nb₃₀Ti₃₅Co₃₅, and Nb₂₅Zr₃₅Co₄₀ possess eutectic structures consisting of fine lamellar morphology with Nb-based bcc and B2 intermetallic phases. The Nb₁₃Zr₄₃Ni₄₄ alloy possesses a eutectic structure consisting of rod-shaped bcc-(Nb, Zr) phase and B33-ZrNi phase which displacively transforms from the B2 high-temperature phase. The eutectic structures in the Nb₂₀Ti₄₀Ni₄₀ and the Nb₂₅Zr₃₅Co₄₀ alloys exhibit a cube-on-cube orientation relationship between the bcc and B2 phases. The eutectic structure in the Nb₁₃Zr₄₃Ni₄₄ alloy also exhibits a cube-on-cube orientation relationship by considering the lattice correspondence between the B2 and the B33 structures. On the other hand, a unique orientation relationship is found out in the Nb₃₀Ti₃₅Co₃₅ alloy, as follows: $(110)_{(\text{Nb, Ti})} // (110)_{\text{TiCo}}$, $[\bar{2}21]_{(\text{Nb, Ti})} // [001]_{\text{TiCo}}$. The atomic arrangements at the eutectic interface are also discussed on the basis of high-resolution observations. [doi:10.2320/matertrans.MA200803]

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1. Introduction

Pd-Ag alloys have been commercially used as hydrogen permeation membranes for separating and purifying hydrogen gas. Since Pd is too expensive and scarce in resources, it is desirable to develop non-Pd-based hydrogen permeation alloys with low cost and high performance. From the viewpoint of the hydrogen permeability for this demand, group 5A metals such as V, Nb, and Ta are promising candidates, because the hydrogen permeability of such metals is higher than those of Pd and Pd-Ag alloys.¹⁻³⁾ However, since these metals suffer from severe hydrogen embrittlement, they cannot be used as membranes at present. Recently, one of the authors found out that the Nb-Ti-Ni alloy consists of bcc-(Nb, Ti) + B2-TiNi eutectic microstructures with an appropriate combination of high-hydrogen permeability and excellent hydrogen embrittlement resistance.^{4,5)} The former property is attributable to the bcc-(Nb, Ti) phase, while the latter property is attributable to the B2-TiNi phase in the eutectic structure. On the basis of the same concept, Nb-Ti-Co,⁶⁾ Nb-Zr-Ni^{7,8)} and Nb-Zr-Co alloys have been developed as new hydrogen permeation materials. In these alloys, the eutectic structure is considered to be valuable and indispensable in achieving the compatible properties. However, no study has yet focused on such eutectic microstructures, except for the Nb₂₀Ti₄₀Ni₄₀ alloy.^{9,10)}

The purpose of this paper is to clarify the morphology and crystallography of the eutectic structures in the four types of the Nb-bearing hydrogen permeation alloys, i.e., Nb₂₀Ti₄₀Ni₄₀, Nb₃₀Ti₃₅Co₃₅, Nb₁₃Zr₄₃Ni₄₄, and Nb₂₅Zr₃₅Co₄₀ by means of conventional transmission electron microscopy (CTEM). The atomic arrangements at the eutectic interface are also discussed on the basis of high-resolution transmission electron microscopy (HRTEM) observations.

2. Experimental Procedure

The eutectic alloys Nb₂₀Ti₄₀Ni₄₀, Nb₃₀Ti₃₅Co₃₅, Nb₁₃Zr₄₃Ni₄₄, and Nb₂₅Zr₃₅Co₄₀ (at%) were prepared from 99.9% Nb, 99.7% Ti, 99.9% Ni, 99.9% Co, and 99.9% Zr (% by mass) by arc melting in an argon atmosphere. The structural and microstructural examinations were carried out by using a X-ray diffractometer (XRD) and a scanning electron microscope (SEM), respectively. The TEM specimens were cut from the as-melted ingots and prepared by the argon ion milling technique. The CTEM and HRTEM observations were performed by using JEM-2000FX and FEI-Tecnai20F microscopes operated at 200 kV, respectively.

3. Results and Discussion

Figure 1 shows the XRD patterns of the four eutectic alloys. The Nb₂₀Ti₄₀Ni₄₀ alloy consists of the bcc-(Nb, Ti) solid solution and B2-TiNi phase,⁴⁾ as shown in Fig. 1(a). The lattice parameters of the (Nb,Ti) solid solution and Ti-Ni phase are calculated to be 0.329 nm and 0.302 nm, respectively. Although a near-equiatomic Ti-Ni alloy undergoes a thermoelastic martensitic transformation from the B2 to B19' structure at approximately 373 K upon cooling,¹¹⁾ the TiNi phase in the eutectic Nb₂₀Ti₄₀Ni₄₀ alloy possesses the B2 structure, as shown in Fig. 1(a). This occurs because the Ms point of the TiNi phase decreases below room temperature by the dissolution of a small amount of Nb in the Ti-Ni phase.¹²⁾ Similarly, the Nb₃₀Ti₃₅Co₃₅ alloy consists of the bcc-(Nb, Ti) solid solution and B2-TiCo phase,⁶⁾ as shown in Fig. 1(b). The lattice parameters of the (Nb, Ti) solid solution and TiCo phase are estimated to be 0.331 nm and 0.301 nm, respectively. The Nb₁₃Zr₄₃Ni₄₄ alloy is composed of the bcc-(Nb, Zr) solid solution and B33-ZrNi phase with an orthorhombic cell,^{7,13)} as shown in Fig. 1(c).

Fig. 1 XRD patterns of the (a) Nb₂₀Ti₄₀Ni₄₀, (b) Nb₃₀Ti₃₅Co₃₅, (c) Nb₁₃Zr₄₃Ni₄₄, and (d) Nb₂₅Zr₃₅Co₄₀ eutectic alloys.

Fig. 3 SEM images of the (a) longitudinal and (b) vertical section of the same part in the Nb₁₃Zr₄₃Ni₄₄ ingot, showing the rod-shaped structure.

Fig. 2 SEM images of the (a) Nb₂₀Ti₄₀Ni₄₀, (b) Nb₃₀Ti₃₅Co₃₅, (c) Nb₁₃Zr₄₃Ni₄₄, and (d) Nb₂₅Zr₃₅Co₄₀ eutectic alloys.

The lattice parameters of the (Nb, Zr) solid solution and B-33 ZrNi phase are calculated to be $a_{(\text{Nb,Zr})} = 0.332$ nm and $a_{\text{ZrNi}} = 0.329$ nm, $b_{\text{ZrNi}} = 0.998$ nm, $c_{\text{ZrNi}} = 0.406$ nm, respectively. The Bragg peaks on the Nb₂₅Zr₃₅Co₄₀ alloy are indexed on the basis of the bcc-(Nb, Zr) solid solution and B2-ZrCo phase, except for the unknown Bragg peaks, as shown in Fig. 1(d). The lattice parameters of the (Nb, Zr) solid solution and ZrCo phase are estimated to be 0.332 nm and 0.319 nm, respectively.

In order to investigate the microstructure of each eutectic alloy, SEM observations are carried out as shown in Fig. 2. The Nb₂₀Ti₄₀Ni₄₀, Nb₃₀Ti₃₅Co₃₅, and Nb₂₅Zr₃₅Co₄₀ alloys possess eutectic structures with a fine lamellar morphology, as shown in Figs. 2(a), 2(b), and 2(d), respectively. The Nb₁₃Zr₄₃Ni₄₄ alloy possesses a eutectic structure with lamellar and granular morphologies, as shown in Fig. 2(c). To clarify the morphology of such eutectic structures, SEM

observations of the longitudinal and vertical sections of the same part in the Nb₁₃Zr₄₃Ni₄₄ ingot are performed, as shown in Figs. 3(a) and 3(b). It is apparent that the Nb₁₃Zr₄₃Ni₄₄ alloy consists of a rod-shaped structure. The results obtained from the XRD and SEM observations are summarized in Table 1. It has been recognized that the eutectic structure possesses a lamellar morphology when the volume fraction of the second phase is greater than 28%. While the rod-shaped morphology is observed for volume fractions less than 28%.¹⁴⁾ Here, the volume fraction of the Nb-based bcc phase in the Nb₂₀Ti₄₀Ni₄₀, Nb₃₀Ti₃₅Co₃₅, and Nb₂₅Zr₃₅Co₄₀ alloys are 33.3, 32.3, and 34.2%, respectively, as listed in Table 1. On the other hand, the volume fraction of the (Nb, Zr) solid solution in the Nb₁₃Zr₄₃Ni₄₄ alloy is 21.9%. Therefore, the Nb₁₃Zr₄₃Ni₄₄ alloy consists of the rod-shaped eutectic structure, as apparent from the abovementioned criteria.

Table 1 Characteristics of the eutectic structure in the four niobium-bearing alloys.

	Nb ₂₀ Ti ₄₀ Ni ₄₀	Nb ₃₀ Ti ₃₅ Co ₃₅	Nb ₁₃ Zr ₄₃ Ni ₄₄	Nb ₂₅ Zr ₃₅ Co ₄₀
Morphology	lamellar	lamellar	rod	lamellar
Nb-based phase lattice parameter (nm)	bcc-(Nb, Ti) $a = 0.329$	bcc-(Nb, Ti) $a = 0.331$	bcc-(Nb, Zr) $a = 0.332$	bcc-(Nb, Zr) $a = 0.332$
Volume fraction of Nb-based phase (%)	33.3	32.3	21.9	34.2
Intermetallic phase lattice parameter (nm)	B2-TiNi $a = 0.302$	B2-TiCo $a = 0.301$	B33-ZrNi $a = 0.329$ $b = 0.998$ $c = 0.406$	B2-ZrCo $a = 0.319$

Fig. 4 (a) A bright field image and (b) the corresponding electron diffraction pattern of the Nb₂₀Ti₄₀Ni₄₀ alloy from the [001]_(Nb, Ti) // [001]_{TiNi} zone axis, showing the cube-on-cube orientation relationship.

CTEM observations are performed to clarify in detail the crystallography of the eutectic structure. Figures 4(a) and 4(b) show the typical bright field image and the corresponding electron diffraction pattern of the Nb₂₀Ti₄₀Ni₄₀ alloy, respectively. From the pattern shown in Fig. 4(b) and the dark field image obtained using 100_{TiNi} reflection, it is identified that the thicker lamellas correspond to the B2-TiNi phase, whereas the thinner lamellas correspond to the bcc-(Nb, Ti) phase. The thickness of the (Nb, Ti) phase varies

from 40 to 60 nm and that of the TiNi phase varies from 100 to 200 nm. The orientation relationship between the (Nb, Ti) and the TiNi phases is determined as follows: [001]_(Nb, Ti) // [001]_{TiNi}, (100)_(Nb, Ti) // (100)_{TiNi}, (010)_(Nb, Ti) // (010)_{TiNi}, that is, the cube-on-cube orientation relationship is maintained between the two phases. The interface plane between the two phases is determined as {110}_(Nb, Ti) // {110}_{TiNi}. Similar morphology and crystallography, i.e., the cube-on-cube relationship between the (Nb, Zr) and the ZrCo phase, are confirmed for the eutectic structure of the Nb₂₅Zr₃₅Co₄₀ alloy. The thickness of the (Nb, Zr) phase varies from 30 to 60 nm and that of the ZrCo phase varies from 60 to 100 nm.

Figure 5 shows the typical bright field image and the corresponding electron diffraction patterns of the eutectic structure in the Nb₃₀Ti₃₅Co₃₅ alloy. The thinner lamellas with widths ranging from 80 to 100 nm correspond to the bcc-(Nb, Ti) phase, and the thicker lamellas with widths ranging from 150 to 200 nm correspond to the B2-TiCo phase. It must be noted that the orientation relationship between the the bcc-(Nb, Ti) and B2-TiCo phases is determined to be $\bar{2}21$ _(Nb, Ti) // [001]_{TiCo}, (110)_(Nb, Ti) // (110)_{TiCo}. This relationship is invariant, even for specimens annealed at 1173 K for 360 ks. However, it is apparent that the interface is parallel to {110}_(Nb, Ti) and {110}_{TiNi}, similar to that in the Nb₂₀Ti₄₀Ni₄₀ alloy. This fact indicates that the two phases relatively rotate approximately 70° around the common (110) plane from the cube-on-cube orientation relationship. So far as we know, this relationship is quite unique in the eutectic

Fig. 5 (a) A bright field image, (b) and (c) the corresponding electron diffraction patterns of the Nb₃₀Ti₃₅Co₃₅ alloy from the $\bar{2}21$ _(Nb, Ti) // [001]_{TiNi} and $\bar{1}1\bar{1}$ _(Nb, Ti) // $\bar{1}1\bar{1}$ _{TiCo} zone axis, respectively.

structure consisting of the bcc and B2 phases.¹⁵⁾ The strain contrast along the interface in the Nb₃₀Ti₃₅Co₃₅ alloy is more complex as compared to that in the Nb₂₀Ti₄₀Ni₄₀ alloy, which is probably due to the different orientation relationship. This will be discussed later in the HRTEM observations. For satisfying this orientation relationship, the direction along which the eutectic interface is observed in the edge-on state from the low index zone axis of both the phases is only $[\bar{1}\bar{1}\bar{1}]_{(\text{Nb,Ti})} // [\bar{1}11]_{\text{TiCo}}$, as shown in the stereographic projection in Fig. 6. This fact is demonstrated in Fig. 5(c).

Figure 7(a) shows the typical bright field image of the $\text{Nb}_{13}\text{Zr}_{43}\text{Ni}_{44}$ alloy. The electron diffraction patterns in Figs. 7(b) and 7(c) are obtained from the elliptical phase A, and those in (b') and (c') are obtained from the matrix region B. Since the patterns (b) and (c) are consistently indexed with the bcc structure of $a_0 = 0.332$ nm determined from the XRD experiment in Fig. 1(c), the elliptical phase A is identified as the (Nb, Zr) solid solution. The longitudinal section of the rod-like bcc phase is observed from another beam direction.

Therefore, the phase A with elliptical shape in Fig. 7(a) indicates the vertical section of the rod-like bcc phase; thus, the $[110]_{\text{bcc}}$ direction is considered to be parallel to the growth direction of the rod-like phase. These observations correspond to the SEM images in Figs. 2(c) and 3. On the other hand, the patterns (b') and (c') can be indexed by the B33 structure with orthorhombic unit cell, as mentioned above. It is apparent from these two pairs of patterns that crystallographic orientation relationships exist between the bcc-(Nb, Zr) and B33-ZrNi phases, as follows: $(1\bar{1}0)_{(\text{Nb, Zr})} // (001)_{\text{ZrNi}}$, $(001)_{(\text{Nb, Zr})} // (100)_{\text{ZrNi}}$, $(110)_{(\text{Nb, Zr})} // (010)_{\text{ZrNi}}$, $[110]_{(\text{Nb, Zr})} // [010]_{\text{ZrNi}}$, and $[001]_{(\text{Nb, Zr})} // [100]_{\text{ZrNi}}$. We have confirmed the existence of reversible endothermic peaks at approximately 1380 K and exothermic peaks at approximately 1300 K in the DTA heating and cooling curves, respectively. It has been reported that near-equiatomic ZrPd alloys undergo martensitic transformation from the B2 to B33 structures.¹⁶⁾ Therefore, we can assume that the ZrNi alloys as well as ZrPd alloys undergo martensitic transformation from the B2 to B33 structures. The lattice correspondence between the B2 parent and B33 martensitic phases is deduced as follows by considering the lattice parameters of both the structures: $[001]_{\text{B2}} // [100]_{\text{B33}}$, $(110)_{\text{B2}} // (010)_{\text{B33}}$, and $(1\bar{1}0)_{\text{B2}} // (001)_{\text{B33}}$. The orientation relationship between the bcc-(Nb, Zr) phase and the B2 parent phase of ZrNi alloy is expressed as follows: $[001]_{(\text{Nb, Zr})} // [001]_{\text{B2-ZrNi}}$, $(110)_{(\text{Nb, Zr})} // (110)_{\text{B2-ZrNi}}$, and $(1\bar{1}0)_{(\text{Nb, Zr})} // (1\bar{1}0)_{\text{B2-ZrNi}}$, that is, they satisfy the cube-on-cube relationship.

The orientation relationships of the eutectic structure in the four niobium-bearing alloys are summarized in Table 2. These observations provide that the eutectic structures in the Nb₂₀Ti₄₀Ni₄₀, Nb₁₃Zr₄₃Ni₄₄, and Nb₂₅Zr₃₅Co₄₀ alloys possess the cube-on-cube relationship, while that in the Nb₃₀Ti₃₅Co₃₅ alloy possesses a unique orientation relationship, i.e., $[221]_{(\text{Nb,Ti})} // [001]_{\text{TiCo}}$ and $(110)_{(\text{Nb,Ti})} // (110)_{\text{TiCo}}$.

Onda *et al.* have investigated the cube-on-cube interface in the Nb₂₀Ti₄₀Ni₄₀ alloy by using HRTEM observations and Ballman's O-lattice theory.⁹⁾ There exist misfit dislocations of $\mathbf{b} = 1/2[\bar{1}11]_{\text{TiNi}}$ or $1/2[1\bar{1}1]_{\text{TiNi}}$ with regular spacings of approximately 2.6 nm in the B2-TiNi phase. Since we also

Fig. 7 (a) A bright field image and the corresponding electron diffraction patterns of (b) and (c) the area A, and (b') and (c') the matrix region B of the $\text{Nb}_{13}\text{Zr}_{43}\text{Ni}_{44}$ alloy, respectively.

Table 2 Orientation relationship between the two phases of the eutectic structure in the four niobium-bearing alloys.

	Nb ₂₀ Ti ₄₀ Ni ₄₀	Nb ₃₀ Ti ₃₅ Co ₃₅	Nb ₁₃ Zr ₄₃ Ni ₄₄	Nb ₂₅ Zr ₃₅ Co ₄₀
Orientation relationship of the eutectic structure	$[001]_{(\text{Nb,Ti})} // [001]_{\text{TiNi}}$ $(100)_{(\text{Nb,Ti})} // (100)_{\text{TiNi}}$ $(010)_{(\text{Nb,Ti})} // (010)_{\text{TiNi}}$	$[\bar{2}21]_{(\text{Nb,Ti})} // [001]_{\text{TiCo}}$ $(110)_{(\text{Nb,Ti})} // (110)_{\text{TiCo}}$	$[001]_{(\text{Nb,Zr})} // [100]_{\text{B33-ZrNi}} // [001]_{\text{B2-ZrNi}}$ $(110)_{(\text{Nb,Zr})} // (010)_{\text{B33-ZrNi}} // (110)_{\text{B2-ZrNi}}$ $(\bar{1}\bar{1}0)_{(\text{Nb,Zr})} // (001)_{\text{B33-ZrNi}} // (\bar{1}\bar{1}0)_{\text{B2-ZrNi}}$	$[001]_{(\text{Nb,Zr})} // [001]_{\text{ZrCo}}$ $(100)_{(\text{Nb,Zr})} // (100)_{\text{ZrCo}}$ $(010)_{(\text{Nb,Zr})} // (010)_{\text{ZrCo}}$

Fig. 8 (a), (c), and (e) Bright field images of the eutectic interface in the Nb₃₀Ti₃₅Co₃₅ alloy, obtained for $g = 011_{(\text{Nb,Ti})} // 101_{\text{TiCo}}$, $101_{(\text{Nb,Ti})} // 011_{\text{TiCo}}$ and $110_{(\text{Nb,Ti})} // 110_{\text{TiCo}}$, respectively. (b), (d), and (f) Enlarged micrographs of the eutectic interface in (a), (c), and (e), respectively.

obtain the same results by the HRTEM observations, although we do not reproduce the micrograph here, only the unique eutectic interface in the Nb₃₀Ti₃₅Co₃₅ alloy is discussed hereafter. Figure 8 shows the bright field images obtained from the $[\bar{1}\bar{1}\bar{1}]_{(\text{Nb,Ti})} // [\bar{1}\bar{1}\bar{1}]_{\text{TiCo}}$ direction of the eutectic interface in the Nb₃₀Ti₃₅Co₃₅ alloy. This direction corresponds to a unique condition in which the eutectic interface is in the edge-on state, observed from the low index zone axis of both the phases, as described in Figs. 5 and 6. In case of $g = 011_{(\text{Nb,Ti})} // 101_{\text{TiCo}}$ and $101_{(\text{Nb,Ti})} // 011_{\text{TiCo}}$, the periodic contrasts due to the misfit dislocations with the spacings of 1.5 to 1.8 nm are observed, as shown in Figs. 8(a) to 8(d). On the other hand, when $g = 110_{(\text{Nb,Ti})} // 110_{\text{TiCo}}$, no contrast is observed, as shown in Figs. 8(e) and 8(f). The two-dimensional lattice image of the eutectic interface from the $[\bar{1}\bar{1}\bar{1}]_{(\text{Nb,Ti})} // [\bar{1}\bar{1}\bar{1}]_{\text{TiCo}}$ zone axis is presented in Fig. 9. The eutectic interface is almost parallel to the (110) plane of both the phases. We observe the extra half planes of (101)_{TiCo} on the eutectic interface, as indicated by the arrows. The

Fig. 9 Two-dimensional lattice image of the eutectic interface in the Nb₃₀Ti₃₅Co₃₅ alloy, obtained from the $[\bar{1}\bar{1}\bar{1}]_{(\text{Nb,Ti})} // [\bar{1}\bar{1}\bar{1}]_{\text{TiCo}}$ zone axis.

spacing between the (101)_{TiCo} plane is of the order of 7–12 layers. This is consistent with the periodic contrasts shown in Fig. 8. In addition to the (101)_{TiCo} plane, we can also identify the extra half planes of (110)_{TiCo} along the eutectic interface. Therefore, it is confirmed that the two types of misfit dislocations are coupled and arranged along the eutectic interface. The complex strain contrast along the interface is probably due to the two types of misfit dislocations. The characterizations such as determination of the Burgers vector of these dislocations have not yet been completed. This analysis is now in progress and will be reported in due course.

Final comments concern about the relationship between the hydrogen permeability and the interface structure. The hydrogen permeability of the Nb-Ti-Ni alloy increases with the volume fraction of the primary (Nb, Ti) phase.^{4,5} On the other hand, the Nb-Ti-Co alloy with the eutectic composition possesses the highest hydrogen permeability among all the Nb-Ti-Co ternary alloys.⁶ This indicates that hydrogen permeability depends on the alloy systems and their compositions. On the basis of the present microstructural observations, the crystal, macro-, and micro-structures of the eutectic Nb-Ti-Ni alloy are similar to those of the eutectic Nb-Ti-Co alloy. However, the orientation relationship between both the alloys and their interface microstructures are quite different. These facts suggest that the hydrogen permeation is probably influenced by the interface microstructure.

4. Conclusions

The morphology and crystallography of the eutectic structures in several niobium-bearing hydrogen permeation

alloys such as Nb₂₀Ti₄₀Ni₄₀, Nb₃₀Ti₃₅Co₃₅, Nb₁₃Zr₄₃Ni₄₄, and Nb₂₅Zr₃₅Co₄₀ have been investigated by means of transmission electron microscopy. The atomic arrangements at the eutectic interface are also discussed on the basis of high-resolution observations. The obtained results are summarized as follows.

- (1) The Nb₂₀Ti₄₀Ni₄₀, Nb₃₀Ti₃₅Co₃₅, and Nb₂₅Zr₃₅Co₄₀ alloys have eutectic structures consisting of fine lamellar morphology with Nb-based bcc and B2 intermetallic phases. The Nb₁₃Zr₄₃Ni₄₄ alloy possesses a eutectic structure consisting of rod-shaped bcc-(Nb, Zr) and B33-ZrNi phases, which displacively transforms from the B2 high-temperature phase.
- (2) The eutectic structure in the Nb₂₀Ti₄₀Ni₄₀ and Nb₂₅Zr₃₅Co₄₀ alloys exhibits a cube-on-cube orientation relationship between the bcc and the B2 phases. The eutectic structure in the Nb₁₃Zr₄₃Ni₄₄ also exhibits the cube-on-cube orientation relationship by considering the lattice correspondence between the B2 and the B33 structures. On the other hand, a unique orientation relationship is found out in the Nb₃₀-Ti₃₅Co₃₅ alloy, as follows: (110)_(Nb, Ti) // (110)_{TiCo} and $[\bar{2}21]_{(Nb, Ti)}$ // $[001]_{TiCo}$.
- (3) The strain contrast along the interface in the Nb₃₀-Ti₃₅Co₃₅ alloy is more complex as compared to that in the Nb₂₀Ti₄₀Ni₄₀ alloy. This is due to the two types of misfit dislocations coupled and arranged along the eutectic interface.

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