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PHASE RELATIONS AND DIFFUSION PATHS IN THE Ti-Ni-Co SYSTEM AT 900 °C

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Summary

We determined the isothermal cross section through the ternary phase diagram Ti-Ni-Co at 900 °C by means of the diffusion couple technique and by the investigation of equilibrated alloys. The course of a number of diffusion paths was established. Use was made of optical, microprobe and X-ray analyses.

1. Introduction

In earlier publications on the systems Ti-Ni-Cu [1], Ti-Ni-Fe [2] and Fe-Ni-Mo, Fe-Co-Mo and Ni-Co-Mo [3] we emphasized the usefulness of the diffusion couple technique in order to obtain reliable isothermal cross sections through phase diagrams.

The present work was started in order to compare the course of the diffusion paths in the three related systems Ti-Ni-Cu, Ti-Ni-Fe and Ti-Ni-Co, especially in couples of the type TiM_xMe_{1-x} against M_yMe_{1-y} . In these couples phases related to $TiNi_3$ often occur in various morphologies [1, 2] and in our opinion such a study may be of great interest in order to obtain more insight into the course of diffusion paths in multiphase ternary systems. Prior to this comparative investigation it was necessary to determine the cross section at 900 °C and the general course of diffusion paths in the Ti-Ni-Co system. The results of this study are the subject of the present paper.

In the literature a number of investigations have been carried out on multiphase diffusion and phase diagrams of the binary systems Ti-Ni and Ti-Co (see, for example, refs. 4, 5). For the ternary system we found only the data of van Vucht [6] on structures of compounds in the quasi-binary system $TiNi_3$ - $TiCo_3$ without any indication of the temperature and data on the same concentration range by Sinha [7] at 750 °C.

2. Experimental procedure

In this investigation we used rods of titanium (99.97 wt.%) and nickel (99.99 wt.%) and cobalt foil (99.99 wt.%) 0.25 mm thick, supplied by Materials Research Corp. The various binary and ternary alloys were prepared by repeated arc melting in argon, after which they were homogenized at 900 °C for at least 1 week in sealed evacuated silica capsules.

Diffusion couples were made in a special furnace in which slices of the starting materials were hot pressed by means of a set of weights for at least 64 h in a vacuum better than 10^{-6} Torr. After diffusion annealing, the couples were embedded, ground and polished parallel to the diffusion direction and, if necessary, were etched with a mixture of 10 wt.% H_2O_2 , 5 wt.% HF and 85 wt.% H_2O .

The couples and alloys were then investigated by means of optical microscopy, X-ray diffraction and microprobe analysis (JEOL Superprobe 733). For the microprobe analysis use was made of the MAGIC-3B computer program by Colby [8] in order to convert the measured X-ray intensities into concentrations. In order to determine the penetration curves for the three elements, point measurements were carried out at intervals as short as were needed in view of the layer morphology.

3. Experimental results

A number of couple types together with the layers that developed are given in Table 1. In couples with single-phase terminal materials most interfaces are planar, but the boundary TiNi-TiNi_3 is unstable in a number of cases. Needles of TiNi_3 and/or $\text{Ti}(\text{Ni}_{0.5}\text{Co}_{0.5})_3$ protrude into the matrix of $\text{TiNi}_x\text{Co}_{1-x}$. Contrary to the observations in the Ti-Ni-Fe system but in agreement with those in the Ti-Ni-Cu system the boundary $\text{TiNi}_3-\gamma(\text{Ni,Co})$ is planar without needles of TiNi_3 protruding into the γ matrix. In Figs. 1 and 2 examples of both planar and non-planar interfaces are shown.

Despite the small concentration differences between adjacent phases in the $\text{Ti}(\text{Ni}_x\text{Co}_{1-x})_3$ region, they are easily distinguishable in the microprobe because of their clearly different appearance in the backscattered electron image. In layers consisting of these compounds the concentrations of nickel and cobalt were found to depend on the specific crystallites in these layers. Concentration differences occur between adjacent grains parallel to the original interface and therefore the penetration curves for nickel and cobalt depend on the lateral position of the microprobe trace.

In Table 2 the phases which are present in a number of equilibrated alloys are given according to optical, microprobe and X-ray diffraction analyses, together with some crystallographic information.

TABLE 1

Types of couples together with the layer sequence developed at 900 °C

Number	Type	Layer sequence
1	Ti–Ni	β -Ti/Ti ₂ Ni/TiNi/TiNi ₃ /γ
2	Ti–Co	β -Ti/Ti ₂ Co/TiCo/TiCo ₂ (cub ^a)/TiCo ₂ (hex ^b)/TiCo ₃ /γ
3	Ti–Ni ₈₀ Co ₂₀	β -Ti/Ti ₂ Ni _x Co _{1-x} /TiNi _x Co _{1-x} /TiNi ₃ /γ
4	Ti–Ni ₆₀ Co ₄₀	β -Ti/Ti ₂ Ni _x Co _{1-x} /TiNi _x Co _{1-x} /TiNi ₃ /γ
5	Ti–Ni ₄₀ Co ₆₀	β -Ti/Ti ₂ Ni _x Co _{1-x} /TiNi _x Co _{1-x} /Ti(Ni _{0.5} Co _{0.5}) ₃ /γ
6	Ti–Ni ₂₀ Co ₈₀	β -Ti/Ti ₂ Ni _x Co _{1-x} /TiNi _x Co _{1-x} /TiCo ₂ (cub ^a)/TiCo ₃ /γ
7	"Ti _{75.5} Ni _{24.5} "(eut ^c)–TiCo	β -Ti + Ti ₂ Ni/Ti ₂ Ni _x Co _{1-x} /TiCo
8	"Ti ₇₇ Co ₂₃ "(eut ^c)–TiNi	β -Ti + Ti ₂ Co/Ti ₂ Ni _x Co _{1-x} /TiNi
9	TiNi–Co	TiNi _x Co _{1-x} + TiNi ₃ /TiCo ₂ (cub ^a) + Ti(Ni _{0.5} Co _{0.5}) ₃ /TiCo ₃ /γ
10	TiNi–Ni ₄₀ Co ₆₀	TiNi _x Co _{1-x} + TiNi ₃ /TiNi ₃ /Ti(Ni _{0.5} Co _{0.5}) ₃ /γ
11	TiCo–Ni	TiCo/TiCo ₂ (cub ^a)/Ti(Ni _{0.5} Co _{0.5}) ₃ /TiNi ₃ /γ
12	TiCo–Ni ₈₀ Co ₂₀	TiCo/TiCo ₂ (cub ^a)/TiCo ₃ /Ti(Ni _{0.5} Co _{0.5}) ₃ /TiNi ₃ /γ
13	TiNi ₃ –TiCo ₂ (cub ^a)	TiNi ₃ /Ti(Ni _{0.5} Co _{0.5}) ₃ /TiCo _x Ni _{1-x} /TiCo ₂ (cub ^a)
14	TiNi ₃ –TiCo ₃	TiNi ₃ /Ti(Ni _{0.5} Co _{0.5}) ₃ /TiCo ₃

^a Cub, cubic.^b Hex, hexagonal.^c Eut, eutectic. Fig. 1. A backscattered electron image of couple 12 (TiCo–Ni₈₀Co₂₀) annealed for 89 h at 900 °C. The length of the white bar indicates 10 μm.

Fig. 2. A backscattered electron image of couple 10 (TiNi–Ni₄₀Co₆₀) annealed for 110 h at 900 °C. The length of the white bar indicates 10 μ m.

4. Evaluation of the experimental results

In Fig. 3 the resulting 900 °C isotherm through the Ti–Ni–Co phase diagram is given. In Fig. 4 a number of diffusion paths are shown on this isotherm.

The phase diagram is dominated by the phases Ti₂Ni_xCo_{1–x}, TiNi_xCo_{1–x} and the three modifications in the Ti(Ni,Co)₃ region. Only in

TABLE 2

Composition and structure data of phases present in alloys equilibrated at 900 °C and quenched to room temperature

Alloy	Phase	Structure type	Lattice parameter (Å)	Volume per atom (Å ³)
Ti ₇₅ Ni ₂₅	Ti _{90.5} Ni _{9.5}	β-Ti (cubic, b.c.c.)	$a = 3.224 \pm 0.002$	16.76 ± 0.02
	Ti ₆₇ Ni ₃₃	Ti ₂ Ni (cubic, f.c.c.)	$a = 11.33 \pm 0.01$	15.15 ± 0.02
Ti ₇₅ Ni ₁₂ Co ₁₃	Ti _{89.5} Ni _{4.5} Co ₆	β-Ti	$a = 3.221 \pm 0.002$	16.71 ± 0.02
	Ti ₆₇ Ni ₁₆ Co ₁₇	Ti ₂ Ni	$a = 11.31 \pm 0.01$	15.07 ± 0.02
Ti ₇₇ Co ₂₃	Ti ₈₈ Co ₁₂	β-Ti	$a = 3.214$	16.60
	Ti ₆₇ Co ₃₃	Ti ₂ Ni	$a = 11.30 \pm 0.01$	15.03 ± 0.02
Ti ₅₈ Ni ₄₂	Ti ₆₆ Ni ₃₄	Ti ₂ Ni	$a = 11.36 \pm 0.02$	15.27 ± 0.05
	Ti _{50.5} Ni _{49.5}	TiNi (monoclinic)	$a = 2.906; b = 4.123$ $c = 4.661; \beta = 98.0$	13.83
Ti ₆₀ Ni ₃₀ Co ₁₀	Ti ₆₆ Ni ₂₅ Co ₉	Ti ₂ Ni	$a = 11.34 \pm 0.01$	15.19 ± 0.02
	Ti ₅₀ Ni ₃₇ Co ₁₃	TiNi (cubic, b.c.c.)	$a = 3.014 \pm 0.002$	13.69 ± 0.02

(continued)

TABLE 2 (continued)

<i>Alloy</i>	<i>Phase</i>	<i>Structure type</i>	<i>Lattice parameter</i> (Å)	<i>Volume per atom</i> (Å ³)
Ti ₅₈ Ni ₂₁ Co ₂₁	Ti ₆₆ Ni ₁₇ Co ₁₇	Ti ₂ Ni	$a = 11.31 \pm 0.01$	15.07 ± 0.02
	Ti ₅₀ Ni _{24.5} Co _{25.5}	TiNi	$a = 3.008 \pm 0.002$	13.61 ± 0.02
Ti ₅₈ Co ₄₂	Ti ₆₆ Co ₃₄	Ti ₂ Ni	$a = 11.31 \pm 0.01$	15.07 ± 0.02
	Ti ₅₁ Co ₄₉	TiNi	$a = 3.003 \pm 0.002$	13.54 ± 0.02
Ti ₄₀ Ni ₆₀	Ti ₄₆ Ni ₅₄	TiNi (cubic, b.c.c.)	$a = 3.005 \pm 0.002$	13.57 ± 0.02
	Ti _{25.5} Ni _{74.5}	TiNi ₃ (hexagonal TiNi ₃)	$a = 5.115 \pm 0.004$; $c = 8.34 \pm 0.01$	11.81 ± 0.03
Ti ₄₀ Ni _{54.5} Co _{5.5}	Ti ₄₆ Ni ₄₈ Co ₆	TiNi	$a = 2.998 \pm 0.002$	13.47 ± 0.02
	Ti ₂₅ Ni ₇₂ Co ₃	TiNi ₃	$a = 5.115 \pm 0.004$; $c = 8.34 \pm 0.01$	11.81 ± 0.03
Ti ₃₇ Ni ₃₂ Co ₃₁	Ti _{44.5} Ni ₁₈ Co _{37.5}	TiNi	$a = 2.979 \pm 0.002$	13.22 ± 0.02
	Ti _{25.5} Ni ₅₃ Co _{21.5}	TiNi ₃	$a = 5.115 \pm 0.004$; $c = 8.34 \pm 0.01$	11.81 ± 0.03
Ti ₃₇ Ni ₂₁ Co ₂₁	Ti ₄₄ Ni _{11.5} Co _{44.5}	TiNi	$a = 2.971 \pm 0.002$	13.11 ± 0.02
	Ti _{25.5} Ni ₃₇ Co _{37.5}	Ti(Ni _{0.5} Co _{0.5}) ₃ (hexagonal VCo ₃)	$a = 5.120 \pm 0.006$; $c = 12.52 \pm 0.02$	11.84 ± 0.04
Ti ₃₇ Ni ₁₃ Co ₅₀	Ti _{42.5} Ni _{8.5} Co ₄₉	TiNi	$a = 2.966 \pm 0.002$	13.05 ± 0.02
	Ti _{25.5} Ni _{27.5} Co ₄₇	Ti(Ni _{0.5} Co _{0.5}) ₃	$a = 5.120 \pm 0.006$; $c = 12.52 \pm 0.02$	11.84 ± 0.04
Ti ₂₆ Ni ₂₀ Co ₅₄	Ti _{32.5} Ni _{9.5} Co ₅₈	TiCo ₂ (cubic MgCu ₂)	—	—
	Ti ₃₂ Ni ₈ Co ₆₀	TiCo ₂ (cubic)	$a = 6.702 \pm 0.002$	12.54 ± 0.01
Ti ₂₈ Ni ₆ Co ₆₆	Ti ₂₅ Ni ₂₂ Co ₅₃	Ti(Ni _{0.5} Co _{0.5}) ₃	$a = 5.120 \pm 0.006$; $c = 12.52 \pm 0.02$	11.84 ± 0.04
	Ti _{31.5} Ni ₃ Co _{65.5}	TiCo ₂ (cubic)	$a = 6.702 \pm 0.002$	12.54 ± 0.01
Ti ₂₈ Ni _{4.5} Co _{67.5}	Ti ₂₅ Ni ₉ Co ₆₆	TiCo ₃ (cubic AuCu ₃)	$a = 3.621 \pm 0.002$	11.87 ± 0.01
	Ti _{30.5} Ni _{2.5} Co ₆₇	TiCo ₂ (hexagonal MgNi ₂)	$a = 4.738 \pm 0.004$; $c = 15.46 \pm 0.01$	12.52 ± 0.02
Ti ₂₈ Ni _{1.5} Co _{70.5}	Ti ₂₅ Ni _{6.5} Co _{68.5}	TiCo ₃	$a = 3.621 \pm 0.002$	11.87 ± 0.01
	Ti ₃₀ Ni ₁ Co ₆₉	TiCo ₂ (hexagonal)	$a = 4.738 \pm 0.004$; $c = 15.46 \pm 0.01$	12.52 ± 0.02
Ti ₂₇ Co ₇₃	Ti ₂₅ Ni _{2.5} Co _{72.5}	TiCo ₃	$a = 3.621 \pm 0.002$	11.87 ± 0.01
	Ti _{29.5} Co _{70.5}	TiCo ₂ (hexagonal)	$a = 4.733 \pm 0.004$; $c = 15.43 \pm 0.02$	12.47 ± 0.03
Ti ₁₅ Ni ₈₅	Ti ₂₅ Co ₇₅	TiCo ₃	$a = 3.620 \pm 0.003$	11.86 ± 0.02
	Ti ₂₄ Ni ₇₆	TiNi ₃	$a = 5.103 \pm 0.004$; $c = 8.316 \pm 0.008$	11.72 ± 0.02
Ti ₂₀ Ni _{49.5} Co _{30.5}	Ti ₁₁ Ni ₈₉	γ (cubic, f.c.c.)	$a = 3.566 \pm 0.002$	11.34 ± 0.01
	Ti _{23.5} Ni _{52.5} Co _{24.5}	TiNi ₃	$a = 5.112 \pm 0.004$; $c = 8.328 \pm 0.008$	11.78 ± 0.02
Ti ₂₃ Ni _{49.5} Co _{27.5}	Ti _{7.5} Ni _{38.5} Co ₅₄	γ	$a = 3.566 \pm 0.002$	11.34 ± 0.01
	Ti _{23.5} Ni ₅₁ Co _{25.5}	TiNi ₃	—	—
Ti ₂₀ Ni ₄₀ Co ₄₀	Ti ₂₃ Ni ₄₉ Co ₂₈	Ti(Ni _{0.5} Co _{0.5}) ₃	—	—
	Ti ₈ Ni ₃₁ Co ₆₁	γ	—	—
	Ti ₂₃ Ni ₄₃ Co ₃₄	Ti(Ni _{0.5} Co _{0.5}) ₃	$a = 5.114 \pm 0.006$; $c = 12.49 \pm 0.02$	11.79 ± 0.04
	Ti _{7.5} Ni _{27.5} Co ₆₅	γ	$a = 3.566 \pm 0.002$	11.34 ± 0.01

Compositions are given in mole per cent; —, lattice parameters not determined because of too weak or coincident reflections.

Fig. 3. The 900 °C isotherm through the Ti-Ni-Co phase diagram according to our measurements: ---, tie lines.

Fig. 4. The 900 °C isotherm through the Ti-Ni-Co phase diagram: —, the diffusion paths found in the couples 3, 4, 5 and 6.

the two modifications of TiCo_2 can atoms of cobalt not be fully substituted by nickel.

From the crystallographic data in Table 2 and from Fig. 5 it is clear that the volumes per atom in Ti-Ni-Co compounds are virtually independent of the Ni:Co ratio, proving that the nickel and cobalt atoms are of equal size in these structures. The three compounds in the Ti(Ni,Co)_3 region are closely interrelated and exhibit the same orientation relations to $\gamma\text{-(Ni,Co)}$ as the

Fig. 5. The volume per atom ($\text{\AA}^3$) plotted against the titanium content in various phases of the Ti-Ni ($\odot$), Ti-Co ($\times$) and Ti-Ni-Co ($\triangle$) systems.

corresponding phases in the Ti-Ni-Cu and Ti-Ni-Fe systems [1, 2] (Table 3).

From Table 2 it follows that in the two-phase $\text{Ti}_{75}\text{Ni}_{25}$ alloy under the experimental conditions the titanium-rich TiNi compound has the same monoclinic structure that was found by Otsuka *et al.* [9]. This phenomenon is related to a martensitic transformation during quenching which we did not find in alloys where nickel is partly substituted by cobalt. The titanium-poor $\text{TiNi}_x\text{Co}_{1-x}$ compounds all have the b.c.c. structure which, according to Gupta *et al.* [10], can exhibit an orientation relation with the TiNi_3 structure.

The reason that we are interested in possible orientation relationships is the conspicuous two-phase character in some couples in which TiNi_3 -type compounds are involved. The needles of this phase which protrude into the TiNi phase in the present Ti-Ni-Co system or protrude into the γ -(Ni,Fe) phase in the Ti-Ni-Fe phase suggest a causal connection between this phenomenon and the orientation-related structures involved. However, this orientation relationship cannot be the only factor which governs the two-phase morphology, since in a number of couples with the same possible orientation relationships the layers are bounded by planar interfaces.

Concerning the general determination of diffusion paths it seems appropriate to mention a particular difficulty. In some couples very steep concentration gradients occur which may easily cause a wrong extrapolation towards the interface concentration. This of course leads to incorrect constructions of the diffusion paths. As a result such a wrong path possibly cuts tie lines in two-phase regions, although the interface in the couple is perfectly planar. In our opinion the correct diffusion path in such a case has to be constructed by assuming equilibrium conditions in the couple. If one boundary concentration is exactly known, the other can be found from the tie

TABLE 3

Orientation relationships and misfit in coexisting γ -(Ni,Co) and $\text{Ti}(\text{Ni},\text{Co})_3$ phases in samples quenched from 900 °C

Structural relation $\gamma/\text{Ti}(\text{Ni},\text{Co})_3$	Misfit (%)
$\{111\}\gamma$ $\left\{ \begin{array}{l} //\{0001\}\text{TiNi}_3 \\ //\{0001\}\text{Ti}(\text{Ni}_{0.5}\text{Co}_{0.5})_3 \\ //\{111\}\text{TiCo}_3 \end{array} \right.$	$\frac{(1/4)c_{\text{TiNi}_3} - (3^{1/2}/3)a_\gamma}{(3^{1/2}/3)a_\gamma} \times 100 = 1.1 \pm 0.1$ $\frac{(1/6)c_{\text{Ti}(\text{Ni}_{0.5}\text{Co}_{0.5})_3} - (3^{1/2}/3)a_\gamma}{(3^{1/2}/3)a_\gamma} \times 100 = 1.1 \pm 0.2$ $\frac{a_{\text{TiCo}_3} - a_\gamma}{a_\gamma} \times 100 = 1.2 \pm 0.1$
$\langle 110 \rangle \gamma$ $\left\{ \begin{array}{l} //\langle 11\bar{2}0 \rangle \text{TiNi}_3 \\ //\langle 11\bar{2}0 \rangle \text{Ti}(\text{Ni}_{0.5}\text{Co}_{0.5})_3 \\ //\langle 110 \rangle \text{TiCo}_3 \end{array} \right.$	$\frac{(1/2)a_{\text{TiNi}_3} - (2^{1/2}/2)a_\gamma}{(2^{1/2}/2)a_\gamma} \times 100 = 1.4 \pm 0.1$ $\frac{(1/2)a_{\text{Ti}(\text{Ni}_{0.5}\text{Co}_{0.5})_3} - (2^{1/2}/2)a_\gamma}{(2^{1/2}/2)a_\gamma} \times 100 = 1.4 \pm 0.1$ $\frac{a_{\text{TiCo}_3} - a_\gamma}{a_\gamma} \times 100 = 1.2 \pm 0.1$

lines in the two-phase region. Therefore we state that in the case of a planar interface the diffusion path runs parallel to the tie lines; apparent deviations are caused by wrong extrapolations towards the equilibrium concentrations.

The same problem arises when the equilibrium concentrations at the boundaries of precipitates in a two-phase layer are determined. In the absence of steep concentration gradients we always found that the concentrations agreed with the tie lines determined from equilibrated alloys. If steep gradients occur, extrapolations easily lead to apparent deviations. Again, we believe that equilibrium concentrations are present at the boundaries of sufficiently large precipitates. The peculiar isoconcentration contours found by Cheng and Dayananda [11] in non-planar interface regions might be explained in this way.

An exception to this rule might occur if the structures of the two phases in question are thermodynamically nearly identical. This is so, for instance, in layers consisting of $\text{Ti}(\text{Ni}_x\text{Co}_{1-x})_3$ -type compounds. The substitution of nickel by cobalt is thermodynamically virtually indifferent. Equilibrium concentration values are then found at the interfaces with adjoining phases of other compositions in the couples. Inside the $\text{Ti}(\text{Ni}_x\text{Co}_{1-x})_3$ layers, however, differences in the Ni:Co ratio may occur in a plane parallel to the original interface, possibly caused by effects such as the presence of grain boundaries or impurity atoms.

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References

- 1 F. J. J. van Loo, G. F. Bastin and A. J. H. Leenen, *J. Less-Common Met.*, 57 (1978) 111.
- 2 F. J. J. van Loo, J. W. G. A. Vrolijk and G. F. Bastin, *J. Less-Common Met.*, 77 (1981) 121.
- 3 F. J. J. van Loo, G. F. Bastin, J. W. G. A. Vrolijk and J. J. M. Hendriks, *J. Less-Common Met.*, 72 (1980) 225.
- 4 G. F. Bastin and G. D. Rieck, *Metall. Trans.*, 5 (1974) 1817.
- 5 P. J. M. van der Straten, G. F. Bastin, F. J. J. van Loo and G. D. Rieck, *Z. Metallkd.*, 67 (1976) 152.
- 6 J. H. N. van Vucht, *J. Less-Common Met.*, 11 (1966) 308.
- 7 A. K. Sinha, *Trans. Metall. Soc. AIME*, 245 (1969) 911.
- 8 J. W. Colby, *Adv. X-Ray Anal.*, 11 (1968) 287.
- 9 K. Otsuka, T. Sawamura and K. Shimizu, *Phys. Status Solidi A*, 5 (1971) 457.
- 10 S. P. Gupta, K. Mukherjee and A. A. Johnson, *Mater. Sci. Eng.*, 11 (1973) 283.
- 11 G. H. Cheng and M. A. Dayananda, *Metall. Trans. A*, 10 (1979) 1407.