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Determination of phase equilibria in the Ni–V–Nb–Ta–Cr–Mo–W system at 1375 K using the graph method

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Abstract

Using the graph method the analysis of the phase equilibria in 35 quaternary systems, 21 quinary systems, seven six-component systems and the seven-component system Ni–V–Nb–Ta–Cr–Mo–W have been realised at 1375 K. The phase equilibria of the quaternary systems have been experimentally established. On the basis of the results obtained the phase equilibria in the Ni–V–Nb–Ta–Cr–Mo–W system at 1375 K have been determined.

Keywords: Ni–V–Nb–Ta–Cr–Mo–W alloys; Phase equilibria; Graph method; Polyhedration of systems; Multicomponent system

1. Introduction

The phase diagrams are the basis of many investigations in solid state chemistry and material science. Advanced materials, as a rule, have many phases and consist of many components. Therefore, for the investigation of processes, that take place during the creation and use of these materials, it is necessary to have information about the multi-component phase diagrams. However, when adding only one component, the experimental work significantly increases. The experimental investigation of any multi-component system is a very labour-consuming task. One of the methods that allow the establishment of a prognosticating scheme of the phase equilibria and to optimise the experiments, is the graph method [1–3].

The analysis of the information about the binary systems of nickel and transition metals of the V group shows, that five intermetallic compounds present on the phase diagrams at 1375 K. In the Ni–V system the σ-phase (FeCr-type) forms. There are two phases: α-phase Ni_3Nb (Cu_3Ti-type) and μ-phase NiNb (Fe_7W_6-phase) in the Ni–Nb system. In the Ni–Ta system four intermetallic compounds exist: α-phase Ni_3Ta (Cu_3Ti-type), Ni_2Ta ($MoSi_2$-type), μ-phase NiTa (Fe_7W_6-type) and $NiTa_2$ ($CuAl_2$-type).

In the binary systems of nickel and transition metals of the VI-group at 1375 K only one intermetallic compound δ-NiMo (own structure type) forms at 1375 K.

In the binary systems of the refractory metals [4–20] three Laves γ_2-phases ($MgCu_2$-type) V_2Ta, Cr_2Nb and Cr_2Ta exist at 1375 K. In the Cr–W system at 1375 K there is stratification of the bcc solid solution.

In the ternary systems V–Nb–Mo, V–Nb–W, Nb–Ta–Mo, Nb–Ta–W, V–Cr–Mo, V–Mo–W, Nb–Mo–W and Ta–Mo–W at 1375 K the continuous sequence of the bcc solid solutions exists [3,21–25]. The isothermal cross-sections of the phase diagrams of these systems and their graphs are given in Fig. 1.

In the V–Nb–Ta, V–Ta–Mo and V–Ta–W systems at 1375 K one two-phase equilibrium γ_2–β exists at 1375 K [26–28]. In the systems V–Nb–Cr, V–Ta–Cr and Nb–Ta–Cr there are regions of the $\gamma_2+\beta_1$ and $\gamma_2+\beta_2$ equilibria (Fig. 1) [29–31]. The β-phase also stratifies in the systems V–Cr–W and Mo–Cr–W (Fig. 1) [32–36].

In the systems Nb–Cr–Mo, Ta–Cr–Mo, Nb–Cr–W and Ta–Cr–W the three-phase equilibrium $\gamma_2+\beta_1+\beta_2$ is realised (Fig. 1) [37–43].

The data on the phase equilibria of the ternary systems on the basis of nickel and transition metals of the V–VI groups are given in Table 1. The isothermal cross-sections of these systems and their graphs are shown in Fig. 1.

The single investigated quaternary system among 35 quaternary systems of nickel and refractory metals of the V–VI groups is the Ni–V–Cr–Mo system. In this system the ternary σ-phase of the Ni–Cr–Mo system and the

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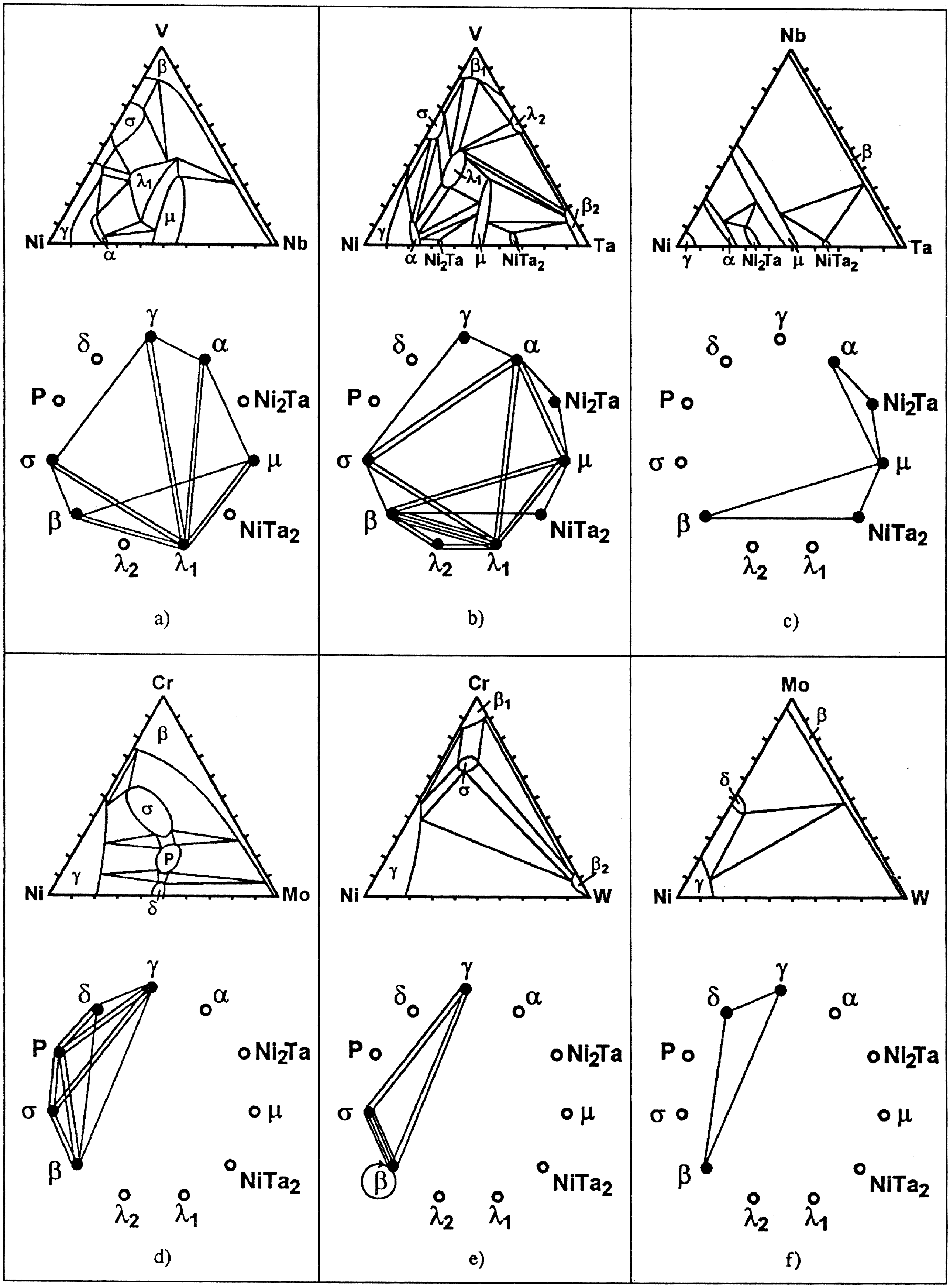
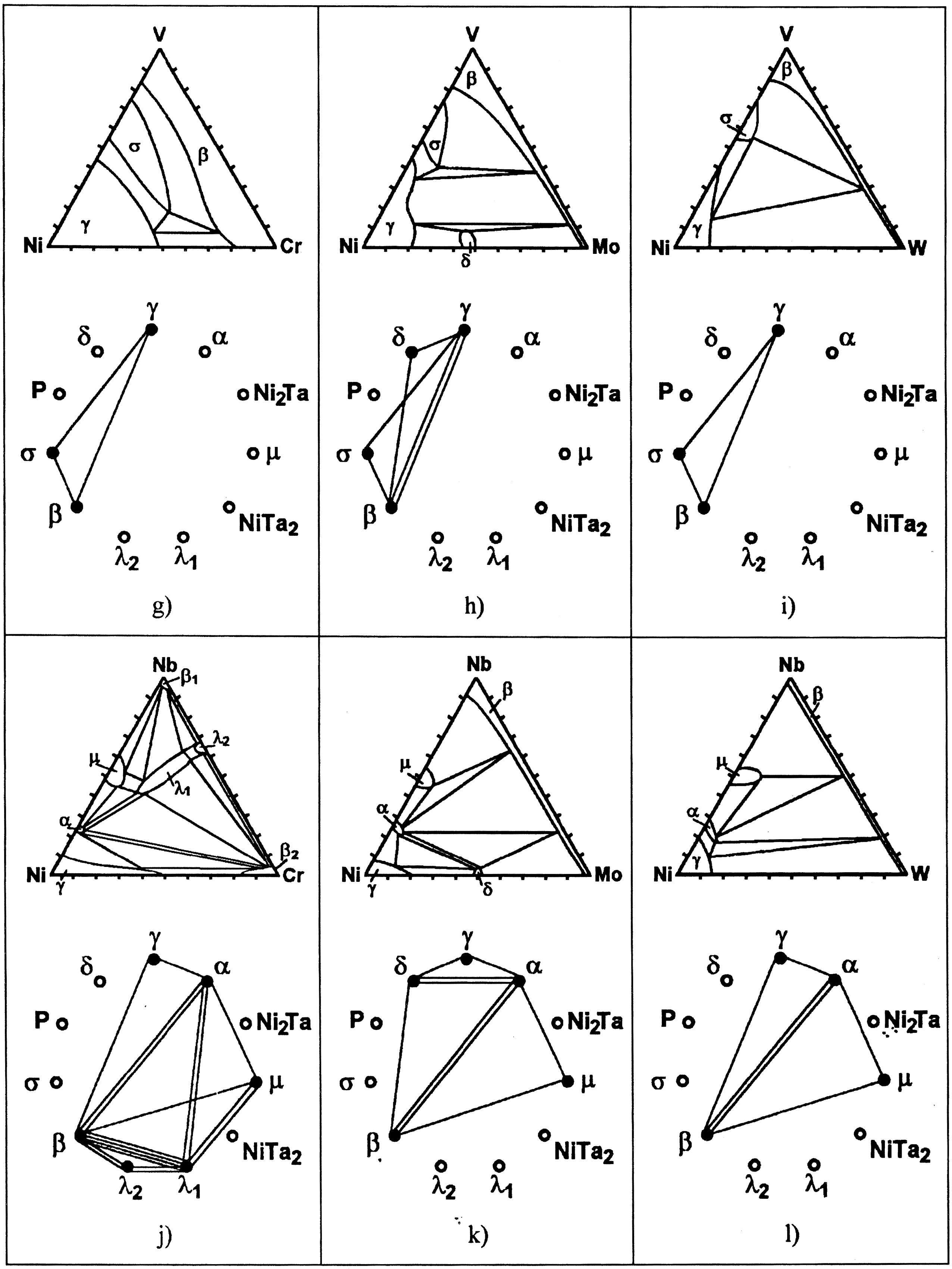


Fig. 1. Isothermal cross-sections of the phase diagrams on the basis of nickel and transition metals of the V–VI groups and their graphs.



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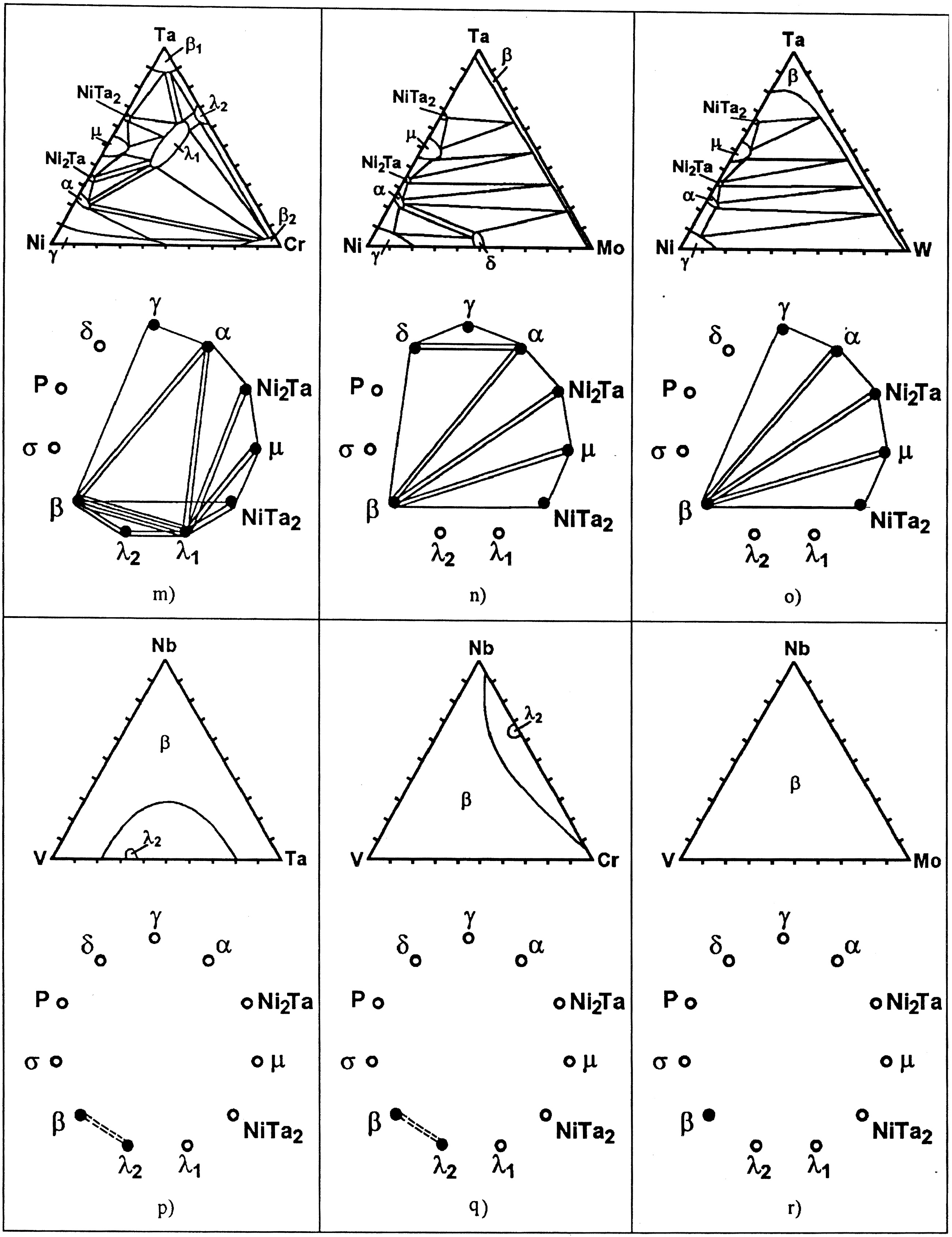

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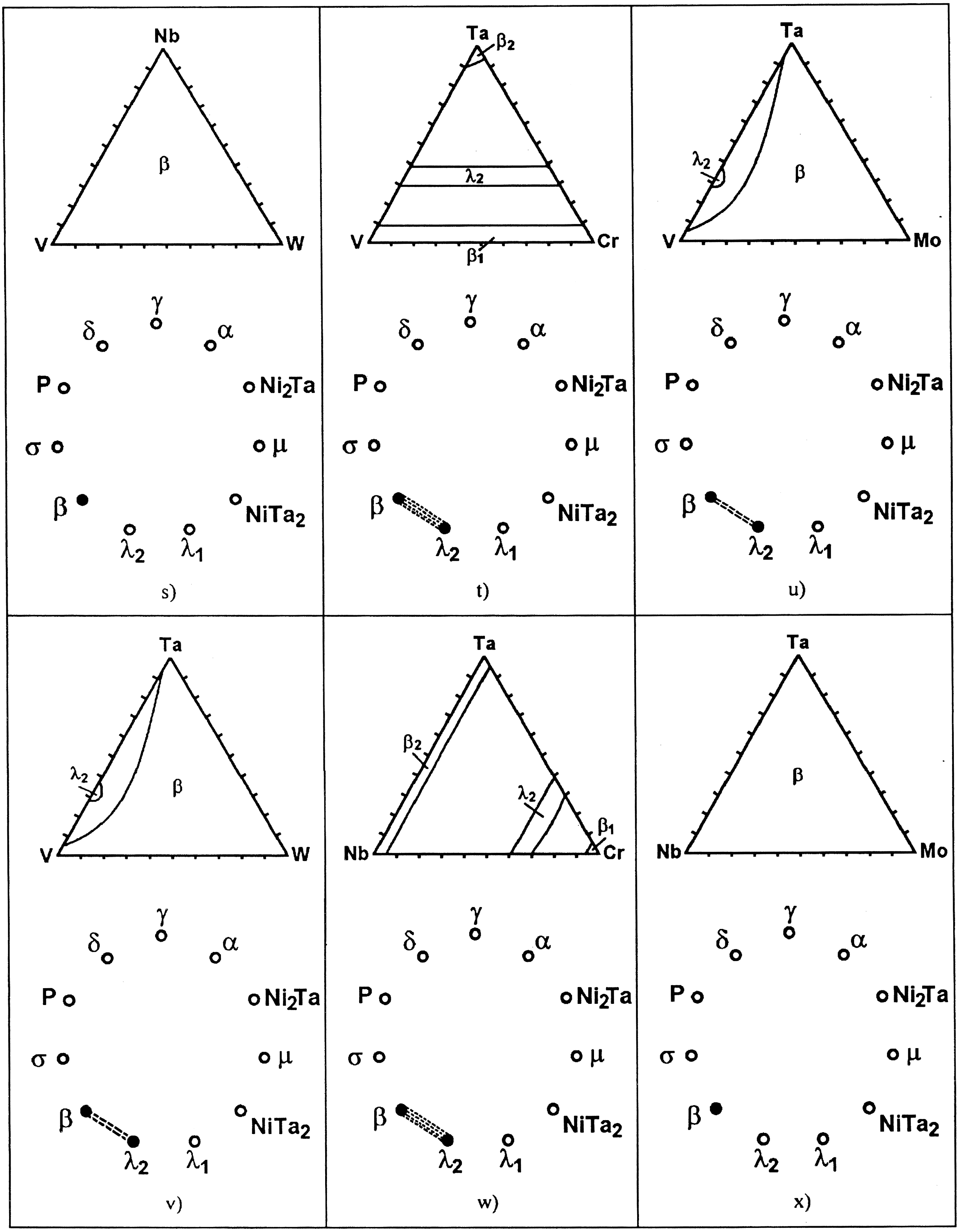

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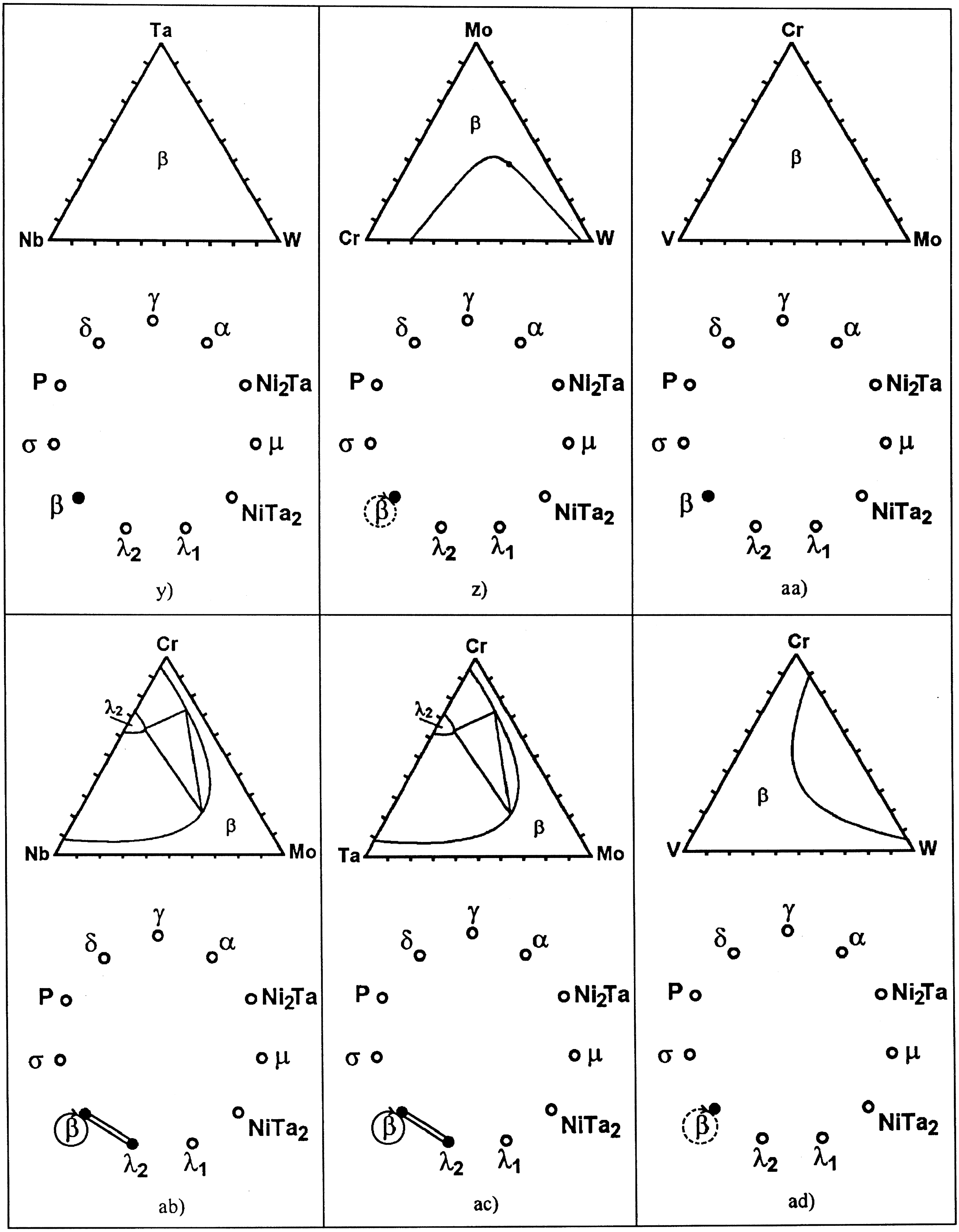

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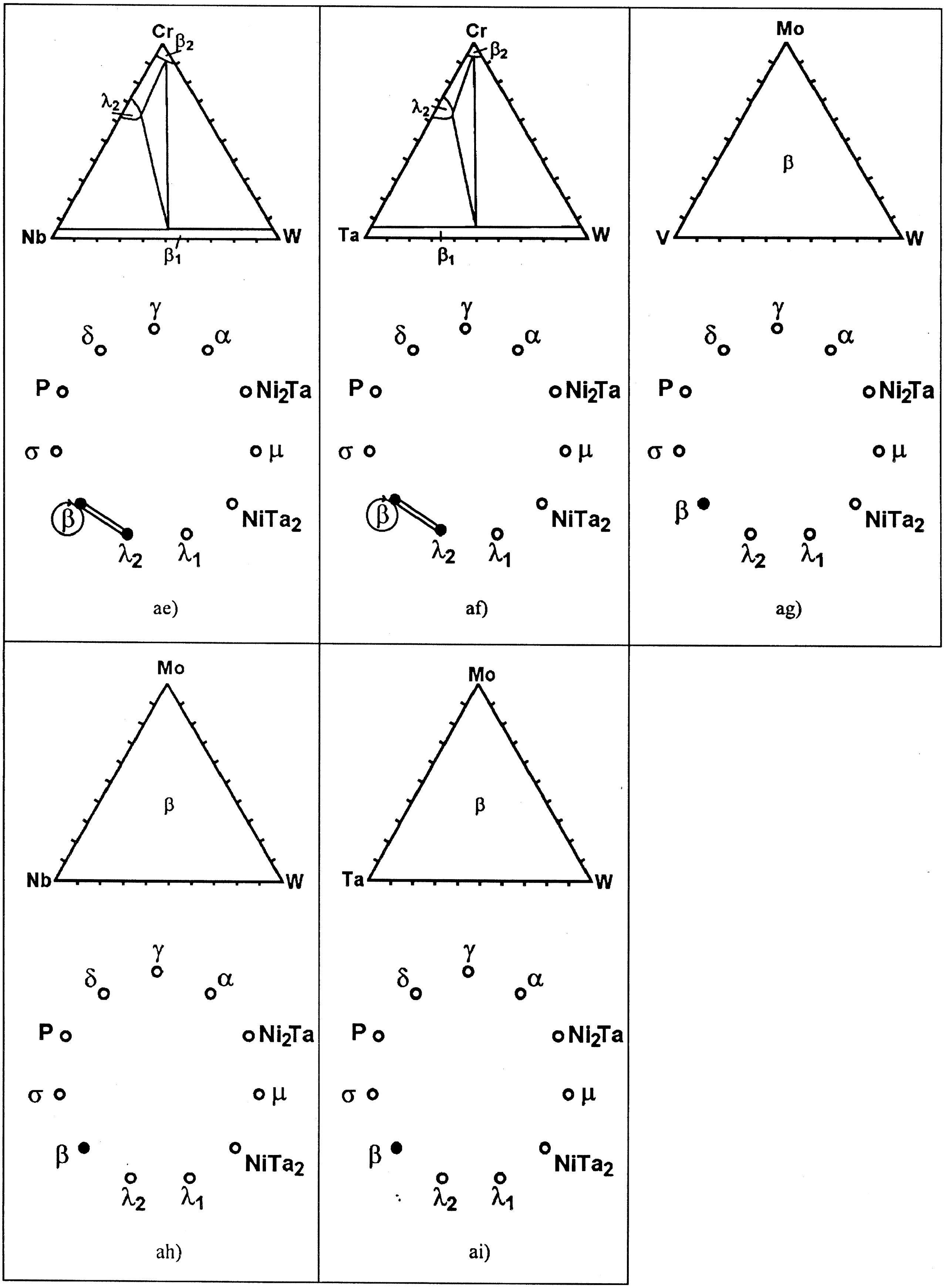

Fig. 1. (*continued*)

Table 1
Phase equilibria of the ternary systems of nickel and transition metals of the V–VI groups

No.	System	Phase	Phase equilibria	Ref.
1	Ni–V–Nb	α, β, γ, μ, γ_1-ternary Laves phase ($MgZn_2$-type)	α–γ–λ_1, γ–σ–λ_1, α–μ–λ_1, β–μ–λ_1, β–σ–λ_1,	[44–47]
2	Ni–V–Ta	α, β, γ, μ, δ, γ_1 Ta_2Ni, $TaNi_2$	α–γ–σ, α–σ–λ, α–μ–λ_1, α–μ–$TaNi_2$, β–μ-Ta_2Ni, β(V)–λ_1–λ_2, β(Ta)–λ_1–λ_2, β(V)–σ–λ_1, β(Ta)–μ–λ_1	[48,49]
3	Ni–Ta–Nb	α, β, γ, μ, σ, δ, γ_1 Ta_2Ni, $TaNi_2$	β–Ta_2Ni–μ; μ–$TaNi_2$–α	[49]
4	Ni–Cr–Mo	β, γ, σ, δ, P - ternary phase	β–γ–σ, γ–P–σ, β–P–σ, β–P–δ, γ–δ–P	[50–61]
5	Ni–Cr–W	β, γ, σ-ternary phase	σ–γ–β_1, σ–γ–β_2, σ–β_1–β_2	[60–69]
6	Ni–Mo–W	β, γ, δ,	β–γ–δ	[70,71]
7	Ni–V–Cr	β, γ, σ,	β–γ–σ	[72–78]
8	Ni–V–Mo	β, γ, σ, δ,	β–γ–σ, β–γ–δ	[44,79,80]
9	Ni–V–W	β, γ, σ,	β–γ–σ	[44,49]
10	Ni–Nb–Cr	α, β, γ, μ, γ_1, γ_2	γ_1–β_1–α, λ_1–μ–α, λ_1–β_2–μ, λ_1–λ_2–β_2, λ_1–λ_2–β_2, α–γ–β_1	[48,81,82]
11	Ni–Nb–Mo	α, β, γ, μ, δ	α–β–μ, α–β–δ, α–γ–δ	[83–85]
12	Ni–Nb–W	α, β, γ, μ	β–α–γ, β–α–μ	[85,86]
13	Ni–Ta–Cr	α, β, γ, μ, γ_1 Ta_2Ni, $TaNi_2$	α–β–γ; α–β–λ; α–Ni_2Ta–λ_1; μ–λ_1–Ni_2Ta; μ–λ_1–$NiTa_2$; β–γ_1–$NiTa_2$; λ_1–λ_2–β_1; λ_1–λ_2–β_2	[87–89]
14	Ni–Ta–Mo	α, β, γ, μ, δ, Ta_2Ni, $TaNi_2$	α–γ–δ; α–β–δ; α–β–Ni_2Ta; β–μ–Ni_2Ta; β–μ–$NiTa_2$	[84,90,91]
15	Ni–Ta–W	α, β, γ, μ, Ta_2Ni, $TaNi_2$	β–$NiTa_2$–μ, β–μ–Ni_2Ta, β–Ni_2Ta–α, β–α–γ	[91,92]

binary σ-phase of the Ni–V system forms mutually continuous sequence of solid solutions. Using the graph method the present authors have prognosticated and then experimentally confirmed the existence of two four-phase equilibria (σ–P–β–γ and δ–P–β–γ) in this system. Besides, the ternary equilibrium σ–β–γ of the Ni–Cr–Mo and Ni–V–Cr systems forms a continuous region in the quaternary Ni–V–Cr–Mo system.

In the present paper the phase equilibria in the Ni–V–Nb–Ta–Cr–Mo–W system at 1375 K have been established.

2. Experimental details

In the present experiments we used electrolytic nickel and chromium, vacuum-melted molybdenum and tungsten and induction-melted vanadium, niobium and tantalum.

The alloys were melted in an arc furnace with an argon atmosphere using a non-consumable tungsten electrode. The ingots were induction remelted five times in suspension and homogenised in vacuum for 650 h at the temperature of investigation. The alloy compositions and the homogeneity were checked by microprobe analysis (Table 2).

The diffusion couples were obtained by diffusion welding of mono-, two- and three-phase alloys with mono-, two-phase alloys and metals for 20 min at 1200 K under pressure of 20 MPa. Obtained couples were thermal treated for 75 h at 1375 K.

The structure and the concentration distribution of the elements in the phases of the equilibrium alloys and the diffusion zones were investigated by scanning electron microscopy, microprobe analysis techniques with a CAMEBAX-microBEAM instrument and by X-ray analysis. The thermal treatment was carried out in a resistance furnace in silica capsules under an argon atmosphere. The temperature was controlled within ±5 K.

DTA-analysis was provided on a VDTA-8M2 (OKTB IMF AN UkSSR) under high purity helium (p=100 kPa) at the heating velocity 80 K min^{-1}. Precision of the method is ±5 K.

3. Results and discussion

There are two reasons for choosing 1375 K as the temperature of the investigation. Firstly, the temperature of the formation of the liquid phase has been established using DTA-analysis. The lowest temperature in the Ni–V–Nb–Cr system is 1393 K. Secondly, many ternary systems were investigated at the temperature near 1375 K. In this case the identification of the phases is significantly simplified because in these systems the solubility of the elements in the phases practically does not change.

Thirty five quaternary systems on the basis of nickel and metals of the VB, VIB groups can be separated on two groups: (1) the systems, which consist only from transitional metals of the V, VI groups and (2) the systems, which include nickel.

Table 2
Global composition of the alloys

System	Concentration of the elements, at.%			
Ni–V–Nb–Ta	Ni	V	Nb	Ta
1	51.2	29.8	8.6	10.4
Ni–V–Nb–Cr	Ni	V	Nb	Cr
2	15.1	21.4	42.0	21.5
3	46.0	21.4	8.8	23.8
Ni–V–Nb–Mo	Ni	V	Nb	Mo
4	53.3	12.1	16.6	18.0
5	35.2	11.9	44.0	8.9
6	24.4	42.4	10.1	23.1
7	10.2	25.1	16.4	48.3
Ni–V–Nb–W	Ni	V	Nb	W
8	40.2	11.3	20.1	28.4
9	35.1	26.0	34.6	10.3
10	44.4	13.9	29.2	12.5
Ni–V–Ta–Cr	Ni	V	Ta	Cr
11	60.3	10.1	11.2	18.4
12	32.8	40.1	15.4	11.7
13	55.3	8.6	29.0	7.1
14	12.7	15.1	55.4	16..8
Ni–V–Ta–Mo	Ni	V	Ta	Mo
15	21.9	7.7	10.3	60.1
16	17.4	16.1	40.2	26.3
17	14.6	15.1	42.1	28.2
18	36.6	44.7	6.9	11.8
19	41.9	8.5	32.5	17.1
Ni–V–Ta–W	Ni	V	Ta	W
20	29.9	16.8	51.1	2.2
21	45.4	30.5	10.2	13.4
22	41.1	18.2	36.7	4.0
23	50.3	8.4	32.2	9.1
Ni–Nb–Ta–Cr	Ni	Nb	Ta	Cr
24	49.2	18.2	24.1	8.5
25	10.0	39.0	16.3	34.7
Ni–Nb–Ta–Mo	Ni	Nb	Ta	Mo
26	55.3	16.4	20.9	7.4
Ni–Nb–Ta–W	Ni	Nb	Ta	W
27	51.1	22.6	17.7	8.6
Ni–Nb–Cr–Mo	Ni	Nb	Cr	Mo
28	21.4	34.5	18.2	25.9
29	23.3	17.0	20.1	39.6
30	61.4	15.7	8.6	14.3
31	52.1	19.4	11.5	17.0
32	54.9	8.3	24.2	12.6
33	61.2	10.7	25.5	2.6
Ni–Nb–Cr–W	Ni	Nb	Cr	W
34	20.9	16.9	31.2	31
Ni–Nb–Mo–W	Ni	Nb	Mo	W
35	54.1	5.9	31.0	9.0
Ni–Ta–Cr–Mo	Ni	Ta	Cr	Mo
36	49.9	36.1	4.4	9.6
37	25.4	34.2	22.7	17.7
38	11.2	51.4	8.2	29.2
39	35.5	7.8	12.2	44.5
40	55.4	4.7	25.4	14.5
41	35.0	11.3	23.3	30.4
42	57.9	12.0	11.1	19.0
43	15.2	25.4	29.6	29.8
Ni–Ta–Cr–W	Ni	Ta	Cr	W
44	30.2	25.5	20.0	24.3
45	20.4	41.2	15.3	23.1
46	50.3	12.0	25.4	12.3
Ni–Cr–Mo–W	Ni	Cr	Mo	W
47	41.1	22.0	31.4	5.5
48	16.6	22.4	26.7	34.3

3.1. Prognosis of the phase equilibria of the quaternary systems of the metals of the VB and VIB groups

All ternary systems (supposedly also quaternary systems) of refractory metals contain only two phases; the bcc-solid solution (β-phase), which consist of the metals of VB and VIB groups, and Laves λ_2-phase, which exists in the V–Ta, Cr–Nb and Cr–Ta systems. It follows, in the multi-component systems of the refractory metals only two-phase equilibria can exist. The Nb–Cr–Mo, Nb–Cr–W, Ta–Cr–Mo and Ta–Cr–W systems are exceptions, because they contain the three-phase equilibria $\lambda_2+\beta_1+\beta_2$. In spite of the existence of only two phases in this system three-phase equilibria are present because of the stratification of the β-solid solution. At addition of the fourth component these regions form the three-phase field in the quaternary systems (in the Nb–Ta–Cr–W systems) or degenerate to the region of the two-phase equilibrium (in the rest of the systems). The review of the quaternary systems of the metals of the VB and VIB groups is given in Table 3.

3.2. Prognosis of the phase equilibria of the quaternary systems of nickel and metals of the VB and VIB groups

In the systems on the basis of nickel and transition metals there are many intermetallic compounds. Schemes of all isothermal cross-sections of the ternary systems and their graphs are given in Fig 1. Analysing the total graph received by summarising the graphs of the ternary systems, it is possible to make the polyhedration of the isothermal cross-sections of the quaternary phase diagrams.

3.3. The Ni–V–Nb–Ta system

The scheme of phase equilibria of the Ni–V–Nb–Ta system at 1375 K was investigated by means of the graph method. The total graph of this system is given in Fig. 2a. After separation of five recombined three-phase equilibria (α–μ–Ni_2Ta, β–μ–$NiTa_2$, β–σ–λ_1, β–λ_1–λ_2, β–μ–λ_1 and α–μ–λ_1) from the total graph only one graph of the four-phase equilibrium α–γ–σ–λ_1(Fig. 2b) remains. Further we will name such the remaining graphs as the remaining graph of the zero rank. If the remaining graphs consist of six phases we have the remaining graph of the first rank and so on. There are no other variants of the decomposition of this system.

The attempt to prepare the four-phase alloy were unsuccessful. The investigation of the alloy 1 (Table 2) of this system has shown that the phases γ, σ and λ_1 (Table 4) form a three-phase equilibrium γ–σ–λ_1,which takes part in the formation of the four-phase equilibrium $\alpha+\gamma+\lambda_1+\sigma$.

Table 3
The equilibria in the quaternary systems of the metals of the VB and VIB groups

Systems	Phases	Phase equilibrium
V–Nb–Mo–W, Nb–Ta–Mo–W	β	–
V–Nb–Ta–Cr, V–Nb–Ta–Mo, V–Nb–Ta–W, V–Ta–Cr–Mo, V–Ta–Mo–W	λ_2, β	λ_2–β
V–Cr–Mo–W	β	Region of the stratification of β-phase
V–Nb–Cr–W, V–Ta–Cr–W, V–Nb–Cr–Mo, Nb–Ta–Cr–Mo,	λ_2, β	Degeneration of the three-phase equilibrium λ_2–β_1–β_2, to the two-phase equilibrium λ_2–β
Nb–Cr–Mo–W	λ_2, β	Region of the three-phase equilibria λ_2–β_1–β_2, crossing from the Nb–Cr–W system to the Ta–Cr–W system

3.4. The Ni–V–Nb–Cr system

The scheme of phase equilibria of the Ni–V–Nb–Cr system at 1375 K was investigated by means of the graph method. After separation from the total graph (Fig 3a) of three recombined three-phase equilibria (α–μ–γ_1, β–μ–λ_1 and β–λ_1–λ_2) we have the remaining graph of the first rank (Fig. 3c). The experimental investigations are necessary for decomposition of the remaining graph.

The decomposition of the remaining graph has been fulfilled by means of equilibrium alloys. The phase composition of the alloy 2 (Table 5) leads to inclusion about the existence of the three-phase equilibrium β–γ–λ_1, which is inside the four-component phase diagram and has no field in the ternary isothermal cross-sections. We will use the word 'unprojected' label in this text for the designation of such *n*-phase equilibria in the $n+1$ component system, which have no fields (projections) on the *n*-component isothermal cross-sections.

The remaining graph can be decomposed on two graphs of the four-phase equilibria α–β–γ–$\lambda_1$and σ–β–γ–λ_1 (Fig. 3d–f) by adding the three-phase equilibrium β–γ–λ_1 which is inside the four-component phase diagram and has no field in the ternary isothermal cross-sections. The phase composition of the alloy 3 corresponds to the existence of the four-phase equilibrium β–γ–λ_1 in this system.

Table 4
Phase composition and concentration of elements in the phases of the equilibrium alloys in the Ni–V–Nb–Ta system at 1375 K

Alloy No.	C_{Ni}, at.%	C_V, at.%	C_{Nb}, at.%	C_{Ta}, at.%	Phase
1	59.0	35.7	2.2	3.1	γ
	48.3	46.6	3.4	2.1	σ
	51.0	25.7	11.0	12.3	λ_1

3.5. The Ni–V–Nb–Mo system

The scheme of phase equilibria of the Ni–V–Nb–Mo system at 1375 K was investigated by means of the graph method (Fig. 4).

There are no recombined three-phase equilibria in the total graph of the Ni–V–Nb–Mo system. In this case the total graph is a remaining graph of the third rank (Fig. 5a). The investigation of the four alloys (4–7) of the Ni–V–Nb–Mo system (Table 6) was realized. The composition of the alloy 4 points to the existence four-phase equilibrium between α–β–γ–λ_1 phases. The tetrahedron of this four-phase equilibrium is central in common block of the four-phase equilibria. It consists of one well known equilibrium (α–γ–λ_1) and three unprojected three-phase equilibria (α–β–γ, β–γ–λ_1, α–β–λ_1). These unprojected three-phase equilibria are common sides with three other four-phase equilibria of the Ni–V–Nb–Mo system. In this case the remaining graph can be divided on four following graphs: α–β–δ–γ, α–β–μ–λ_1, α–β–γ–$\lambda_1$and σ–β–γ–λ_1 (Fig. 5f). Alloys 5–7 do not give new information for decomposition of the remaining graph.

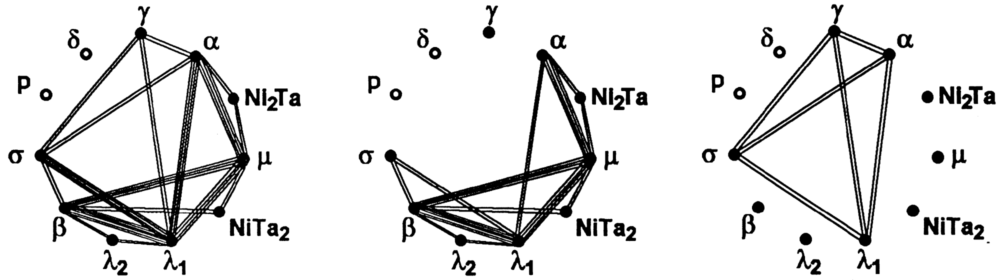

Fig. 2. Total graph (a) of the Ni–V–Nb–Ta system, six recombined three-phase equilibria (b) and remaining graph of the zero rank (c) – four-phase equilibrium $\alpha+\gamma+\lambda+\sigma$.

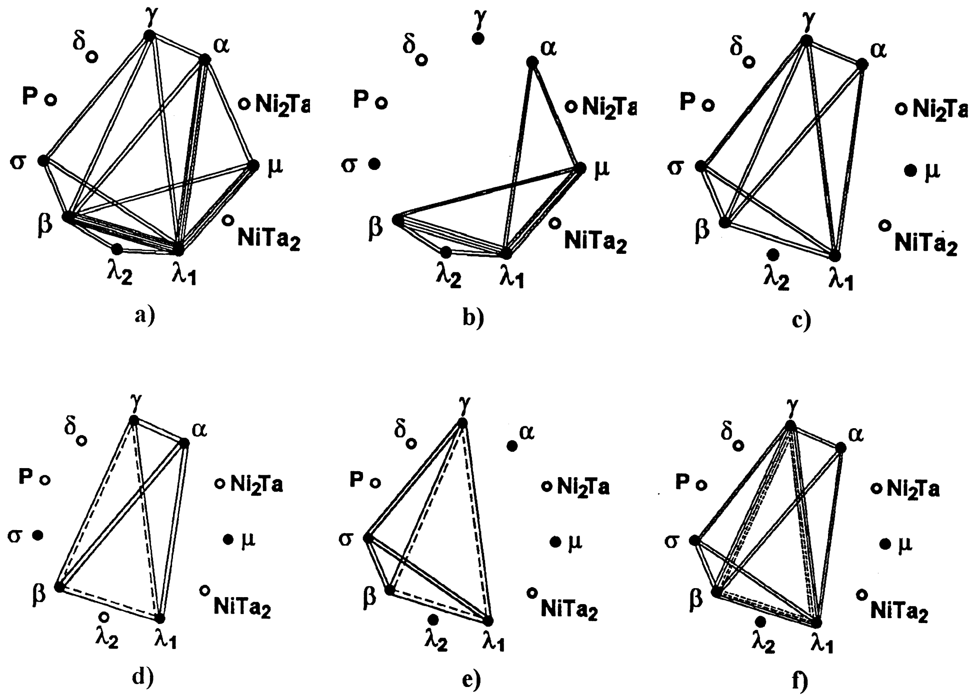

Fig. 3. The total graph (a) of the Ni–V–Nb–Cr system, recombined three-phase equilibria (b), the remaining graph of the first rank (c), its decomposition on the four-phase equilibria (d,e) and the graph of four-phase equilibria Ni–V–Nb–Cr system (f).

3.6. The Ni–V–Nb–W system

The scheme of phase equilibria of the Ni–V–Nb–W system at 1375 K was investigated by means of the graph method. There are no recombined three-phase equilibria in this system. In this case the total graph is a remaining graph of the second rank (Fig. 5a).

The decomposition of the remaining graph by means of alloys 8–10 has been realized. The results of the investigation of the alloys 8–10 are given in Table 7. The four-phase equilibrium α–β–μ–λ_1 forming in the alloy 9 contains two unprojected three-phase equilibria (α–β–λ_1 and β–γ–λ_1). These three-phase equilibria is realized in the alloys 8 and 10 also. It shows that three four-phase equilibria take place (Fig. 5b–d). The central equilibrium (α–β–γ–λ_1) has the common sides with the α–β–μ–λ_1 equilibrium – (α–β–λ_1) and with the σ–β–γ–λ_1 equilibrium – (β–γ–λ_1).

3.7. The Ni–V–Ta–Cr system

The scheme of the phase equilibria of the Ni–V–Ta–Cr system at 1375 K was investigated by means of the graph method. There are two of the same recombined three-phase equilibria λ_1–λ_2–β_1 and λ_1–λ_2–β_2 in the total graph of the Ni–V–Ta–Cr system (Fig. 6b and c). After separation these three-phase equilibria graph decompose in the three remaining graphs: two remaining graphs of the zero rank (Fig. 6d and e) and one remaining graph the first rank. (Fig. 6f). The last graph may decompose only by the experimental investigations.

The results of the investigation of the alloys 11–14 are given in Table 8. The decomposition of the remaining graph of the first rank by means of alloy 11 has been realized. The alloy 11 contains the α, β and σ-phases. There is no equilibrium (α–β–σ) in ternary systems that is unprojected equilibrium. Thus, the remaining graph of the

Table 5
Phase composition and concentration of the elements in the phases of equilibrium alloys for the Ni–V–Nb–Cr system at 1375 K

Alloy No.	C_{Ni}, at.%	C_V, at.%	C_{Nb}, at.%	C_{Cr}, at.%	Phase
2	6.5	25.5	50.0	18.0	β
	55.5	12.8	13.9	17.8	γ
	33.3	25.1	30.2	11.4	λ_1
3	9.8	34.7	0.7	54.8	β
	70.5	16.6	4.0	8.9	γ
	32.0	34.1	4.8	29.1	σ
	29.8	31.5	31.1	7.6	λ_1

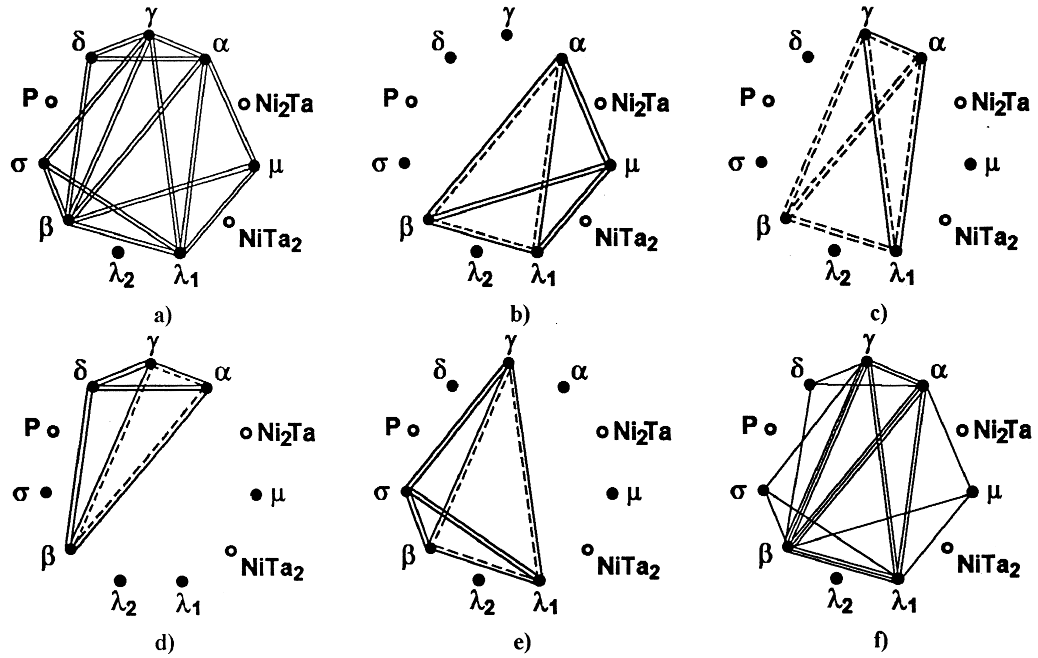

Fig. 4. The total (remaining graph of the third rank) graph three-phase equilibria (a) of the Ni–V–Nb–Mo system, its experimental decomposition on the four-phase equilibria (b–e) and the graph of the four-phase equilibria of the Ni–V–Nb–Mo system (f).

first rank can be decomposed on two four-phase equilibria: α–β–γ–σ and α–β–σ–λ_1 (Fig. 6g and h). The three-phase equilibrium α–β–σ is their common side. The existence of the equilibrium α–μ–λ_1–Ni_2Ta has been confirmed by the phase composition of the alloy 13 (Table 8).

Thus, there are four four-phase equilibria in this system: α–β–γ–σ, α–β–σ–λ_1, α–μ–λ_1–Ni_2Ta and β–μ–λ_1–$NiTa_2$ (Fig. 6i).

3.8. The Ni–V–Ta–Mo system

The scheme of phase equilibria of the Ni–V–Ta–Mo system at 1375 K was investigated by means of the graph

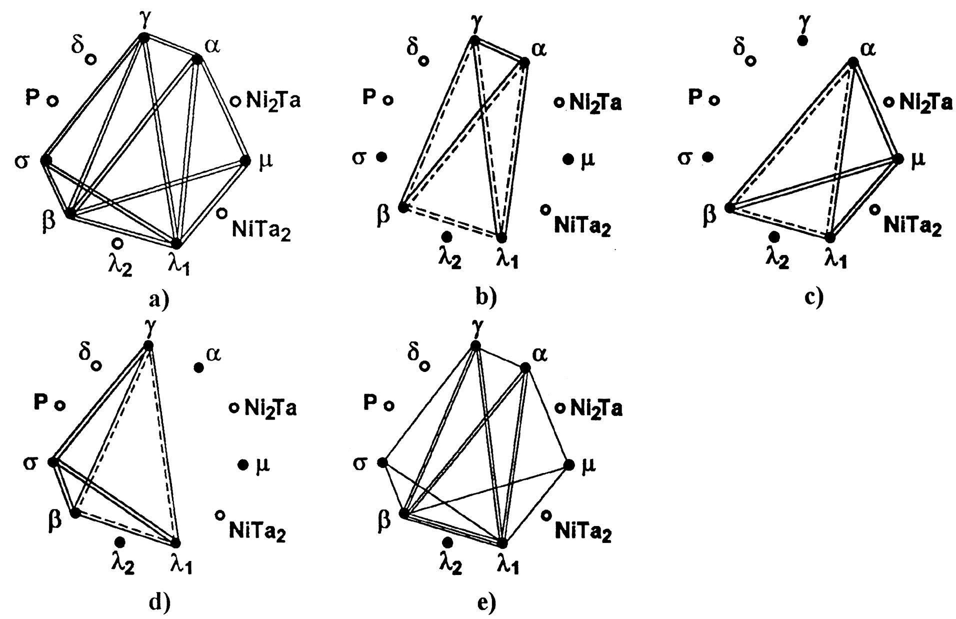

Fig. 5. The total (remaining graph of the second rank) graph (a) of the Ni–V–Nb–W system, its experimental decomposition on the four-phase equilibria (b–d) and the graph of the four-phase equilibria Ni–V–Nb–W system (e).

Table 6
Phase composition and concentration of the elements in the phases of the equilibrium alloys for the Ni–V–Nb–Mo system at 1375 K

Alloy No.	C_{Ni}, at.%	C_V, at.%	C_{Nb}, at.%	C_{Mo}, at.%	Phase
4	76.1	1.9	21.0	1.0	α
	73.6	16.4	4.2	5.8	γ
	1.8	12.3	13.3	72.6	β
	49.0	9.6	23.7	17.7	λ
5	4.8	10.6	38.5	46.1	β
	33.2	13.5	50.0	3.3	μ
	40.7	14.2	38.1	7.0	λ
6	3.8	48.8	5.4	42.0	β
	33.2	48.8	7.0	11.0	σ
	38.5	34.9	18.1	8.5	λ
7	4.4	26.4	12.1	57.1	b
	44.1	20.4	22.8	12.7	μ

method received after exclusion of the recombined equilibria (β–μ–$NiTa_2$ and β–λ_1–λ_2) from the total graph (Fig. 7a) The decomposition of the remaining graph can be carried out only experimentally.

Five alloys were melted and in this system (Table 2). Besides, two diffusion couples were obtained: (1) the three-phase (α+β+δ) alloy with gross composition $Ni_{45}Ta_{15}Mo_{40}$ + vanadium, (2) the two-phase (α+γ) alloy with gross composition $Ni_{85}Ta_{15}$ + the mono-phase (β) alloy with gross composition $V_{50}Mo_{50}$. The phase composition and concentration of the elements in the phases of the alloys are given in Table 9. The unprojected three-phase equilibria (α–β–σ and α–β–γ) have been established by the consequence of the phase layers in the diffusion couple 1 and in the diffusion couple 2.

α+β+δ	α+β	σ+β	β	(1)

α+γ	β+γ	β	(2)

It proves the existence of two four-phase equilibria α–β–γ–σ and α–β–γ–δ (Fig. 7d and e). The phase composition of the alloys 15–18 does not give new information for us. Four-phase equilibrium α–β–μ–Ni_2Ta (alloy 19) contains the unprojected equilibrium α–β–μ. It indicates the existence of the block of four-phase equilibria consisting of five phases: α–β–μ–γ and σ. There is such a block in the Ni–V–Ta–W system and consists of two four-phase equilibria: α–β–λ_1–σ and α–β–λ_1–μ. The first equilibrium exists in the Ni–V–Ta–Cr system and the last equilibrium exists in the Ni–V–Nb–Mo, Ni–V–Nb–W, Ni–Nb–Cr–Mo and Ni–Nb–Cr–W systems. It has aroused speculation that the unprojected three-phase equilibrium α–β–λ_1 exists in the Ni–V–Ta–W system. Thus, the chain from five four-phase equilibria is realised in the system by adding four three-phase equilibria: α–β–μ, α–β–γ, α–β–σ and α–β–λ_1 as shown in Fig. 7i.

3.9. The Ni–V–Ta–W system

The scheme of phase equilibria of the Ni–V–Ta–W system at 1375 K was investigated by means of the graph method. At comparing the total graph of this system (Fig. 8a) and the total graph of the Ni–V–Ta–Mo system (Fig 7a) it is obvious that they are almost similar to each other. The recombined three-phase equilibria are similar: β–μ–$NiTa_2$ and β–λ_1–λ_2 (Fig. 8b). Only the δ-phase is absent on the graph of the Ni–W–Ta–W system, therefore the four-phase equilibrium including this phase is not realised. As results we have the remaining graph of the third rank

Table 7
Phase composition and concentration of the elements in the phases of the equilibrium alloys for the Ni–V–Nb–W system at 1375 K

Alloy No.	C_{Ni}, at.%	C_V, at.%	C_{Nb}, at.%	C_W, at.%	Phase
8	73.5	5.4	20.9	0.2	α
	7.7	14.6	5.1	72.5	β
	51.5	20.3	25.5	2.5	λ_1
9	72.7	5.4	21.9	0.2	α
	2.9	12.5	12.6	72.1	β
	32.9	22.9	38.3	5.9	μ
	51.8	19.5	26.2	2.7	λ_1
10	12.4	11.4	27.2	49.1	β
	66.3	15.2	6.6	11.9	γ
	47.5	14.9	34.9	2.7	λ_1

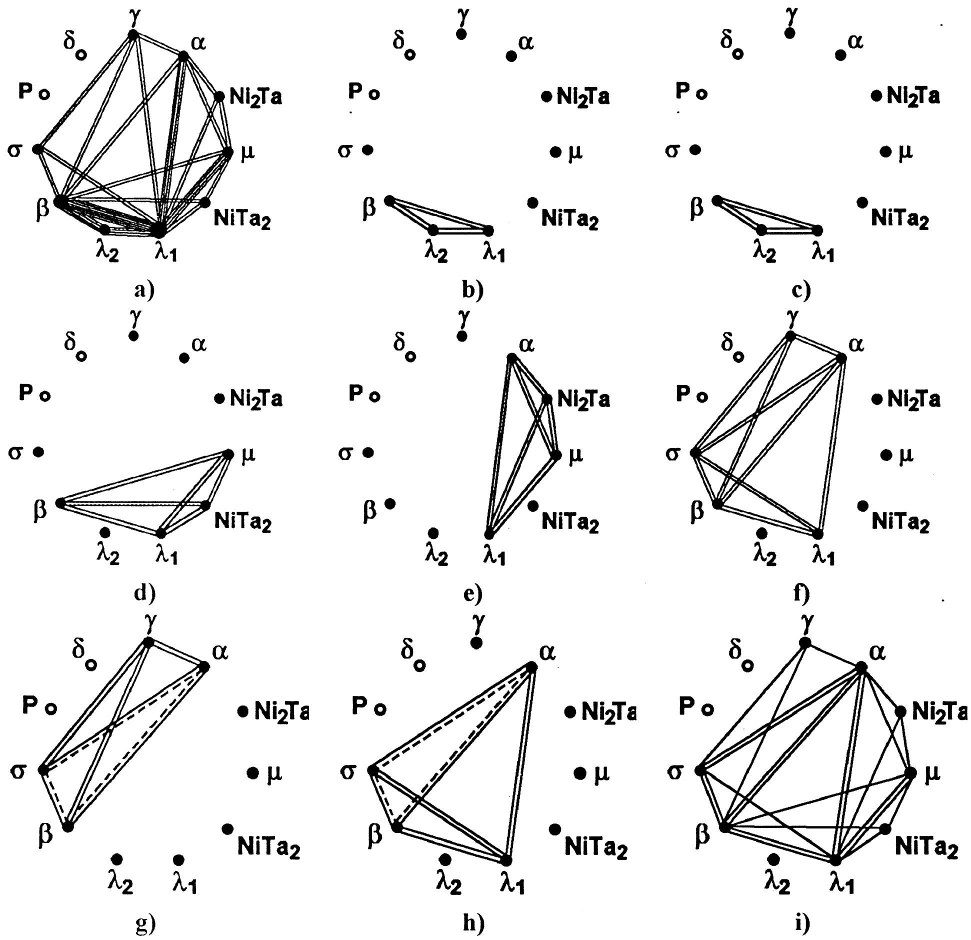

Fig. 6. The total graph three-phase equilibria (a) of the Ni–V–Ta–Cr system, recombined equilibria (b, c), the remaining graphs of the zero rank (d, e), the remaining graphs of the first rank (f), its decomposition on the four-phase equilibria (g, h) and the graph of the four-phase equilibria Ni–V–Ta–Cr system (i).

(Fig. 8c). Thus, in this system four four-phase equilibria α–β–μ–Ni_2Ta, α–β–γ–σ, α–β–μ–λ_1 and α–β–λ_1–σ can exist. The phase composition of the alloys (Table 10) confirms the existence of the chain of the four four-phase equilibria α–β–σ–λ_1, α–β–γ–σ, α–β–μ–λ_1 and α–β–μ–Ni_2Tα. The existence of two unprojected three-phase equilibria α–β–σ and α–β–λ_1 have been confirmed by phase composition of the alloy 21. The alloy 23 contains another unprojected three-phase equilibrium α–β–μ. The alloy 20 contains the recombined three-phase equilibrium β–μ–$NiTa_2$. Phase equilibrium β–μ–λ_1 (alloy 22) correlates to the existence of the equilibrium α–β–μ–λ_1.

Table 8
Phase composition and concentration of the elements in the phases of the equilibrium alloys for the Ni–V–Ta–Cr system at 1375 K

Alloy No.	C_{Ni}, at.%	C_V, at.%	C_{Ta}, at.%	C_{Cr}, at.%	Phase
11	74.2	3.8	20.1	1.9	α
	16.8	19.3	11.3	52.6	β
	36.0	44.2	3.7	17.1	σ
12	32.6	48.7	5.0	13.0	σ
	33.2	13.5	50.0	3.3	λ
13	75.7	0.9	22.7	0.7	α
	57.4	6.1	30.9	5.6	μ
	47.5	11.0	31.1	10.4	λ_1
	65.5	3.0	31.0	1.5	Ni_2Ta
14	2.9	14.7	77.3	5.1	β
	23.5	16.2	48.7	11.6	μ

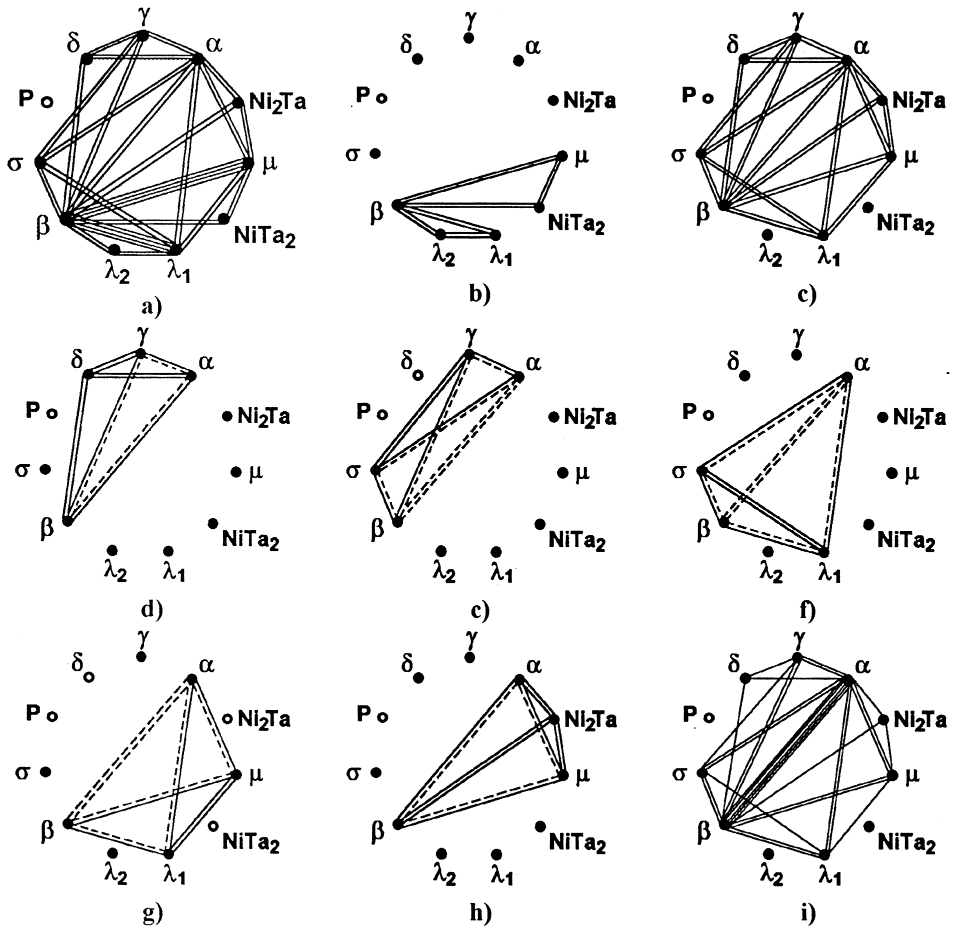

Fig. 7. The total graph (a) of the Ni–V–Ta–Mo system, recombined three-phase equilibria (b), the remaining graph of the fourth rank (c), its decomposition on the four-phase equilibria (d–h) and the graph of the four-phase equilibria Ni–V–Ta–Mo system (i).

3.10. The Ni–V–Cr–Mo system

The scheme of phase equilibria of the Ni–V–Cr–Mo system at 1375 K was investigated earlier by means of the graph method and experimentally [1,3,93]. The total graph (Fig. 9a) decomposes into one recombined graph three-phase equilibrium β–γ–σ (Fig. 9b) and remaining graph of the first rank (Fig. 9c). This graph can be divided on two

Table 9
Phase composition and concentration of the elements in the phase of the alloys for the Ni–V–Ta–Mo system at 1375 K

Alloy No.	C_{Ni}, at.%	C_{V}, at.%	C_{Ta}, at.%	C_{Mo}, at.%	Phase
15	74.5	3.3	20.1	2.1	α
	8.8	9.2	7.3	74.7	β
	39.9	8.2.	10.7	41.2	δ
16	46.7	32.3	17.8	3.2	β
	3.7	59.9	4.6	31.8	$λ_1$
17	3.5	13.7	51.2	29.9	β
	41.7	18.3	35.1	4.9	μ
18	3.1	38.3	5.6	53.0	β
	40.0	42.4	5.4	12.2	σ
	45.0	30.2	14.4	10.5	$λ_1$
19	75.9	1.4	22.4	0.3	α
	5.5	7.8	31.1	55.6	β
	35.7	11.6	48.8	3.9	μ
	50.8	11.2	28.4	9.6	Ni_2Ta

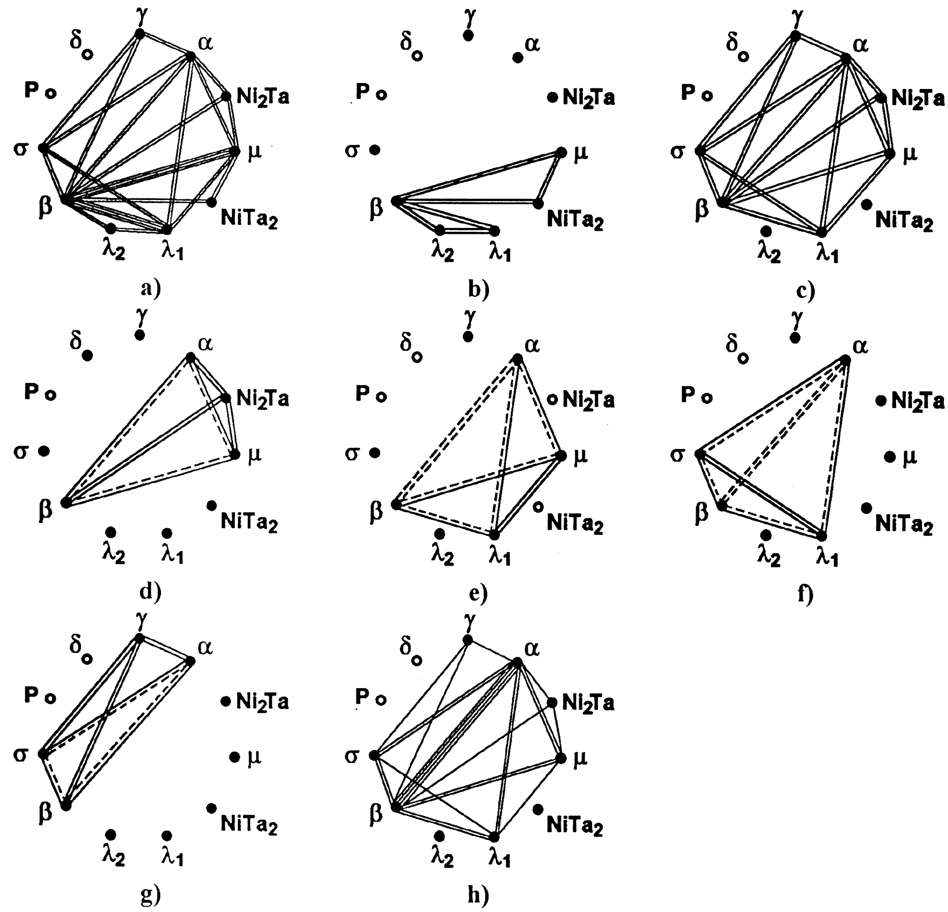

Fig. 8. The total graph (a) of the Ni–V–Ta–W system, recombined three-phase equilibria (b), its the remaining graph of the fourth rank (c), its formal decomposition on the graphs of the four-phase equilibria (d–g) and the graph of the four-phase equilibria Ni–V–Ta–Cr system (h).

graphs of the four-phase equilibrium β–γ–σ–P and β–γ–δ–P (Fig. 9d and e) by adding the three-phase equilibrium β–γ–P (Fig. 9f). The existence of these equilibria has been experimentally confirmed [93].

3.11. The Ni–V–Cr–W system

The scheme of phase equilibria of the Ni–V–Ta–Cr system at 1375 K was investigated by means of the graph

Table 10
Phase composition and concentration of the elements in the phases of the alloys of the Ni–V–Ta–W system at 1375 K

Alloy No.	C_{Ni}, at.%	C_V, at.%	C_{Ta}, at.%	C_W, at.%	Phase
20	1.3	13.6	50.7	34.4	β
	37.0	25.9	36.3	0.8	μ
	29.6	14.9	56.1	0.4	$NiTa_2$
21	73.3	16.3	8.8	1.6	α
	1.8	30.1	3.9	64.4	β
	47.1	44.9	5.4	2.7	σ
	48.7	28.5	20.5	2.3	$λ_1$
22	1.3	8.8	34.1	55.8	β
	34.9	13.4	51.6	0.2	μ
	45.8	20.6	33.2	0.5	$λ_1$
23	72.4	6.2	19.6	1.8	α
	2.2	11.6	20.0	66.8	β
	38.5	12.5	48.0	1.0	μ

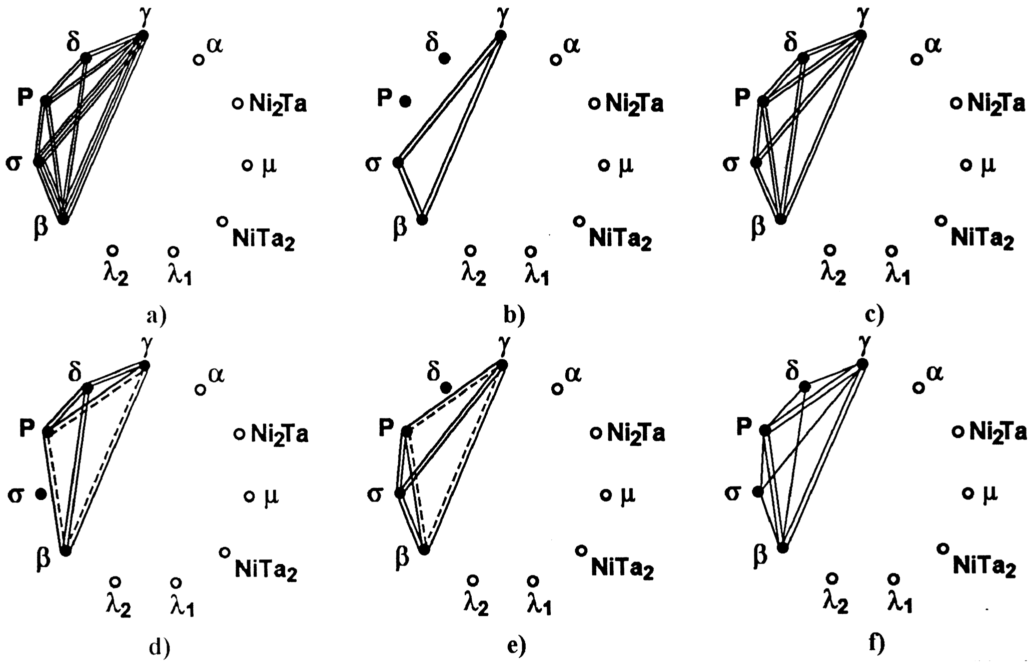

Fig. 9. The total graph (a) of the Ni–V–Cr–Mo system, recombined three-phase equilibrium (b), the remaining graph of the first rank (c), its decomposition on the graphs of the four-phase equilibria 9 (d, e) and the graph of the four-phase equilibria Ni–V–Cr–Mo system (f).

method. There are only three recombined three-phase equilibria in this system (Fig. 10b and c). These phases form the continuous region of the three-phase equilibrium β–γ–σ (from the Ni–V–Cr system to the Ni–V–W system). The four-phase equilibria are absent in the system.

3.12. The Ni–V–Mo–W system

The scheme of phase equilibria of the Ni–V–Mo–W system at 1375 K was investigated by means of the graph method There is also no four-phase equilibrium in the system Ni–V–Mo–W (Fig. 11), despite the fact that here four phases exist. Two recombined three-phase equilibria (β–γ–σ and β–γ–δ) form two three-phase regions in the quaternary system.

3.13. The Ni–Nb–Ta–Cr system

The scheme of phase equilibria of the Ni–Nb–Ta–Cr system at 1375 K was investigated by means of the graph method. The total graph of this system (Fig. 12a) contains four recombined three-phase equilibria: α–β–γ (Fig. 12b), α–β–λ_1 (Fig. 12c), λ_1–λ_2–β_1 and λ_1–λ_2–β_2 (Fig. 12d) and two remaining graphs of the zero rank (four-phase equilibria: α–μ–λ_1–$NiTa_2$ and β–μ–λ_1–$NiTa_2$). Although this variant of decomposition is the only one and does not demand any experimental evidence, two alloys investigated in this system (Table 2). The phases α, μ, λ_1 and Ni_2Ta are in equilibrium (Table 11) in the alloy 24 that reaffirm the obtained variant of decomposition. Alloy 25 does not gave any new information about multiphases equilibria in this system.

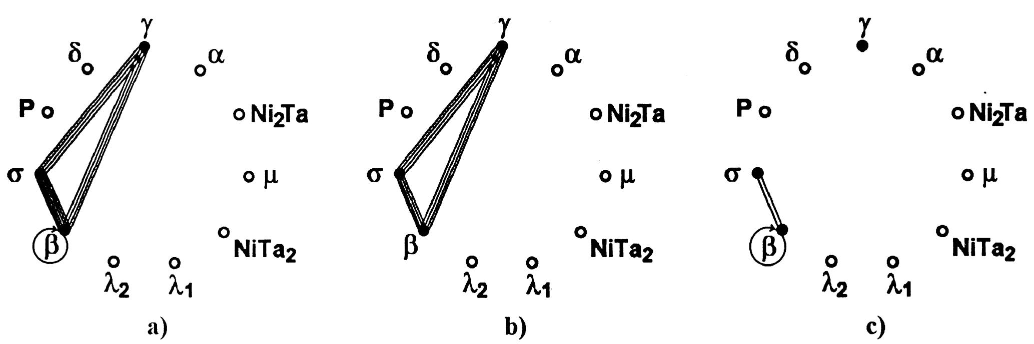

Fig. 10. The total graph of the Ni–V–Cr–W system and three recombined three-phase equilibria (b, c).

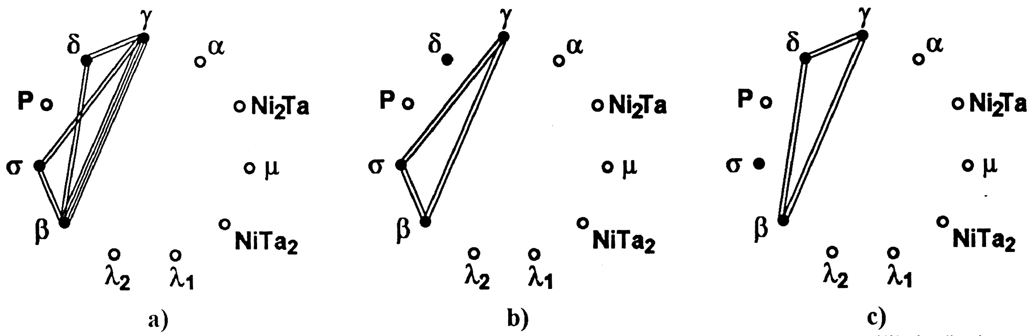

Fig. 11. The total graph of the Ni–V–Mo–W system (a) and recombined three-phase equilibria (b, c).

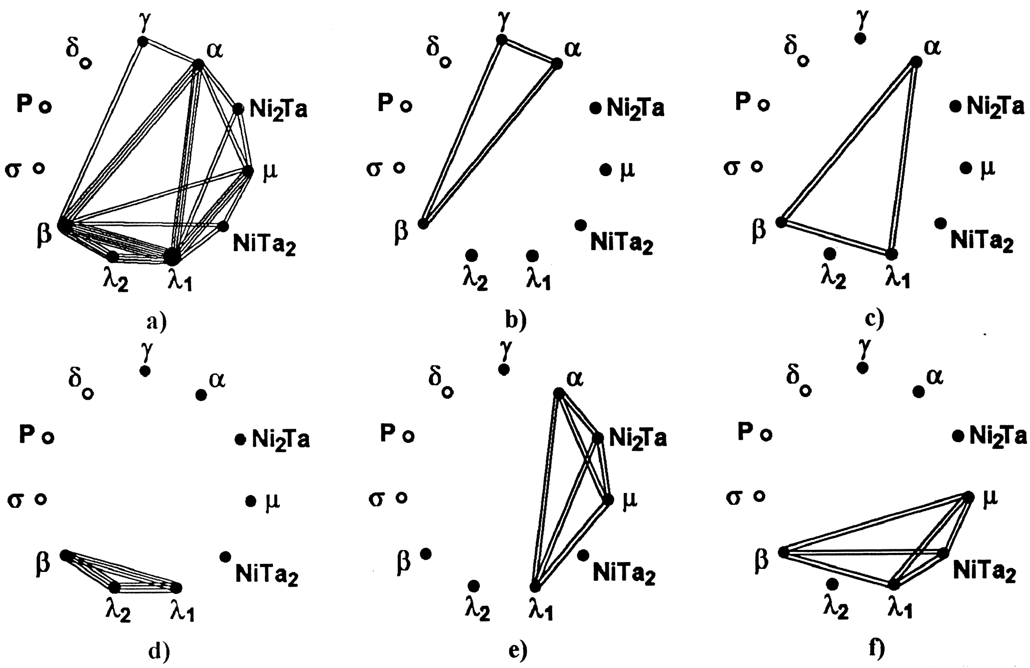

Fig. 12. The total graph (a) of the Ni–Nb–Ta–Cr system, recombined three-phase equilibrium (b–d) and two remaining graphs of the zero rank (e, f).

3.14. The Ni–Nb–Ta–Mo system

The scheme of phase equilibria of the Ni–Nb–Ta–Mo system at 1375 K was investigated by of the graph method. After the separation of three three-phase equilibria α–γ–δ, α–β–δ and β–μ–$NiTa_2$ (Fig. 13b) from the total graph (Fig. 13a) we obtain the graph of the four-phase equilibrium α–β–μ–Ni_2Ta (Fig. 13c). There is no other variant of the decomposition.

The results of polyhedration of the Ni–Nb–Ta–Mo system have been checked by means of equilibrium alloys. The alloy 26 of this system contains all phases, which take part in the formation of the equilibrium α–β–μ–Ni_2Ta (Table 12).

Table 11
Phase composition of the alloys and concentration of the elements in the phases of the Ni–Nb–Ta–Cr system at 1375 K

Alloys No.	C_{Ni}, at.%	C_{Nb}, at.%	C_{Ta}, at.%	C_{Cr}, at.%	Phase
24	75.1	13.6	10.2	1.1	α
	31.7	25.3	39.5	3.5	μ
	50.7	16.8	18.9	13.6	$λ_1$
	60.5	12.5	22.5	4.5	Ni_2Ta
25	3.3	40.2	52.9	3.5	β
	18.4	37.9	12.3	31.5	μ

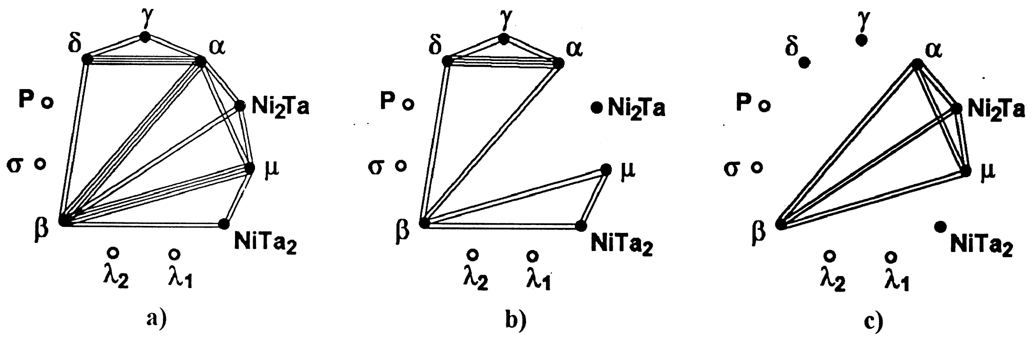

Fig. 13. The total graph (a) of the Ni–Nb–Ta–Mo system, three recombined three-phase equilibria (b) and the remaining graph of the zero rank (c).

Table 12
Phase composition and concentration of the elements in the phases of the alloys in the Ni–Nb–Ta–Mo system at 1375 K

Alloy No.	C_{Ni}, at.%	C_{Nb}, at.%	C_{Ta}, at.%	C_{Mo}, at.%	Phase
26	73.6	10.8	15.2	0.4	α
	5.9	21.2	23.8	49.1	β
	52.9	22.7	17.7	6.7	μ
	66.1	14.9	16.3	2.6	Ni_2Ta

3.15. The Ni–Nb–Ta–W system

The scheme of phase equilibria of the Ni–Nb–Ta–W system at 1375 K was investigated by means of the graph method. The polyhedration of this system is similar to polyhedration of the Ni–Nb–Ta–Mo system.

After the separation of two three-phase equilibria (α–β–γ and β–μ–$NiTa_2$) we obtain the graph of the zero rank corresponding to four-phase equilibrium α–β–μ–Ni_2Ta. There is no other variant of the decomposition (Fig. 14). The results of the polyhedration of the Ni–Nb–Ta–W system have been checked by means of equilibrium alloys. As in the case for the system Ni–Nb–Ta–Mo, the phase composition of the alloy 27 (Table 13) proves the existence of the single four-phase equilibrium α–β–μ–Ni_2Ta in this system.

3.16. The Ni–Nb–Cr–Mo system

The scheme of phase equilibria of the Ni–Nb–Cr–Mo system at 1375 K was investigated by means of the graph method. We can separate the total graph (Fig. 15a) of this

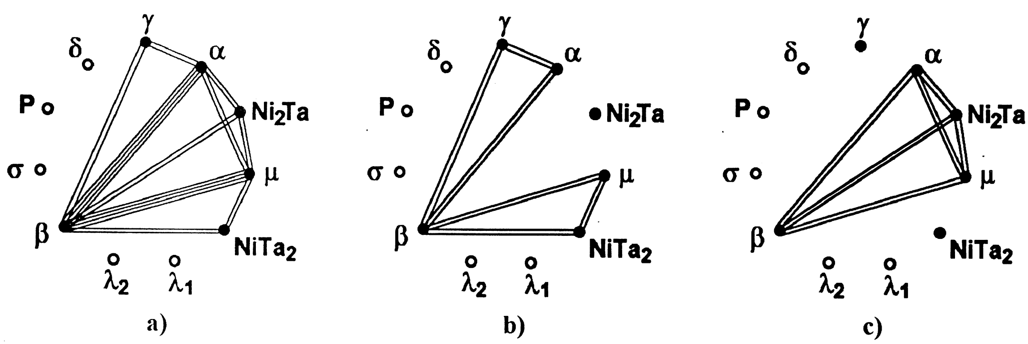

Fig. 14. The total graph (a) of the Ni–Nb–Ta–W system, two recombined three-phase equilibria (b) and the remaining graph of the zero rank (c).

Table 13
Phase composition and concentration of the elements in the phases of the alloys of the Ni–Nb–Ta–W system at 1375 K

Alloy No.	C_{Ni}, at.%	C_{Nb}, at.%	C_{Ta}, at.%	C_{W}, at.%	Phase
27	74.4	9.7	15.7	0.2	α
	11.4	10.9	23.3	54.5	β
	51.3	24.1	20.3	4.3	μ
	65.5	31.9	2.3	0.3	Ni_2Ta

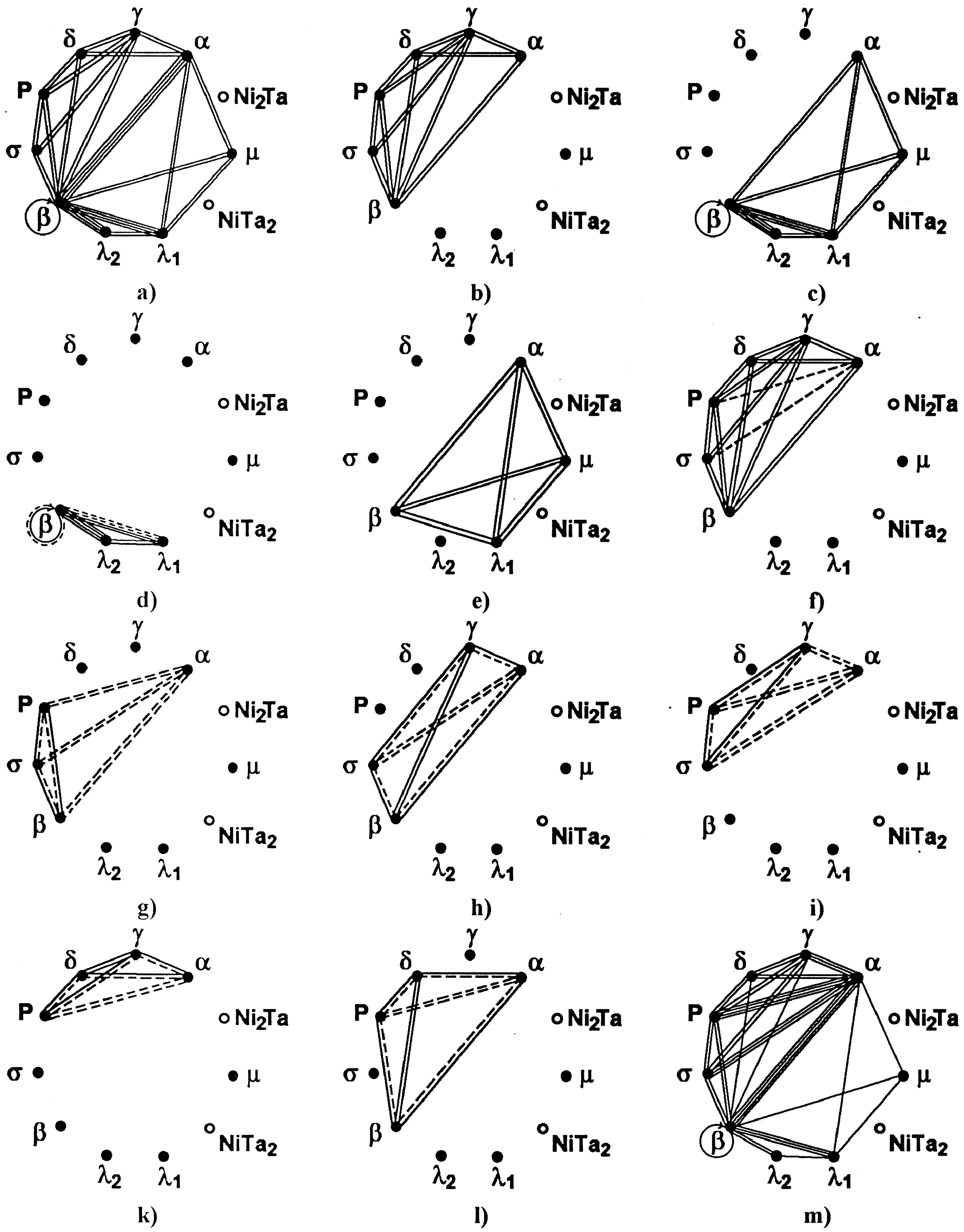

Fig. 15. The total graph (a) of the Ni–Nb–Cr–Mo system, two remaining graphs of the second rank (b, c), decomposition of the remaining graph (b) on the graphs of the four-phase equilibria (d, e, g–l) and graph of the four-phase equilibria (b–e) in the Ni–Nb–Cr–Mo system (m).

system on two remaining graphs: the graph of the second rank (Fig. 15b) and very surprisingly the graph of the second rank including three edges between λ_1 and λ_2 phases (Fig. 15c). This case is connected with degeneration of the β-phase. There is unprojected three-phase equilibrium β_1–β_2–λ_2 degenerating into two-phase equilibrium β–λ_2. Adding this equilibrium to the graph Fig. 15c we can divide it into two remaining graphs of the zero rank (Fig. 15d and e). The remaining graph Fig. 15b may decompose only by the experimental investigations. The results of polyhedration of the Ni–Nb–Cr–Mo system have been checked by means of equilibrium alloys (Table 14) and one diffusion couples.

According to data given in Table 14 there are two unprojected two-phase equilibria: α–P and α–σ (Fig. 15f). The unprojected equilibria: α–γ–P, α–γ–σ, α–β–σ, α–σ–P were determined by means of alloys (alloys 30–33). Besides, the consequence of the phase layers formed in the

Table 14
Phase composition and concentration of the elements in the phases of the alloys of Ni–Nb–Cr–Mo system at 1375 K

Alloy No.	C_{Ni}, at.%	C_{Nb}, at.%	C_{Cr}, at.%	C_{Mo}, at.%	Phase
28	6.9	48.5	7.6	37.0	β
	37.2	40.3	14.8	7.7	μ
	42.0	12.4	26.4	19.2	λ_1
29	5.7	16.1	16.2	62.0	β
	41.4	18.2	28.7	11.7	λ_1
30	77.5	18.9	1.7	1.8	α
	47.4	12.0	16.1	24.4	P
	60.3	19.7	7.2	12.8	γ
	74.9	21.7	1.4	2.0	α
31	4.4	10.5	6.7	78.4	β
	39.7	13.3	35.3	11.7	σ
32	71.9	17.3	8.4	2.4	α
	40.6	3.5	40.5	15.4	σ
	45.3	5.0	14.8	34.9	P
33	72.2	21.7	4.3	1.8	α
	62.6	4.1	24.9	8.5	γ
	40.5	7.2	32.7	19.6	σ

diffusion couples composed of $Ni_{70}Mo_{30}$ two-phase (δ + γ) alloy and $Nb_{60}Cr_{40}$ mono-phase (b) alloy is the following:

δ+γ	P	α+P	P+β	β+α	μ	β+μ	β

Hence it appears that the equilibrium α–β–P exists in this system. After addition this five unprojected three-phase equilibria to the remaining graph we have three four-phase equilibria: α–P–γ–δ, α–P–β–σ, α–β–γ–σ (Fig. 15g–i) and the remaining graph of the first rank consisting of α, β, γ, δ and P This graph decomposes into two four-phase equilibria α–β–δ–P and α–γ–δ–P (Fig. 15k and l). The other variant of the decomposition demands the existence of the equilibrium β–γ. It is impossible that is explained by geometric ban.

Thus, it is single variant is decomposition of the total graph on seven graphs of four-phase equilibria: α–γ–σ–P, α–β–γ–P, α–β–γ–δ, α–P–γ–σ, α–P–β–σ, $-\beta_1-\beta_2-\lambda_1-\lambda_2$ and $\alpha-\beta-\mu-\lambda_1$ (Fig. 15m).

3.17. The Ni–Nb–Cr–W system

The scheme of phase equilibria of the Ni–Nb–Cr–W system at 1375 K was investigated by means of the graph method. There are the same equilibria in this system as in the Ni–Nb–Cr–Mo system with the exception of equilibria consisting of P- and δ-phase (Fig. 16a). There is the same equilibrium between the α- and σ-phase (Fig. 16b). The recombined three-phase equilibria does not form, so as equilibrium $\beta_1-\beta_2$ of system Nb–Cr–W not degenerates in four system. Two regions β-phase form in the system Ni–Nb–Cr–W–β_1 (Cr) and β_2 (Nb, W). As results, three-phase equilibrium $\alpha-\beta_1-\lambda_1$ from system Ni–Nb–Cr does not take part in the formation of the four-phase equilibrium $\alpha-\beta_2-\mu-\lambda_1$. The four-phase equilibrium $\alpha-\beta_2-\mu-\lambda_1$ excludes from the total graph by addition of the unprojected three-phase equilibrium $\alpha-\beta_2-\lambda_1$ (Fig. 16c). The second four-phase equilibrium $\beta_1-\beta_2-\lambda_1-\lambda_2$ excludes from the total graph by addition of the unprojected three-phase equilibrium $\beta_1-\beta_2-\lambda_1$ to the total graph (Fig. 16d). In contrast to the Ni–Nb–Cr–Mo system the equilibrium $\beta_1-\beta_2-\lambda_1$ does not degenerate into the two-phase equilibrium $\beta_1-\lambda_1$. The remaining graph of the first rank (Fig 16e) decomposes in the following way. The equilibrium $\alpha-\beta_1-\lambda_1$ from system Ni–Nb–Cr and two unprojected three-phase equilibria $\beta_1-\beta_2-\lambda_1$and $\alpha-\beta_2-\lambda_1$ after addition of the unprojected three-phase equilibrium $\alpha-\beta_1-\beta_2$ form the four-phase equilibrium $\alpha-\lambda_1-\beta_1-\beta_2$ (Fig. 16f). The equilibrium $\sigma-\beta_1-\beta_2$ from system Ni–W–Cr and unprojected three-phase equilibrium $\alpha-\beta_1-\beta_2$ after addition of the two unprojected three-phase equilibria $\alpha-\sigma-\beta_1$ and $\alpha-\sigma-\beta_2$ form the four-phase equilibrium $\alpha-\sigma-\beta_1-\beta_2$ (Fig. 16g). Equilibria $\sigma-\gamma-\beta_1$ and $\sigma-\gamma-\beta_2$ in the system Ni–Cr–W as well as the equilibrium $\alpha-\gamma-\beta_1$ (system Ni–Nb–Cr) and the equilibrium $\alpha-\gamma-\beta_2$ (system Ni–Nb–W) with unprojected three-phase equilibria $\alpha-\sigma-\beta_1$ and $\alpha-\sigma-\beta_2$ form two four-phase equilibria ($\sigma-\alpha-\gamma-\beta_1$ and $\sigma-\alpha-\gamma-\beta_2$) as shown in Fig. 16h and i.

The results of polyhedration of the Ni–Nb–Cr–W system have been checked by means of alloys and diffusion couples. In the diffusion couple composed of the $Ni_{55}Nb_{35}Cr_{10}$ three-phase ($\alpha + \mu + \lambda_1$) alloy and tungsten the following sequence of the diffusion layers exists:

$\alpha+\mu+\lambda_1$	β

The formation of a new phase in the diffusion zone is not

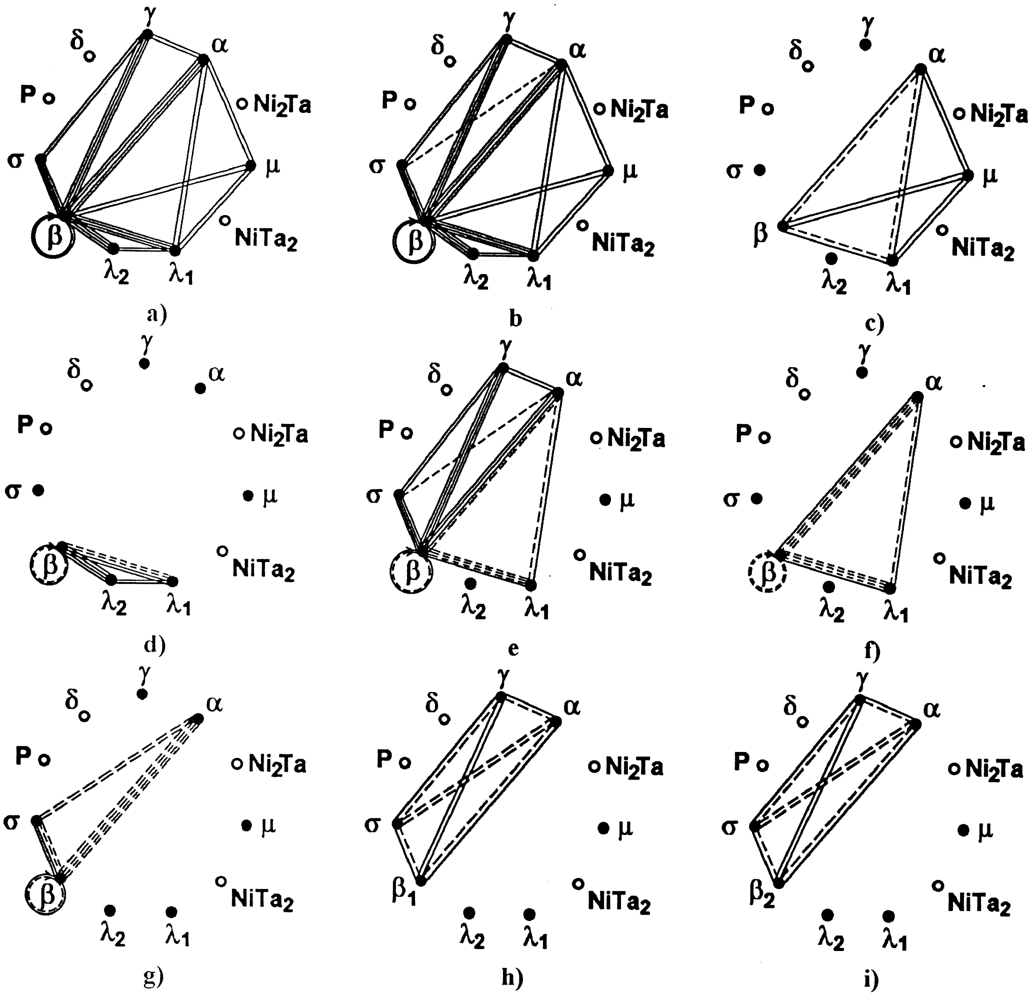

Fig. 16. The total (remaining) graph (a) of the Ni–Nb–Cr–W system, remaining graphs of the zero rank (b, c), remaining graph of the first rank (d) and its decomposition into graphs of the four-phase equilibria (f–i).

observed. Therefore, the equilibrium α–β–μ–λ_1 presents in this system. The phase composition of the alloy 34 (Table 15) does not give new information.

Decomposition of the remaining graph was not checked, so as the four-phase equilibria from this graph in the more complex systems recombine and degenerate, with the exception of the equilibrium σ–α–γ–β.

3.18. The Ni–Nb–Mo–W system

The scheme of phase equilibria of the Ni–Nb–Mo–W system at 1375 K was investigated by means of the graph method. The analysis of the total-graph (Fig. 17a) of this system shows that only one variant of the polyhedration is possible. As a result there are three-phase recombined equilibrium α–β–μ (Fig. 17b) and four-phase equilibrium α–β–γ–δ (Fig. 17c).

The results of polyhedration of the Ni–Nb–Mo–W system have been checked by means of equilibrium alloys and diffusion couples. The four-phase equilibrium (α–β–γ–δ) has been completely defined by the sequence of the diffusion layers after the annealing of the diffusion couple composed of the $Ni_{70}Nb_{23}Mo_7$ two-phase (α + γ) alloy and tungsten:

α+γ	α+γ+δ	β

The phase composition of the alloy 35 (Table 16) does not give new information.

Table 15
Phase composition and concentration of the elements in the phases of the alloys of the Ni–Nb–Cr–W system at 1375 K

Alloy No.	C_{Ni}, at.%	C_{Nb}, at.%	C_{Cr}, at.%	C_W, at.%	Phase
34	2.2	6.6	26.8	66.4	β
	41.4	47.4	10.1	1.1	μ
	21.1	23.9	42.8	12.2	λ_1

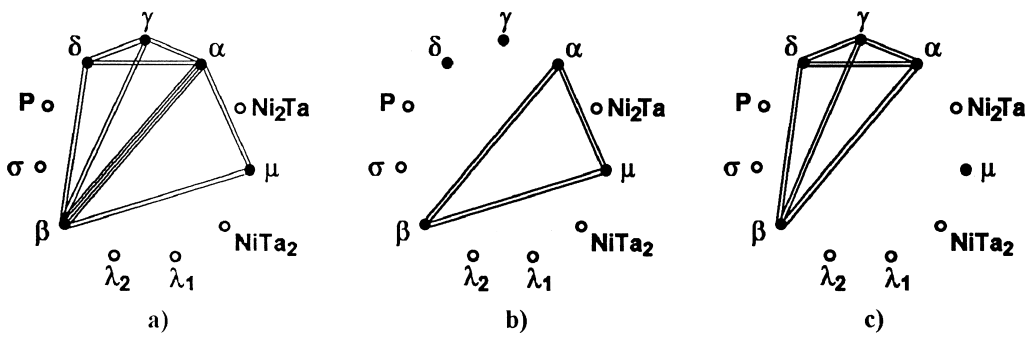

Fig. 17. The total graph (a) of the Ni–Nb–Mo–W system, recombined three-phase equilibrium (b) and the graph of the four-phase equilibrium (c).

Table 16
Phase composition and concentration of the elements in the phases of the alloy of the Ni–Nb–Mo–W system at 1375 K

Alloy No.	C_{Ni}, at.%	C_{Nb}, at.%	C_{Mo}, at.%	C_{W}, at.%	Phase
35	4.0	5.9	25.5	64.6	β
	70.9	6.6	14.3	8.2	γ
	44.6	5.3	47.2	2.9	δ

3.19. The Ni–Tα–Cr–Mo system

The scheme of phase equilibria of the Ni–Ta–Cr–Mo system at 1375 K was investigated by means of the graph method. From the total graph (Fig. 18a) received three remaining graphs (Fig. 18b–d) by addition of the unprojected three-phase equilibrium λ_1–β_1–β_2 as in the system Ni–Nb–Cr–Mo.

Means equilibrium alloys have checked the results of polyhedration of the Ni–Ta–Cr–Mo system. The phase composition of the alloys of this system is given in Table 17.

The remaining graphs (Fig. 18c and d) are completely similar to the same graphs in the Ni–Nb–Cr–Mo system. Also there is unprojected three-phase equilibrium β_1–β_2–λ_2 degenerating into two-phase equilibrium β–λ_2. The remaining graph (Fig. 18d) consists of five four-phase equilibria (α–β–δ–P, α–γ–δ–P, α–γ–σ–P, α–β–σ–P and α–β–γ–σ). The same solution follows from the investigation of the alloys 39–42. Alloy 43 does not give new information. Alloys 36–38 do not give new information about equilibria in the remaining graph Fig. 18b. However, the remaining graph Fig. 18b is completely similar to the same graphs in the Ni–Ta–Cr–W system (Fig. 19f). From here we have, the chain of three four-phase equilibria

Table 17
Phase composition and concentration of the elements in the phases of the alloys of the Ni–Ta–Cr–Mo system at 1375 K

Alloy No.	C_{Ni}, at.%	C_{Ta}, at.%	C_{Cr}, at.%	C_{Mo}, at.%	Phase
36	72.5	23.2	3.1	1.3	α
	35.8	41.7	15.5	7.0	λ_1
	67.2	32.3	0.3	0.2	Ni_2Ta
37	3.9	56.8	7.1	32.2	β
	41.1	42.3	11.8	4.8	μ
	40.0	21.8	32.2	6.0	λ_1
38	31.1	65.2	3.5	0.2	$NiTa_2$
	6.2	45.3	10.3	38.2	1β
39	73.3	19.2	4.8	2.7	α
	42.2	6.2	20.4	31.2	P
40	73.6	20.2	2.0	4173.6	α
	2.4	3.9	7.3	86.3	β
	42.3	6.2	15.8	35.7	P
41	74.9	17.1	4.9	5.1	α
	63.3	1.4	29.6	5.7	γ
	39.0	1.1	42.1	18.8	α
42	74.1	20.0	2.8	3.5	α
	63.8	13.8	8.3	14.0	7
	41.2	6.1	19.9	32.9	P
43	5.4	65.1	28.2	1.3	β
	40.7	17.6	27.1	14.7	σ
	42.0	6.4	22.2	29.4	P

Table 18
Phase composition and concentration of the elements in the phases of the alloys of the Ni–Ta–Cr–W system at 1375 K

Alloy No.	C_{Ni}, at.%	C_{Ta}, at.%	C_{Cr}, at.%	C_{W}, at.%	Phase
44	2.2	26.5	19.0	53.3	β
	34.5	21.2	37.8	6.5	λ_1
	66.3	32.6	1.2	0.2	Ni_2Ta
45	1.9	10.6	30.3	67.2	β
	35.4	50.1	12.4	2.1	μ
	26.9	16.9	48.4	7.8	λ_1
	31.1	64.2	4.4	0.3	$NiTa_2$
46	72.2	19.0	7.2	1.6	α
	19.2	27.2	37.0	16.6	λ_1

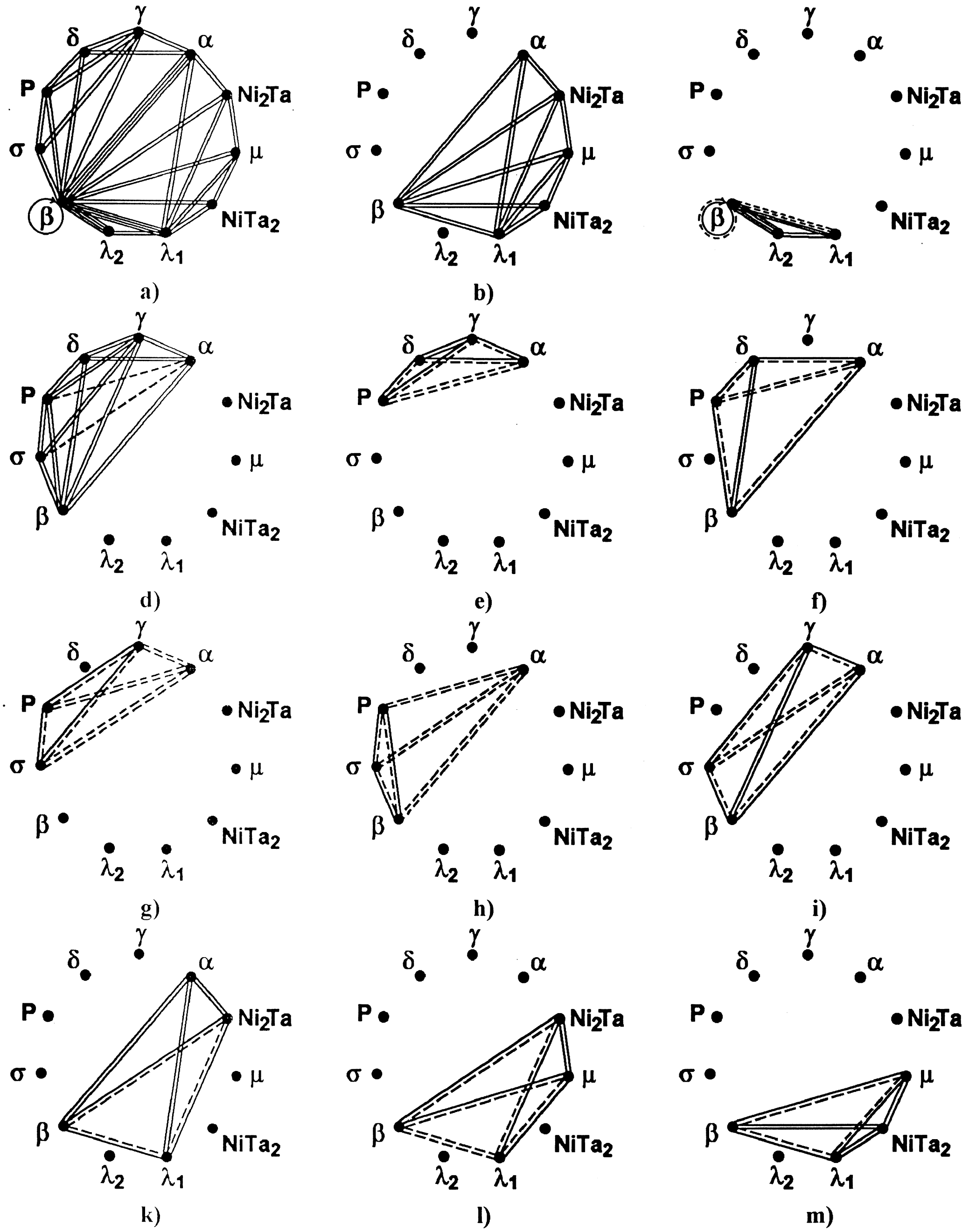

Fig. 18. The total graph (a) of the Ni–Ta–Cr–Mo system, remaining graphs of the second rank (b), zero rank (c), first rank (d) and decomposition of these graphs in the graphs of the four-phase equilibria (e–m).

α–β–λ_1–Ni_2Ta, β–μ–λ_1–Ni_2Ta and β–μ–λ_1–$NiTa_2$ in the system Ni–Ta–Cr–Mo (Fig. 18k–m).

Thus, the polyhedration of this total graph gives the single variant of the decomposition on nine four-phase equilibria: β_1–β_2–λ_1–λ_2, α–β–δ–P, α–γ–δ–P, α–γ–σ–P, α–β–σ–P, α–β–γ–σ, α–β–λ_1–Ni_2Ta, β–μ–λ_1–Ni_2Ta and β–μ–λ_1–$NiTa_2$.

3.20. The Ni–Ta–Cr–W system

The scheme of phase equilibria of the Ni–Ta–Cr–W system at 1375 K was investigated by means of the graph method. The total graph (Fig. 19a) has to contain equilibrium α–σ (Fig. 19b) and decomposes into three remaining graphs as in the system Ni–Nb–Cr–W. The four-phase equilibrium β_1–β_2–λ_1–λ_2, (Fig. 19c) excludes from the total graph by addition of the unprojected three-phase equilibrium β_1–β_2–λ_1 to the total graph.

The remaining graph of the second rank (Fig. 19d) excludes from the total graph by addition of the unprojected three-phase equilibrium α–β_2–λ_1. The third remaining graph is the same as in the system Ni–Nb–Cr–W and

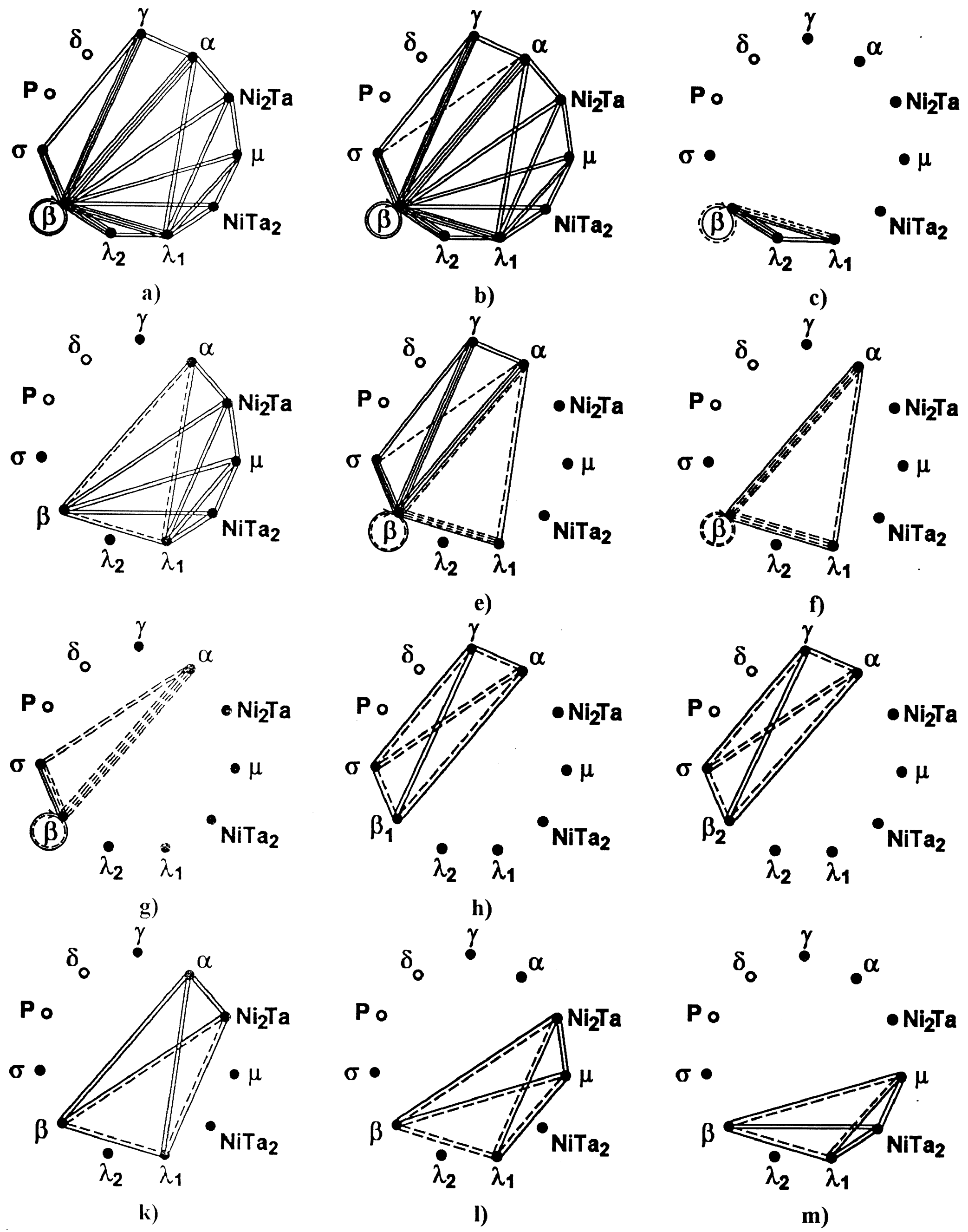

Fig. 19. The total graph of the Ni–Ta–Cr–W system (a, b), remaining graphs of the zero (c), second (d) and first rank (e), decomposition remaining graph (d) into four-phase equilibria (f–i) and decomposition of the remaining graph of the first rank (k–m).

contains four equilibria (Fig. 19e–h). The remaining graph of the second rank (Fig. 19d) may be decomposed only experimentally.

The results of polyhedration of the Ni–Ta–Cr–W system have been checked by means of equilibrium alloys. The phase composition of the alloys of this system is given in Table 18. The alloy 45 contains the four-phase equilibrium β–μ–λ_1–$NiTa_2$ and the alloy 44 – unprojected equilibrium β–λ_1–Ni_2Ta. The unprojected equilibrium β–λ_1–Ni_2Ta (alloy 44) is common to the two tetrahedrons of the four-phase equilibria α–β–λ_1–Ni_2Ta and β–μ–λ_1–Ni_2Ta. It shows that the chain of the four-phase equilibrium exists in this system: α–β–λ_1–Ni_2Ta, β–μ–λ_1–Ni_2Ta and β–μ–λ_1–$NiTa_2$ (Fig. 19k–m).

3.21. The Ni–Ta–Mo–W system

The scheme of phase equilibria of the Ni–Ta–Mo–W system at 1375 K was investigated by means of the graph method. After the separation the three recombined three-phase equilibria β–α–Ni_2Ta, β–μ–$NiTa$ and β–μ–$NiTa_2$ (Fig. 20b) from the total graph (Fig. 20a) of this system

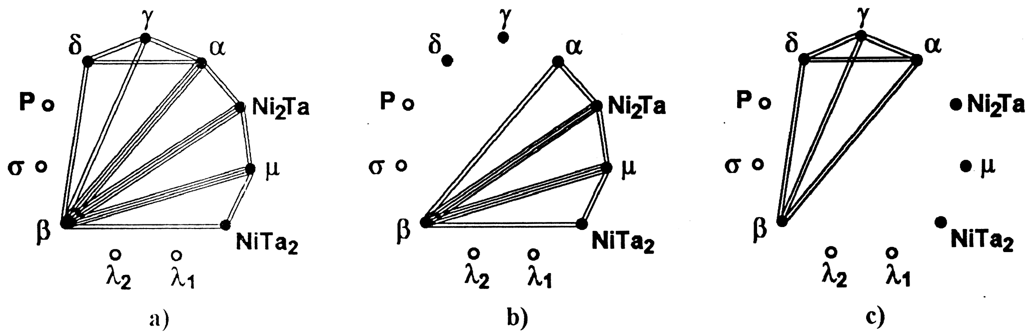

Fig. 20. The total graph (a) of the Ni–Ta–Mo–W system, three recombined three-phase equilibria (b) and the remaining graph of the zero rank (c).

one graph of the zero rank corresponding to α–β–γ–δ equilibrium remains (Fig. 20c).

The results of polyhedration of the Ni–Ta–Mo–W system have been checked by means of diffusion couples. After annealing of the diffusion couple composed of the $Ni_{75}Ta_{15}Mo_{10}$ three-phase (α–γ–δ) alloy and tungsten, the following sequence of the layers of phases is formed:

α+γ+δ	β+δ	β

This sequence of the phase layers points to the existence of the four-phase equilibrium α–β–γ–δ in this system.

3.22. The Ni–Cr–Mo–W system

The scheme of phase equilibria of the Ni–Cr–Mo–W system at 1375 K was investigated by means of the graph method. In this system two ternary σ-phases of the systems Cr–Mo–Ni and Cr–W–Ni exist. These phases form the mutually continuous sequence of the solid solutions in the quaternary system.

At the decomposition of the total graph (Fig. 21a) we have recombined three-phase equilibrium: β–γ–σ (Fig. 21b) and three-phase equilibrium β_1–β_2–σ degenerating into two-phase equilibrium β–σ, (Fig. 21c) and also the remaining graph of the first rank (Fig. 21d). The results of polyhedration of the Ni–Cr–Mo–W system have been checked by means of equilibrium alloys. The phase composition of the alloys of this system is given in Table 19.

The phase composition of the alloy 47 confirms the existence of the unprojected three-phase equilibrium β–γ–P, which is general for the tetrahedrons β–γ–δ–P and β–γ–σ–P. At the decomposition of the remaining graph

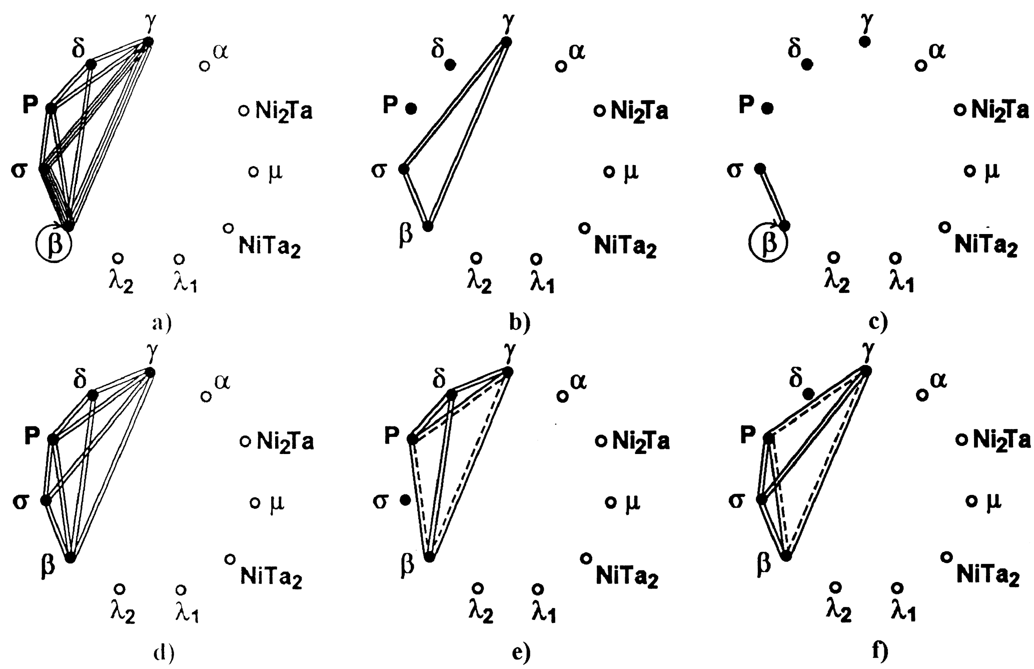

Fig. 21. The total graph (a) of the Ni–Cr–Mo–W system, recombined three-phase equilibrium (b), degenerating three-phase equilibrium (c), remaining graph (d) and its decomposition on the graphs of the four-phase equilibria (e, f).

Table 19
Phase composition and concentration of the elements in the phases of the alloys of the Ni–Cr–Mo–W system at 1375 K

Alloys No.	C_{Ni}, at.%	C_{Cr}, at.%	C_{Mo}, at.%	C_W, at.%	Phase
47	6.2	11.2	56.3	26.3	β
	62.1	30.1	7.0	0.8	γ
	40.5	20.1	34.5	4.9	P
48	7.7	10.6	55.1	26.6	β
	33.1	39.9	8.8	18.2	σ
	31.3	25.5	40.1	3.1	P

the unprojected three-phase equilibrium β–γ–P has been added (Fig. 21e and f). The phase composition of the alloy 48 does not give new results.

The established four-phase equilibria of the quaternary systems on the basis of nickel and transition metals of the V–VI groups are given in Table 20.

3.23. The phase equilibria in the Ni–V–Nb–Ta–Cr–Mo–W system

The five-phase equilibria in quinary systems that form the seven-component system Ni–V–Nb–Ta–Cr–Mo–W, can be obtained on the basis of the analysis of the blocks of the experimentally established four-phase equilibria of the quaternary systems. The single variant of the five-phase equilibria and the recombined four-phase equilibria in the quinary systems is given in Table 21.

The results of polyhedration of the six-component systems on the basis of nickel and transition metals of the V–VI groups at 1375 K are given in Table 22.

Table 20
The results of the experimental polyhedration of the quaternary systems on the basis of nickel and transition metals of the V–VI groups

No.	System	Phase	Established four-phase equilibria
1	Ni–V–Nb–Ta	α, β, γ, σ, μ, λ_1, λ_2, Ni_2Ta, $NiTa_2$	α–σ–γ–λ_1
2	Ni–V–Nb–Cr	α, β, γ, σ, μ, λ_1,λ_2,	α–β–γ–λ_1, σ–β–γ–λ_1,
3	Ni–V–Nb–Mo	α, β, γ, δ, σ, μ, λ_1,	α–β–γ–δ, α–β–μ–λ_1, β–γ–σ–λ_1, 0α–β–γ–λ_1
4	Ni–V–Nb–W	α, β, γ, σ, μ, λ_1,	α–β–γ–λ_1, α–β–μ–λ_1, α–β–γ–λ_1
5	Ni–V–Ta–Cr	α, β, γ, σ, μ, λ_1,λ_2, $Ni_2T\alpha$, $NiTa_2$	α–β–γ–σ, α–β–σ–λ_1, α–μ–λ_1–Ni_2Ta, β–μ–λ_1–$NiTa_2$
6	Ni–V–Ta–Mo	α, β, γ, δ, σ, μ, λ_1,λ_2, Ni_2Ta, $NiTa_2$	α–β–γ–δ, α–β–σ–λ_1, α–β–μ–λ_1, α–β–γ–σ, α–β–μ–Ni_2Ta
7	Ni–V–Ta–W	α, β, γ, σ, μ, λ_1, λ_2, Ni_2Ta, $NiTa_2$	α–β–γ–σ, α–β–σ–λ_1, α–β–μ–λ_1, α–β–μ–Ni_2Ta
8	Ni–V–Cr–Mo	β, γ, δ, σ, P	β–γ–σ–P, β–γ–δ–P
9	Ni–V–Cr–W	β, γ, σ	–
10	Ni–V–Mo–W	β, γ, δ, σ	–
11	Ni–Nb–Ta–Cr	α, β, γ, μ, λ_1,λ_2, Ni_2Ta, $NiTa_2$	α–μ–λ_1–Ni_2Ta, β–μ–λ_1–$NiTa_2$
12	Ni–Nb–Ta–Mo	α, β, γ, δ, μ, Ni_2Ta, $NiTa_2$	α–β–μ–Ni_2Ta
13	Ni–Nb–Ta–W	α, β, γ, μ, Ni_2Ta, $NiTa_2$	α–β–μ–Ni_2Ta
14	Ni–Nb–Cr–Mo	α, β, γ, δ, σ, μ, λ_1,λ_2, P	α–β–μ–λ_1, α–β–δ–P, α–γ–δ–P, α–β–σ–P, α–γ–σ–P, α–β–γ–σ, λ_1–λ_2–β_1–β_2
15	Ni–Nb–Cr–W	α, δ, γ, σ, μ, λ_1,λ_2,	α–β–μ–λ_1, λ_1–λ_2–β_1–β_2, α–λ_1–β_1–β_2, α–σ–β_1–β_2, α–σ–γ–β_1, α–σ–γ–β_2
16	Ni–Nb–Mo–W	α, β, γ, δ, μ	α–β–γ–δ
17	Ni–Ta–Cr–Mo	α, β, γ, δ, σ, μ, λ_1, λ_2, P, Ni_2Ta, $NiTa_2$	α–β–δ–P, α–γ–δ–P, α–β–σ–P, α–γ–σ–P, α–β–γ–α, α–β–λ_1–Ni_2Ta, β–μ–λ_1–Ni_2Ta, β–μ–λ_1–$NiTa_2$, λ_1–λ_2–β_1–β_2
18	Ni–Ta–Cr–W	α, β, γ, σ, μ, λ_1, λ_2, Ni_2Ta, $NiTa_2$	α–β–λ_1–Ni_2Ta, β–μ–λ_1–Ni_2Ta, β–μ–λ_1–$NiTa_2$, λ_1–λ_2–β_1–β_2, α–λ_1–β_1–β–$_2$, α–σ–β_1–β_2, α–σ–γ–β_1, α–σ–γ–β_2
19	Ni–Ta–Mo–W	α, β, γ, δ, μ, Ni_2Ta, $NiTa_2$	α–β–γ–δ
20	Ni–Cr–Mo–W	β, γ, δ, α, P	β–γ–δ–P, β–γ–σ–P

Table 21
The five-phase equilibria and the recombined four-phase equilibria in the quinary systems on the basis of nickel and transition metals of the V–VI groups

No.	System	The five-phase equilibria	The recombined and degenerated (with underlining) four-phase equilibria
1	Ni–V–Nb–Ta–Cr	α–β–γ–σ–λ_1	α–μ–λ_1–Ni_2Ta, β–μ–λ_1–$NiTa_2$
2	Ni–V–Nb–Ta–Mo	α–β–γ–σ–λ_1	α–β–γ–δ, α–β–μ–λ_1, α–β–μ–Ni_2Ta
3	Ni–V–Nb –Ta–W	α–β–γ–σ–λ_1	α–β–μ–λ_1, α–β–μ–Ni_2Ta
4	Ni–V–Nb–Cr–Mo	α–β–γ–δ–P, α–β–γ–σ–P	β–γ–σ–λ_1, α–β–γ–λ_1, α–β–μ–λ_1, λ_1–λ_2–β_1–β_2
5	Ni–V–Nb –Cr–W	–	β–γ–σ–λ_1, α–β–γ–λ_1, α–β–μ–λ_1, α–σ–β–γ, λ_1–λ_2–β_1–β_2, α–λ_1–β_1–β_2, α–σ–β_1–β_2
6	Ni–V–Nb–Mo–W	–	β–γ–α–λ_1, α–β–γ–λ_1, α–β–μ–λ_1, α–β–γ–δ
7	Ni–V–Ta–Cr–Mo	α–β–γ–δ–P, α–β–γ–σ–P α–β–μ–λ_1–Ni_2Ta	α–β–σ–λ_1, α–β–γ–σ, λ_1–λ_2–β_1–β_2
8	Ni–V–Ta–Cr–W	α–β–μ–λ_1–Ni_2Ta	α–β–γ–σ, α–β–σ–λ_1, β–μ–λ_1–$NiTa_2$ α–σ–β–γ, λ_1–λ_2–β_1–β_2, α–λ_1–β_1–β_2, λ_1–λ_2–β_1–β_2
9	Ni–V–Tα–Mo–W	–	α–β–γ–δ, α–β–σ–λ_1, α–β–μ–λ_1, α–β–γ–σ, α–β–μ–Ni_2Ta
10	Ni–V–Cr–Mo–W	–	β–γ–σ–P, β–γ–δ–P
11	Ni–Nb–Ta–Cr–Mo	α–β–μ–λ_1–Ni_2Ta	β–μ–λ_1–$NiTa_2$, α–γ–δ–P, α–β–δ–P, α–γ–σ–P, α–β–σ–P, α–β–γ–σ, λ_1–λ_2–β_1–β_2
12	Ni–Nb–Ta–Cr–W	α–β–μ–λ_1–Ni_2Ta	β–μ–λ_1–$NiTa_2$, α–σ–β_1–γ, α–σ–β_2–γ, λ_1–λ_2–β_1–β_2, α–λ_1–β_1–β_2, α–σ–β_1–β_2
13	Ni–Nb–Ta–Mo–W	–	α–β–μ–Ni_2Ta, α–β–γ–δ
14	Ni–Nb–Cr–Mo–W	α–β–γ–δ–P, α–β–γ–σ–P	α–β–μ–λ_1, λ_1–λ_2–β_1–β_2, α–σ–β–γ, α–λ_1–β_1–β_2, α–σ–β_1–β_2
15	Ni–Ta–Cr–Mo–W	α–β–γ–δ–P, α–β–γ–σ–P	α–β–λ_1–Ni_2Ta, β–μ–λ_1–Ni_2Ta, α–β–γ–δ, λ_1–λ_2–β_1–β_2, α–σ–β–γ, α–λ_1–β_1–β_2, α–σ–β_1–β_2

The number systems, in which the five-phase equilibria are realised, is equal to 10. However, the number of types of five-phase equilibria is equal to four. For the formation of the six-phase equilibrium it is necessary to have six different types of the five-phase equilibria. Consequently, in the Ni–V–Nb–Ta–Cr–Mo–W system at 1375 K the

Table 22
Multi-phase equilibria in the six-component systems on the basis of nickel and transition metals of the V–VI groups

No.	System	Six-phase equilibria	Recombined five-phase equilibria
1	Ni–V–Nb–Ta–Cr–Mo	–	α–β–γ–δ–P, α–β–γ–σ–P, α–β–μ–λ_1–Ni_2Ta, α–β–γ–σ–λ_1
2	Ni–V–Nb–Ta–Cr–W	–	α–β–μ–λ_1–Ni_2Ta, α–β–γ–α–λ_1
3	Ni–V–Nb–Ta–Mo–W	–	α–β–γ–δ–P, α–β–γ–σ–P, α–β–μ–λ_1–Ni_2Ta, α–β–γ–σ–λ_1
4	Ni–V–Nb–Cr–Mo–W	–	α–β–γ–δ–P, α–β–γ–σ–P, α–β–γ–σ–λ_1
5	Ni–V–Ta–Cr–Mo–W	–	α–β–γ–δ–P, α–β–γ–σ–P, α–β–μ–λ_1–Ni_2Ta, α–β–γ–σ–λ_1
6	Ni–Nb–Ta–Cr–Mo–W	–	α–β–γ–δ–P, α–β–γ–σ–P, α–β–μ–λ_1–Ni_2Ta, α–β–γ–σ–λ_1

formation of the six-phase equilibria is not possible. Accordingly, the seven-phase equilibrium also does not exist.

4. Conclusion

The polyhedration of the Ni–V–Nb–Ta–Cr–Mo–W system at 1375 K using graphs has been released.

1. The seven- and six-phase equilibria are absent in this system.
2. The following five-phase equilibria have been established in the system: $\alpha-\beta-\gamma-\delta-P$, $\alpha-\beta-\gamma-\sigma-P$, $\alpha-\beta-\mu-\lambda_1-Ni_2Ta$ and $\alpha-\beta-\gamma-\sigma-\lambda_1$.
3. The four-phase equilibria established in the system are given in Table 21.

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