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Constitution of the Ni_3Cr–Ni_3Al–Ni_3W system

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Isothermal sections of the Ni–Cr–Al–W system have been investigated at 75 at% Ni and temperatures of 1523 and 1273 K, by means of phase compositional analysis, X-ray diffraction and microscopical examination. The alloys studied lay in the range 2.5 to 10 at% Cr, 12.5 to 20 at% Al, 2.5 to 6.25 at% W. The phases formed were γ, γ' and the b c c solid solution based on tungsten (designated α_2). The maximum extent of the γ' region was found to be ~ 3 at% each of chromium and tungsten. Preferential partitioning of tungsten to γ occurred. Study of an Ni–10Cr–12.5Al–2.5W alloy aged at 1273 and 1073 K, after quenching from 1573 K, showed that changes in γ and γ' compositions and lattice parameters occur as a function of ageing time.

1. Introduction

Among the refractory metals, tungsten has found considerable application as an alloying element in nickel-based superalloys. Of particular current interest is its role in alloys for single-crystal turbine blades [1, 2]. The research reported here forms part of a series of constitutional studies of nickel-based superalloys containing refractory metals. The programme has aimed to establish data on the relationships between the nickel-based solid solution (γ) and intermetallic compounds, particularly γ', based on Ni_3Al. Model ternary and quaternary systems have been selected for study including Ni–Al–Mo–Ta [3, 4], Ni–Al–Mo–W [5] and also chromium-containing systems Ni–Cr–Al–Mo [6–8] and Ni–Cr–Al–W. The present paper reports an investigation of part of the isothermal section of the Ni–Cr–Al–W system in the range 1523 to 1073 K. The application of electron probe microanalysis to only a few equilibrated alloys provides tie-line data to show the main constitutional features of the γ–γ' relationships.

Investigations of the constitution of the Ni–Cr–Al–W system have been reported in the literature [9, 10] and these are discussed below, together with relevant data for the ternary systems Ni–Al–Cr, Ni–Al–W and Ni–Cr–W. The ternary system literature is quite extensive and certain recent reviews and investigations are summarized here, particularly in relation to understanding the 75 at% alloys of the quaternary system.

1.1. Ni–Al–Cr system

A full review of the system [11] includes data for nickel-rich alloys covering the liquidus and isothermal sections of the range 1423 to 1023 K. The γ' phase shows substantial solubility for chromium, ranging from ~ 7.3 at% at 1473 K to ~ 20 at% at 1023 K. Thermodynamically calculated isothermal sections for the complete system in the range 1300 to 1600 K have recently been reported [12].

1.2. Ni–Al–W system

The Ni–W binary system has been recently reviewed [13–15]. Also, experimentally determined and calculated phase diagrams have been reported together with a literature review [16]. There is a eutectic at 1766 K and ~ 21 at% W, forming γ and tungsten (containing ~ 2 at% Ni in solution). This solid solution tungsten (W) is referred to as α_2 in the Ni–Cr–W and Ni–Cr–Al–W systems because there is a miscibility gap in the Cr–W system. Three peritectic reactions are reported: γ (~ 16 at% W) + (W) $\rightarrow$ NiW at ~ 1325 K; Ni + (W) $\rightarrow$ NiW_2 (at between 1313 and 1343 K); γ + NiW $\rightarrow$ Ni_4W (at ~ 1243 K). In studies of a directionally solidified Ni–20.7 at% W alloy, including ageing behaviour at 1248 and 1023 K, f c tetragonal Ni_4W was found to precipitate coherently initially [17].

In the Ni–Al–W system, work by Nash *et al.* [18] found equilibria between $\gamma + \gamma' +$ (W) and $\gamma' + \beta +$ (W) at 1523 K which is in agreement with the calculated phase diagram of Kaufman and Nesor [19]. It differs, however, from the data of Budberg [20] who studied the system at 1473, 1273 and 1073 K and reported equilibria between $\gamma + \gamma' + \beta$ and $\gamma + \beta +$ (W). Nash *et al.* [18] proposed that a peritectoid $\beta + \gamma \rightarrow \gamma' +$ (W) occurs above 1523 K and that the resultant $\gamma + \gamma' +$ (W) and $\gamma' + \beta +$ (W) fields are stable below the peritectoid. The solubility of W in γ' was reported [18] as ~ 4.5 at% at 1523 K and ~ 6 at% at 1273 K; also it was found that furnace cooling from 1523 to 1273 K and holding for 1 week produced a change in the (W) to a phase with a substantial content of nickel and aluminium.

1.3. Ni–Cr–W system

The literature of the ternary system has been recently reviewed [21, 22], covering liquidus data and isothermal sections from 1973 to 1473 K (e.g. [23–28]). The Cr–W system shows complete solid solubility above ~ 1970 K;

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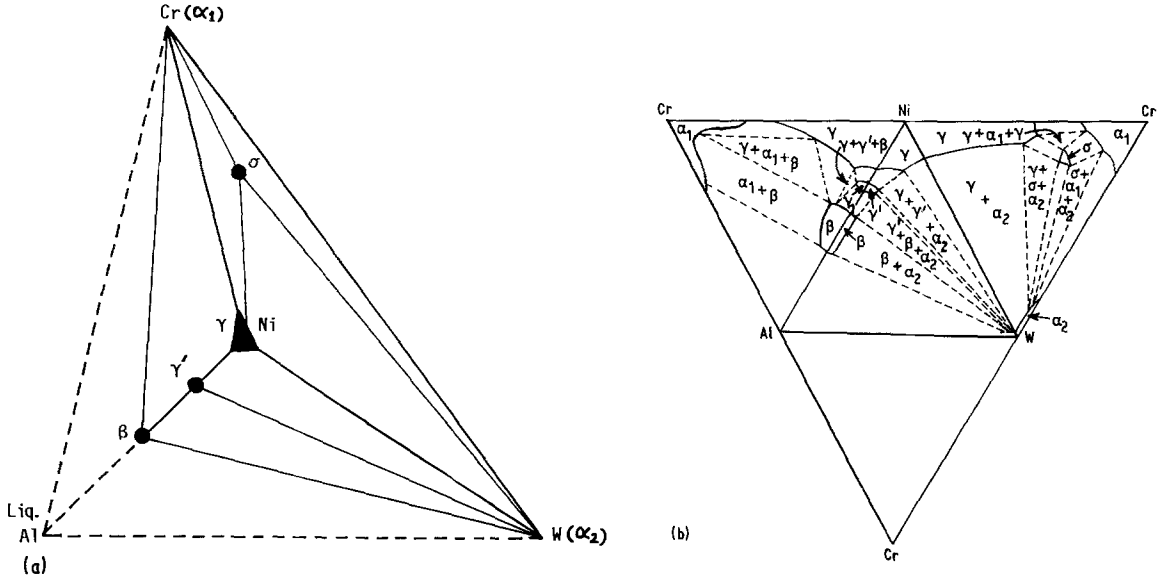


Figure 1 Nickel-rich portion of the Ni–Cr–Al–W system at 1523 K viewed towards the nickel-rich corner of an isothermal tetrahedron. (a) Schematic illustration of phases present in Ni–Al–Cr [11], Ni–Al–W [18], and Ni–Cr–W [21, 22] systems. NiAl designated β. (b) Exploded partial isothermal sections of constituent ternary systems based on previous work [11, 18, 21, 22].

at lower temperatures a miscibility gap exists, the chromium-rich solid solution being designated α_1 and the tungsten-rich solution α_2. There is a ternary sigma phase, reported to form by the peritectic reaction: $L + \alpha_1 + \alpha_2 \rightarrow \sigma$ [23] at a temperature possibly slightly below 1813 K. Two other invariant solidification reactions have been proposed: $L + \alpha_2 \rightarrow \sigma + \gamma$ and $L + \sigma \rightarrow \gamma + \alpha_2$ [23]. The results of Grundy [29] on directionally solidified alloys show the formation of a eutectic of $\gamma + \alpha_1$ up to 5.4 at % W. The 1523 K isothermal includes a single-phase σ region (located at ~60 at % Cr, 10 at % W); three phase equilibria exist: $\gamma + \sigma + \alpha_2$; $\gamma + \sigma + \alpha_1$; $\alpha_1 + \sigma + \alpha_2$. The same equilibria occur at 1273 K, but with some change in phase compositions. A recent paper by Kikuchi *et al.* [27] provides evidence of the eutectoidal decomposition of σ below 1223 K: $\sigma \rightarrow \alpha_1 + \alpha_2 + \gamma$.

1.4. Ni–Cr–Al–W system

Alisova *et al.* [9] have reported detailed data on the constitution of the quaternary system at 1373 K. The alloys investigated lay on three sections of the isothermal tetrahedron passing through the Ni–Cr side with W–Al ratios (wt %) of 3 : 1, 1 : 1, and 1 : 3. Within each section, alloys lay on sub-sections parallel to the Ni–Cr side with total (Al + W) contents from 10 to 50 at % at intervals of 2.5 or 5% and with chromium levels up to 40%. Homogenization was carried out at 1523 to 1623 K for 200 to 350 h, prior to annealing for 150 h at 1373 K. The constitution of the ternary Ni–Al–W system was taken from the work of Budberg showing the $\beta + \gamma + \gamma'$ and $\beta + \gamma + \alpha_2$ fields [20].

From the available ternary data, the phases encountered in the nickel-rich portion of the system at 1523 K are shown schematically in Fig. 1a. The full extent of the single-phase regions is not shown and the two-phase regions are represented by straight lines. The three-phase triangle for γ, γ', β is virtually coincident with the Ni–Al edge of the tetrahedron with the method of representation used. Fig. 1b depicts ternary isothermal sections relevant to the phase fields in the quaternary system.

2. Experimental procedure

Four Ni–Cr–Al–W alloys were investigated of nominal nickel content 75 at % (Table I); the compositions were in the range 2.5 to 10 at % Cr, 12.5 to 20 at % Al, 2.5 to 6.25 at % W. These compositions were selected with the particular objective of investigating γ/γ' equilibria. Ingots (~30 g) were made by arc melting, using high-purity metals: nickel and aluminium (~99.99%), chromium and tungsten (~99.9%). Several remelts were made to aid in obtaining uniformity of composition in the ingots. Bulk compositions, as determined by electron probe microanalysis (EPMA) showed significant preferential aluminium loss and some significant scatter between compositions determined on different specimens (Table II).

As-solidified structures were examined, and the remaining parts of the ingot were sealed in a silica tube under vacuum with a partial pressure of argon. Heat treatments were given as follows: (a) 2 weeks at 1573 K, furnace cooled (FC) to 1523 K and holding for 4 weeks followed by quenching in iced water (WQ), (b) as in (a) plus 6 weeks at 1273 K (WQ), and (c) as in (a) plus 8 weeks at 1073 K. Also some specimens of alloy 1 were WQ directly from 1523 K and annealed for 1 and 100 h at 1273 and 1073 K.

Structural examination was carried out using light microscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Phase compositional analysis was carried out by EPMA using a Jeol JSM-35 CF instrument with LINK system software. The relative error of the measurements on a given sample is up to $\sim \pm 1\%$ of an individual element. Local equilibrium was deduced from the absence of detectable concentration gradients within phase regions, although features derived from the original "coring" in the as-solidified material still persisted after the prolonged annealing. STEM phase compositional analysis was carried out on thin foils of

TABLE I Nominal alloy compositions, hardness values, experimental and calculated lattice parameters (nm) and γ/γ' lattice mismatch values (%)

Alloy no.	Nominal alloy composition (at %)				Treatment (K)	Hardness, *H*v 10	Phases present	Structure of phases present and lattice parameters (nm)		
	Ni	Cr	Al	W				γ fcc a	γ' (based on Ni_3Al) Ll_2 cubic a	α_2 (based on W solid solution) bcc a
1	75	10	12.5	2.5	As-solidified	368	$\gamma + \gamma'$	0.3566 (0.3562)* [+0.084]*	0.3569 (0.3560)	
					1523	309	γ	0.3572 (0.3561)		
					1273	258	$\gamma + \gamma'$	0.3568 [+0.168]	0.3574	
					1073	380	$\gamma + \gamma'$	0.3578 [−0.22]	0.3570	
2	75	4.0	17.0	4.0	As-solidified	312	$\gamma + \gamma'$	0.3574 (0.3568) [+0.084]	0.3577 (0.3572)	
					1523	285	$\gamma + \gamma'$	0.3575 (0.3564) [+0.112]	0.3579 (0.3572)	
					1273	262	$\gamma + \gamma'$	0.3577 [+0.112]	0.3581	
					1073	254	$\gamma + \gamma'$	0.3573 [+0.139]	0.3578	
3	75	2.5	20	2.5	As-solidified	217	$\gamma + \gamma'$	0.3567 (0.3565) [+0.084]	0.3570 (0.3571)	
					1523	197	γ'		0.3580 (0.3569)	
					1273	178	$\gamma + \gamma'$	0.3576 [+0.139]	0.3581	
					1073	137	$\gamma + \gamma'$	0.3574 [−0.139]	0.3569	
4	75	2.5	16.25	6.25	As-solidified	374	$\gamma + \gamma'$	0.3573 (0.3572) [+0.112]	0.3577 (0.3572)	
					1523	333	$\gamma + \gamma + \alpha_2$	0.3576 (0.3573) [+0.084]	0.3579 (0.3576)	0.3164
					1273	222	$\gamma + \gamma' + \alpha_2$	0.3573 [+0.084]	0.3576	0.3172
					1073	310	$\gamma + \gamma' + \alpha_2$	0.3657 [−0.216]	0.3578	0.3172

*Figures in square brackets represent % lattice mismatch (i.e. $(a_{\gamma'} - a_{\gamma})/a_{\gamma} \times 100$). Figures in parentheses represent calculated lattice parameters.

alloy 1 annealed at 1273 and 1073 K using a Jeol JEM 2000 FX instrument with an EDX spectrometer and a LINK system analyser. Typically three or four foil areas were examined to obtain average values; measurements were made on the thinnest areas at the foil edges, aiming to examine γ' particles, and γ matrix regions, which occupy the complete foil thickness.

X-ray diffractometry of bulk polished specimens was carried out using Cu$K\alpha$ radiation, a graphite monochromator and a specimen spinner. Lattice spacing measurements were estimated to have an accuracy better than $\sim \pm 0.2\%$.

3. Results

3.1. As-solidified structures

All four alloys in the as-solidified state showed cored γ dendritic structures, e.g. Fig. 2. Table II shows compositions representing the dendrite centres. The values showed a trend to lower aluminium content than the bulk alloy composition, but a higher tungsten content (consistent with a distribution coefficient > 1). The interdendritic regions showed high aluminium contents with low chromium and tungsten contents indicative of the presence of γ'.

X-ray diffraction showed the presence of γ and γ' in all four alloys (Table I). The γ/γ' mismatch values were virtually zero, the γ and γ' parameters being identical within the limits of accuracy of measurement.

3.2. Constitution in the range 1523 to 1073 K

Figs 3a and b show isothermal sections at 1523 and 1273 K at 75 at % Ni. The boundaries of the phase fields in the ternary systems, corresponding to the edges of the $Ni_{75}Al_{25}$–$Ni_{75}Cr_{25}$–$Ni_{75}W_{25}$ composition

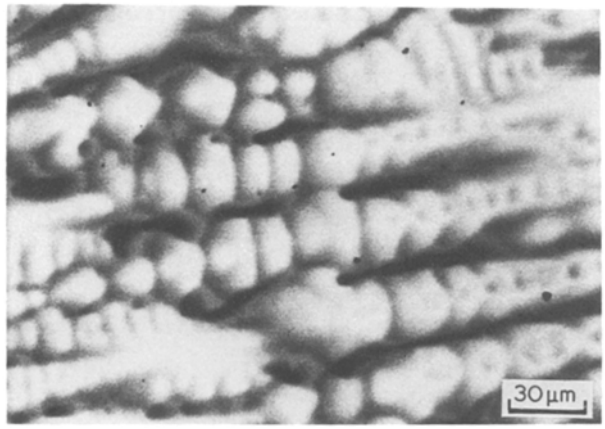


Figure 2 Alloy 2, Ni75Cr4Al17W4. As-solidified dendritic structure containing predominantly γ (LRBEI).

TABLE II Analysed alloy and phase compositions and phase volume fractions

Alloy no.	Alloy composition determined by EMPA (at %)* Ni–Cr–Al–W	Alloy treatment (K)	Phases present and approximate volume fractions	Phase composition determined by EPMA (at %) Ni–Cr–Al–W		
				γ	γ'	α_2
1	⟨75–10–12.5–2.5⟩					
	76.4–10.3–10.7–2.6	As-solidified	$\gamma + \gamma'$	77.7–9.6–9.4–3.3†	Δ	
	76.3–10.4–10.7–2.6	1523	γ	76.3–10.4–10.7–2.6		
	75.8–8.4–12.9–2.9	1273	$\gamma + \gamma'$	78.6–11.9–6.4–3.1	73.8–5.6–18.0–2.6	
	74.4–10.3–12.5–2.5‡	1073 (100 h)	$\gamma + \gamma'$	75.3–13.2–8.0–3.5	75.9–6.2–15.2–2.7	
2	⟨75–4.0–17.0–4.0⟩					
	77.3–4.2–15.3–3.2	As-solidified	$\gamma + \gamma'$	78.6–3.9–12.9–4.6†	Δ	
	76.9–4.1–15.4–3.6	1523	$\gamma + \gamma'$ (60–40)	78.0–6.5–11.7–3.8	76.4–2.9–17.2–3.5	
	75.7–2.5–16.9–4.9	1273	$\gamma + \gamma'$	78.4–6.6–6.7–8.3	74.9–1.9–19.9–3.3	
3	⟨75–2.5–20–2.5⟩					
	77.6–2.6–17.6–2.2	As-solidified	$\gamma + \gamma'$	79.3–2.5–15.1–3.1†	Δ	
	76.8–2.8–18.0–2.4	1523	γ'		76.8–2.8–18.0–2.4	
	77.2–2.7–17.7–2.4	1273	$\gamma + \gamma'$ (5–95)	79.8–5.8–12.2–2.2	77.1–2.0–17.9–3.0	
4	⟨75–2.5–16.25–6.25⟩					
	78.0–2.6–14.0–5.4	As-solidified	$\gamma + \gamma'$	79.4–2.2–12.0–6.4†	Δ	
	77.6–2.7–14.2–5.5	1523	$\gamma + \gamma' + \alpha_2$ (50–48–2)	78.5–4.3–10.7–6.5	76.9–1.6–16.8–4.7	Δ
		1273	$\gamma + \gamma' + \alpha_2$ (40–50–10)	78.9–3.0–12.6–5.5	77.2–2.2–15.4–5.2	3.6–10.3–2.8–83.3
	76.4–2.5–14.9–6.2‡	1073 (8 weeks)	$\gamma + \gamma' + \alpha_2$	76.2–5.2–10.4–8.2	76.6–1.3–18.5–3.6	8.1–13.1–0.3–78.5

*Nominal compositions in brackets ⟨ ⟩.
†Composition of primary dendrites at the centre. Composition of interdendritic region given in square brackets.
‡STEM analysis.
ΔParticle size too small for EPMA.

triangles, have been deduced from previous work (e.g. [11, 18, 22]). Tables I and II show the data for phase compositions, lattice parameters and hardness.

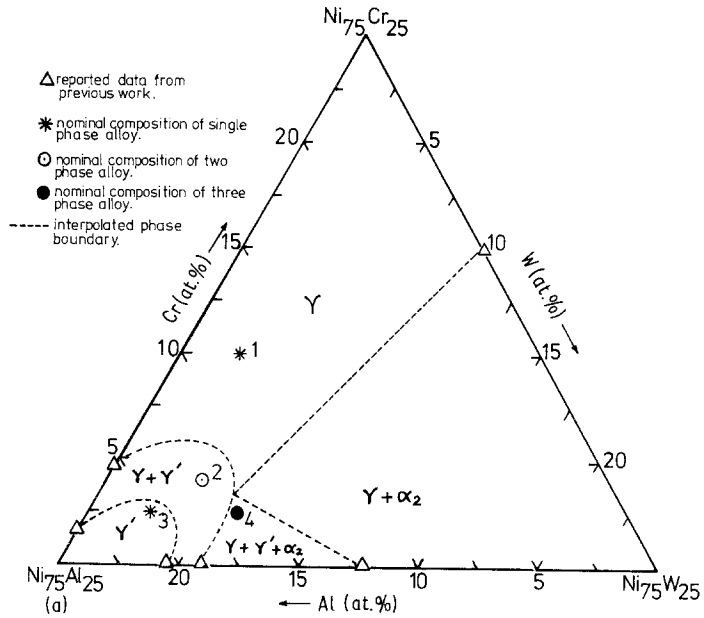
At 1523 K, the data show the presence of γ, γ', $\gamma + \gamma'$ and $\gamma + \gamma' + \alpha_2$ phase fields, while the presence of a $\gamma + \alpha_2$ field is also inferred. The γ field is a major feature. The γ/γ' tie line in alloy 2 does not lie exactly in the plane of the section so that the locations of the boundaries of the $\gamma + \gamma'$ region are not precisely defined. The data from alloy 2 indicate that the γ' field extends up to at least ~3 at % each of chromium and tungsten. Slight partitioning of W to γ is found in the $\gamma + \gamma'$ alloy while more substantial partitioning of W to γ occurs in the $\gamma + \gamma' + \alpha_2$ alloy.

The same phase fields are present at 1273 K as at 1523 K but the $\gamma + \gamma'$ field has increased substantially as a result of a decrease in aluminium and an increase in chromium contents of the $\gamma + \gamma'/\gamma$ boundary, and a shift in the $\gamma/\gamma + \alpha_2$ boundary towards the $Ni_{75}Cr_{25}$ corner; the extent of the γ field is consequently decreased. Although the samples had been initially homogenized for 1 week at 1523 K the distribution of γ and γ' phase regions present after subsequent annealing at lower temperatures still reflected the original dendritic pattern. Fig. 4 illustrates the structure of alloy 2 after annealing at 1273 K; γ (light) regions correspond to the original dendrite "centres"; some γ' had precipitated during furnace cooling from 1573 to 1523 K, and further γ' precipitation had occurred on annealing at 1273 K.

STEM phase analysis and X-ray analysis on a sample of alloy 4 annealed for 8 weeks at 1073 K showed the presence of γ, γ' and α_2; there was a small increase of tungsten content of γ and a small decrease in tungsten content of γ' as compared with the 1273 K annealed material (Table II); the tungsten-rich α_2 phase has a negligible solubility for aluminium.

Lattice parameter measurements (Table I) show, as in the case of the as-solidified alloys, a very small γ/γ' mismatch. Neither the γ nor the γ' parameters varied substantially with annealing temperature, with the exception of γ in alloy 4 annealed at 1073 K where a significant increase was observed. Little difference between the alloys was found in terms of γ and γ' parameters. In alloy 4, the lattice parameter of the α_2 phase was close to the lattice parameter of pure tungsten (i.e. 0.3165 nm).

Some data on phase composition and lattice parameters were obtained on alloy 1 quenched directly from 1573 K and annealed for 1 h and 100 h at 1273 and 1073 K (Table I). After the initial quench the supersaturated γ contained some γ' particles (~15 nm diameter) which had formed during the quench. A very small increase in γ lattice parameter accompanied by a small decrease in γ' parameter occurred between 1 and 100 h ageing with a change in mismatch from a positive to a negative value. The phase compositions after 1 h annealing were not accurately determined by STEM, because of the small particle size of the γ' phase. However, after annealing for 100 h, chromium partitioned strongly to the γ phase and tungsten to a smaller extent, while aluminium partitioned to γ'. The data showed quite good agreement with those obtained in samples quenched from 1523 K and annealed for 6 weeks at 1273 K.



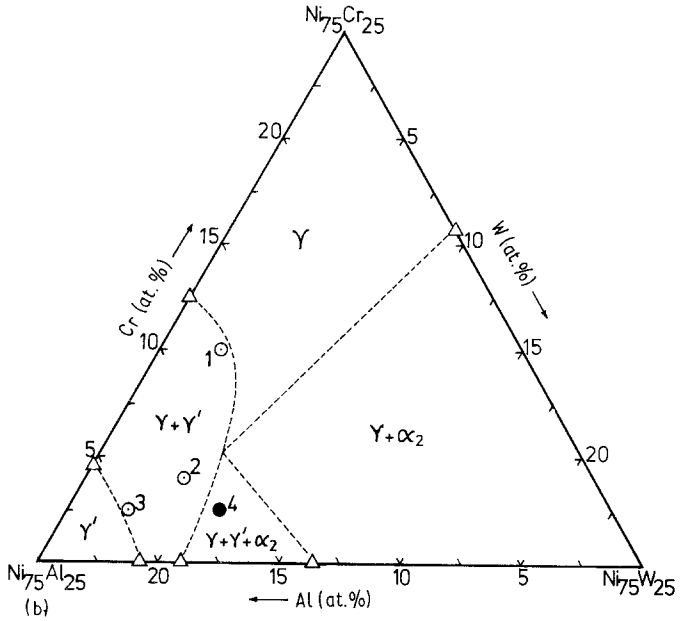


Figure 3 Semi-schematic partial isothermal sections of Ni–Cr–Al–W system at 75 at % Ni. (a) 1523 K, (b) 1273 K.

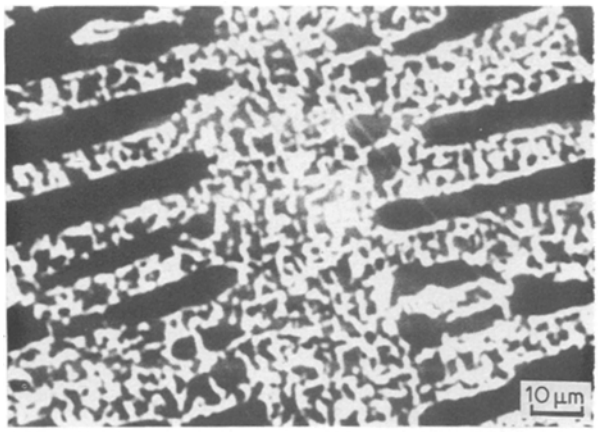


Figure 4 Alloy 2, Ni75Cr4Al17W4. Annealed 1573 K FC to 1523 K WQ + 1273 K 6 weeks WQ: γ (light), γ' (dark) (LRBEI).

4. Discussion

The constitutional data for the quaternary Ni–Cr–Al–W system, together with similar information for the Ni–Al–Mo–Ta [3, 4] and Ni–Al–Mo–W [5] systems can be related to the constitution of single-crystal alloys in which tungsten and tantalum are important elements. The compositions (at %) of two single crystal alloys are shown in Table III. Such alloys are solution treated at ~1570 K and are typically given a

TABLE III Compositions (at %) of two single-crystal alloys

	Ni	Co	Cr	Al	Ti	Mo	Ta	W	C
SRR99 (1)	66.7	5.0	9.6	12	2.7		0.9	3.04	~0.07
CMSX-2 (2)	68.4	4.7	9.2	12.3	0.5	0.37	1.9	2.6	< ~0.02

TABLE IV Composition (at %) of the two alloys in terms of four components

	(Ni + Co)	Cr	(Al + Ti)	Refractory metals
SRR99	71.7	9.6	14.7	3.9
CMSX-2	73.1	9.2	12.8	4.9

two-stage ageing treatment in which the second stage is at ~1020 K, to produce ~60 to 70 vol % γ'. To simplify the interpretation of the constitution, the composition (at %) may be expressed in terms of four "components", see Table IV. The composition (at %) of γ' in alloy CMSX-2 has been reported as: (Ni + Co) 73.7; Cr 2.4; (Al + Ti) 18.4; Mo 0.2; Ta 3.0; W 2.3 (i.e. 5.5 refractory metals); the lattice parameter was 0.358 65 nm. In terms of chromium, aluminium and tungsten contents, this composition is close to that of γ' in alloy 3 annealed at 1523 K in the present work, i.e. Ni 76.8; Cr 2.8; Al 18.0; W 2.4. γ' in alloy 2 is also similar although the tungsten content is higher (~3.5 at %). The γ' lattice parameters for alloys 2 and 3 annealed in the range 1073 to 1573 K (Table I) lie between ~0.357 and 0.358 nm, being slightly less than that for CMSX-2, presumably due to the lower total content of refractory metal in the γ'.

Alloy 1 in the present work has a bulk composition closest to that of SRR99 and CMSX-2; the γ' composition differs somewhat from alloys 2 and 3 at 1273 K in having a higher chromium content, ~5.5 at %.

Concerning the data for ageing alloy 1 at 1273 and 1073 K, the partitioning of the tungsten is interpreted as a significant source of the lattice parameter changes, because of its relatively large atomic size. Ageing at lower temperatures requires quite long times to reach the appropriate equilibrium.

Quaternary alloy data of the type reported here and previously [30] may be linked more closely to the higher order systems represented by the single-crystal alloys. For example, data for Ni–Cr–Al–Mo and Ni–Al–Mo–W may be used to deduce information on the quinary system Ni–Cr–Al–Mo–W. Isothermal sections at 1523 K can be constructed taking the corners of the isothermal tetrahedron as the compositions

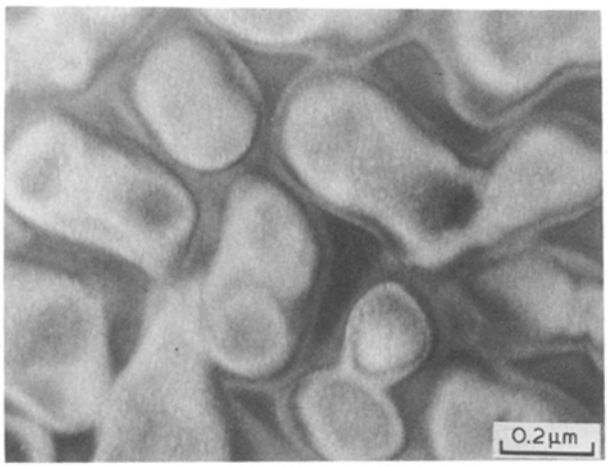


Figure 5 Alloy 4, $Ni_{75}Cr_{2.5}Al_{16.25}W_{6.25}$. Annealed 1573 K for 1523 K WQ + 1073 K 2 weeks WQ. $\gamma + \gamma'$.

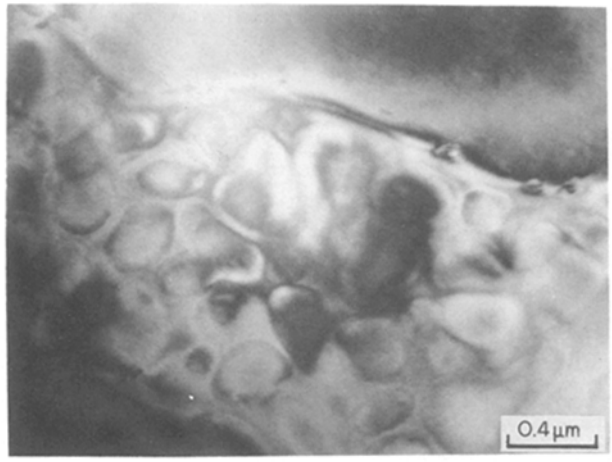


Figure 6 Alloy 1, $Ni_{75}Cr_{10}Al_{12.5}W_{2.5}$. Annealed 1523 K WQ + 1073 K 100 h WQ. $\gamma + \gamma'$.

$Ni_{75}Al_{25}$, $Ni_{75}Cr_{25}$, $Ni_{75}Mo_{25}$, $Ni_{75}W_{25}$. The faces of the tetrahedra comprise the 75 at % Ni sections of the quaternary systems Ni–Cr–Al–Mo, Ni–Cr–Al–W, Ni–Al–Mo–W and Ni–Cr–Mo–W. To aid in the diagrammatic representation of the isothermal tetrahedron data, sections may be taken at a constant proportion of one of the elements. Fig. 7a represents the "ternary" systems while Fig. 7b shows a section through the quinary system at 3 at % W. It should be noted that γ/γ' tie lines are not known and experimental work is needed to establish the data. The γ and γ' compositions may deviate significantly from the plane of the section so that tie line calculations cannot be carried out using the boundaries of the $\gamma + \gamma'$ field as delineated in Fig. 7b.

5. Conclusions

Isothermal sections of the Ni–Cr–Al–W system at 75 at % Ni and at 1523 and 1273 K contain the phases γ, γ' and tungsten-based solid solution (α_2). Phase fields have been found as follows: γ (occupying a major part of the sections), γ' (extending up to ~3 at % each of chromium and tungsten), $\gamma + \gamma'$, and $\gamma + \gamma' + \alpha_2$; the presence of a $\gamma + \gamma'$ field is greater at 1273 K than at 1523 K. Tungsten partitions preferentially to γ.

On ageing a supersaturated alloy containing 2.5 at % W at 1273 and 1073 K up to 100 h, changes in lattice parameter of the γ and γ' occur as a function of time, indicating that the full partitioning of tungsten to the γ is not achieved at short ageing time.

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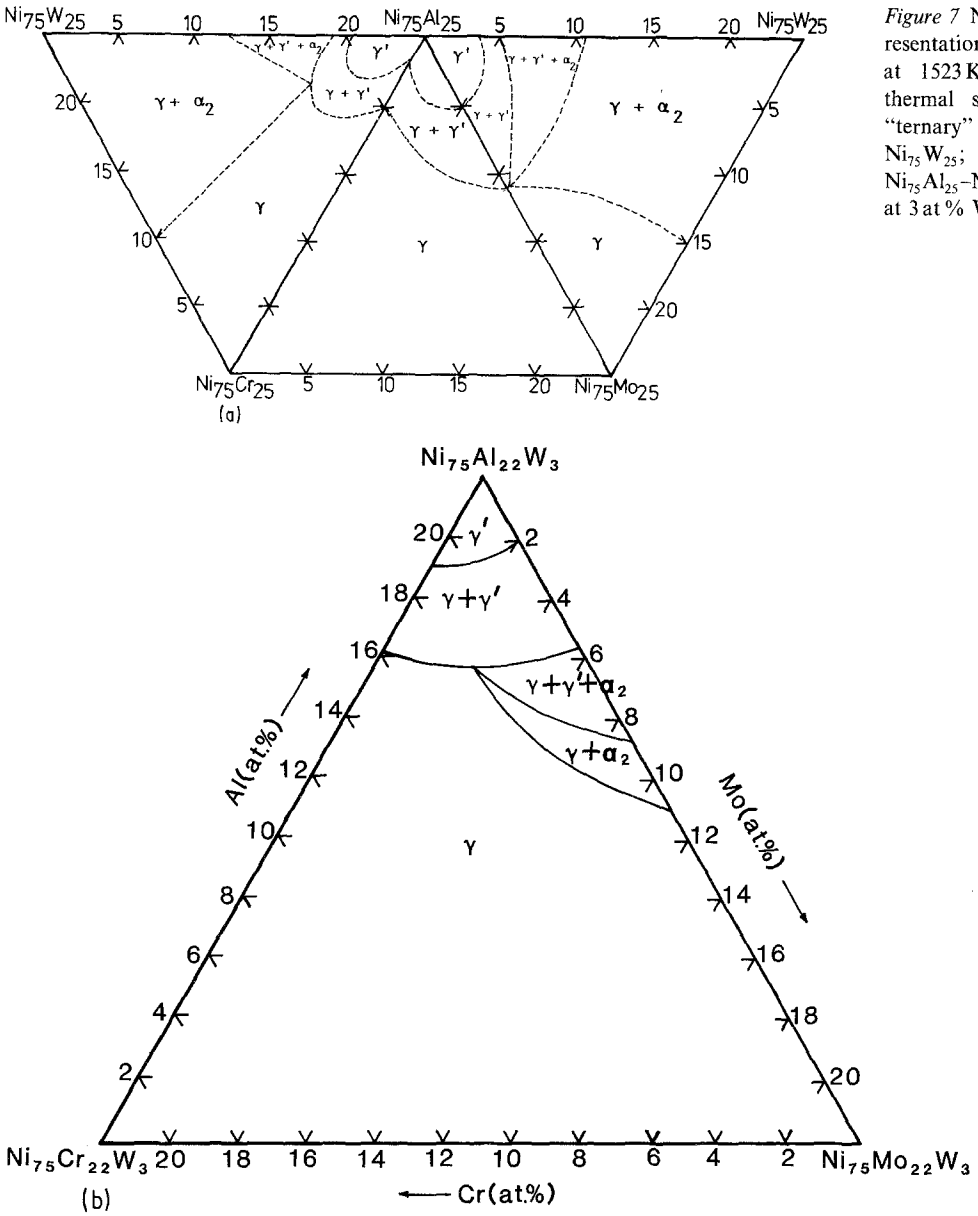

Figure 7 Ni–Al–Cr–Mo–W system. Representation of isothermal section data at 1523 K. (a) Exploded partial isothermal sections taken as constituent "ternary" systems. $Ni_{75}Al_{25}$–$Ni_{75}Cr_{25}$ – $Ni_{75}W_{25}$; $Ni_{75}Al_{25}$–$Ni_{75}Cr_{25}$–$Ni_{75}Mo_{25}$; $Ni_{75}Al_{25}$–$Ni_{75}Mo_{25}$–$Ni_{75}W_{25}$. (b) Section at 3 at % W.

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