Phase equilibria of the Al-Co-W system at 600 °C

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Abstract: Phase relationship in the ternary Al-Co-W system was established for the whole composition range at 600 °C by X-ray powder diffraction, scanning electron microscopy and energy dispersive **spectroscopy**. Isothermal section of this system comprises of 15 **three phase** and 28 **two phase** regions. Except the $L1_2$ - γ' phase, a new ternary phase T has been found. The average composition of the T phase is 22.6 at.% Al, 67.0 at.% Co and W in balance. The solubility of W in AlCo is 3.0 at%, the solubility of Al in Co_3W and Co_7W_6 is both 3.1 at%, and the solubility of Co in Al_4W reaches 3.6 at%. Solubility of the third component in the other binary phases **is** limited. The present work is essential to develop a thermodynamic database for developing Co-related high-temperature alloys.

Keywords: high-temperature material; Al-Co-W; phase equilibria; thermodynamic

1. Introduction

Ni-based alloy is the conventional high-temperature structural material due to its excellent high-temperature strength and creep resistance properties. Such metallic alloy are strengthened with dispersed $L1_2$ - γ' precipitations distributing among the FCC- γ matrix. Since the discovery of a ternary γ' - $Co_3(Al,W)$ intermetallic compound in the Al-Co-W system [1], Co-based alloy has been widely investigated to develop superior high-temperature materials [2-9]. Though the γ' - Ni_3Al with the $L1_2$ structure is very stable and this phase exists in a wide composition range in the Ni-Co-Al ternary system, the stability of the γ' - $Co_3(Al,W)$ phase in the Al-Co-W ternary system remains contradictory [10-18]. The reviewed literature will be provided in the “literature survey” session. To understand the microstructure and subsequent property enhancement of Co-base alloys, knowledge on phase equilibrium of the ternary Al-Co-W system and a reliable Al-Co-W related

multicomponent thermodynamic database is necessary. Though the Co-rich corner of the Al-Co-W system has been thermodynamically evaluated by several researchers [17-19], information on the phase equilibrium is still incomplete and even controversial, and especially isothermal section of the ternary Al-Co-W system in the whole composition range has not yet been determined. In the present work, an isothermal section of the Al-Co-W system in the entire composition range at 600 °C has been established experimentally with techniques combining optical microscopy, scanning electron microscopy with energy dispersive x-ray spectroscopic capability (SEM-EDS), and x-ray diffraction. This work is essential to accumulate the required phase equilibria data for construction the Al-Co-W related thermodynamic database.

2. Literature survey

2.1 Al-Co-W related binary systems

The three constituting binaries in the Al-Co-W ternary system, Al-Co, Al-W and Co-W systems are shown in Fig. 1. Though several assessments of the Al-Co binary system utilizing Calphad method have been reported [20-21], the composition range of the AlCo phase is not well described, so the Al-Co binary diagram from Ref. [22] was adopted in this work. Five compounds, i.e. Al_9Co_2 , $\text{Al}_{13}\text{Co}_4$, Al_3Co , Al_5Co_2 and AlCo, exist in this system. The Al-W phase diagram [23] has at least three intermediate compounds: Al_4W , Al_5W , and Al_{12}W . The details of other possible high temperature phases are not yet known. Okamoto reviewed the research status of the Co-W system [24]. Based on the Co-W binary phase diagram reported by Nagender Naidu et al. [25], Zhao et al. studied the $(\alpha\text{Co})/(\alpha\text{Co}) + \text{Co}_3\text{W}$ phase boundary in detail [26]. Guillermet et al. [27] and Östberg et al. [28] investigated the ferromagnetic transformation in (αCo) in further. The Co-W phase diagram depicts two compounds: Co_3W and Co_7W_6 [25-28]. The information of the stable solid phases in the three binary systems mentioned above is summarized in Table 1.

2.2 The Al-Co-W ternary system

Isothermal sections of the Al-Co-W system in the Co-rich corner at 900 and 1000 °C determined by Sato et al. [1] are presented in Fig.2, (a) and (b), respectively. The ternary γ' - $\text{Co}_3(\text{Al,W})$ phase was first identified using a field emission electron probe microanalyzer (FE-EPMA). The solvus temperature of the γ' phase in Co-(9-10)Al-(7.5-10)W (at.%) is ~990 °C according to the differential scanning calorimetry (DSC) examination. This phase is stable at 900 °C but unstable at 1000 °C as shown in Fig.2 [1].

Dmitrieva et al. [10] investigated the fusion diagram of the Al-Co-W system in the Co-CoAl-W using optical light, differential thermal, X-ray diffraction and electron microprobe analysis. A liquidus projection consisting of four primary phase regions: (Co), AlCo, Co₇W₆ and W, were reported and two isothermal three-phase fields corresponding to four-phase invariant reactions with participation of liquid: $L \leftrightarrow \text{Co} + \text{CoAl} + \text{Co}_7\text{W}_6$ (1380°C) and $L + \text{W} \leftrightarrow \text{Co}_7\text{W}_6 + \text{CoAl}$ (1490°C), were established. The vertical section of the Co-CoAl-W system at 75 at.% Co was constructed based on the constitution of the liquidus and solidus surfaces and the isothermal sections at 1200 °C and 900 °C. No ternary intermediate phase was found in this partial system above 900°C.

Lass et al. [11] studied stability of the γ' phase and phase equilibria at 900°C in the Co-rich Co-Al-W ternary system through isothermal annealing of six alloys for times up to 8000 h. Volume fraction of the γ' phase decreased with increasing annealing time, and this phase was determined to be unstable in the ternary system at 900 °C. Based on microstructure and EPMA analysis on a cold rolled bulk alloy followed by heat-treatment from 100 to 2000 h in evacuated silica tube, Tsukamoto et al. [12] observed that the γ' dissolved in the vicinity of the CoAl and Co₃W phase with increasing annealing time. These observations are also consistent with those in a diffusion-couple experiment by Kobayashi et al. [13]. In addition, phase stability of the L₁₂-Co₃Al_{0.5}W_{0.5} compound was found to be unstable at 0 K according to the first-principles SQS calculations [14-17].

In a recent differential thermal analysis (DTA) from Zhu et al. [18], the solvus for the γ' phase in Co-8Al-13W and Co-8Al-24W alloys are 1037 and 1057 °C, respectively. At 900 °C, the γ' phase is in equilibrium with the adjacent three phases (Co), AlCo and Co₇W₆. This agrees well with the phase diagram reported by Sato et al. [1].

3. Experimental procedure

The phase relationship in the system was deduced by studying the phase constitution of the alloys listed in Table 2. Nominal compositions of these alloys were marked in the calculated phase diagram using thermodynamic description by Zhu et al. [18] as shown in Fig.3. The alloys were prepared using Al blocks (99.99%), Co pellets (99.99%) and W pellets (99.999%). Due to their much higher melting points, the dissolution and diffusion of Co and W in the samples were expected to be slow during the homogenizing treatment. Consequently, Co and W pellets used were 1~2 mm in size. Samples were prepared by carefully weighing Al, Co and W, (20g in total for each sample). All masses were weighed to an accuracy of 0.0001 g. The samples with designed compositions were

melted under argon atmosphere using a non-consumable tungsten electrode. The ingots were remelted five times to improve their homogeneity. Plate specimens were cut from the button ingots with weight loss under 1% after melting, and then sealed in an evacuated quartz tube under an argon gas atmosphere. Specimens in the Al-rich corner were annealed at 600 °C for 90 days, and the others containing more Co or W were annealed at 600 °C for 120 days, and were then water quenched at the end of the treatment.

The samples were mounted, ground and polished according to standard metallographic practices. A JSM-6510 SEM (JEOL, Japan) equipped with an Oxford INCA EDS (Oxford instrument, UK), with probe diameter of 1 μm, accelerating voltage of 20 kV, was subjected to detailed metallographic examinations and compositional analyses. The compositions reported herein were averages of at least five measurements. The phase makeup of the alloys was further determined by analyzing X-ray diffraction patterns generated by a D/max 2500 PC X-ray diffractometer (Rigaku, Japan) with Cu Kα radiation and a step increase of 0.02° in the 2θ angle. Si powders were used as external calibrated standard. Jade software package was used to index and calculate the XRD patterns.

4. Results and discussion

Results of our experimental investigation of the samples annealed at 600 °C are presented in Fig.4. Table 2 summarizes the nominal compositions of the alloys and the phases in equilibrium which were identified by a combination of XRD and SEM-EDS. The following fourteen three-phase equilibria were well determined: (1) (Al)+Al₁₂W+Al₉Co₂, (2) Al₅W+Al₁₂W+Al₉Co₂, (3) Al₅W+Al₄W+Al₉Co₂, (4) Al₁₃Co₄+Al₄W+Al₉Co₂, (5) Al₁₃Co₄+Al₄W+Al₃Co, (6) Al₅Co₂+Al₄W+Al₃Co, (7) Al₅Co₂+Al₄W+(W), (8) Al₅Co₂+AlCo+(W), (9) T+AlCo+(W), (10) T+Co₇W₆+(W), (11) T+Co₇W₆+Co₃W, (12) T+γ'+Co₃W, (13) (Co)+γ'+Co₃W and (14) (Co)+γ'+T. All the phases can be easily differentiated based on their brightness on grayscale images and chemical composition. Microstructures in back scattered electrons (BSE) of the key alloys are shown in Fig.5. The XRD patterns of the representative ternary alloys are presented in Figs.6-8.

The isothermal section is mainly characterized by tie-lines between binary phases. The following binary phases were found stable at 600 °C: Al₉Co₂, Al₁₃Co₄, Al₃Co, Al₅Co₂, AlCo, Co₃W, Co₇W₆, Al₄W, Al₅W and Al₁₂W. Except for Al₃Co, Al₅Co₂, AlCo, Co₃W, Co₇W₆ and Al₄W, negligible solubility of the third component in the binary phases can be deduced from our

measurements. The solubility of W in AlCo is 3.0 at%. The solubility of Al in Co_3W and Co_7W_6 are both 3.1 at%, and the solubility of Co in Al_4W reaches 3.6 at%.

4.1 Phase relationship in the Al-rich corner

In the Al-rich part of the triangle, six three-phase regions, including (1) $(\text{Al})+\text{Al}_{12}\text{W}+\text{Al}_9\text{Co}_2$, (2) $\text{Al}_5\text{W}+\text{Al}_{12}\text{W}+\text{Al}_9\text{Co}_2$, (3) $\text{Al}_5\text{W}+\text{Al}_4\text{W}+\text{Al}_9\text{Co}_2$, (4) $\text{Al}_{13}\text{Co}_4+\text{Al}_4\text{W}+\text{Al}_9\text{Co}_2$, (5) $\text{Al}_{13}\text{Co}_4+\text{Al}_4\text{W}+\text{Al}_3\text{Co}$ and (6) $\text{Al}_5\text{Co}_2+\text{Al}_4\text{W}+\text{Al}_3\text{Co}$ were defined from the micrographs of alloy A1-6 (see Fig.5 (a-f)) and typical XRD patterns shown in Fig.6 (a-d). Within the BSE micrographs of alloys (A1-6), the phase with higher atomic number appeared to be brighter.

In the microstructure image of alloy A1 ($\text{Al}_{91}\text{-Co}_6\text{-W}_3$) Fig.5 (a), the dark areas corresponds to the (Al) phase, the dark-grey areas stand for the Al_9Co_2 phase, and the light-grey areas represent the Al_{12}W phase. Its XRD pattern is presented in Fig.6 (a), where the characteristics peaks of (Al) , Al_9Co_2 and Al_{12}W phases are well marked by different symbols.

Fig.5 (b) exhibits the BSE micrograph of alloy A2 ($\text{Al}_{86}\text{-Co}_5\text{-W}_9$), three phases $\text{Al}_5\text{W}+\text{Al}_{12}\text{W}+\text{Al}_9\text{Co}_2$ are observed. The identified XRD pattern of alloy A2 is shown in Fig.6 (b), where the existence of Al_5W , Al_{12}W , and Al_9Co_2 is confirmed.

Fig.5 (c) exhibits the BSE micrograph of alloy A3 ($\text{Al}_{80}\text{-Co}_5\text{-W}_{15}$). The dark grey matrix phase is Al_9Co_2 , and the contrast between Al_5W and Al_4W is low, but we can distinguish them from their shapes. The large blocks belong to Al_5W , and small entrapped in the Al_5W phase is the Al_4W phase. Its XRD pattern is presented in Fig.6 (c), where the characteristics peaks of Al_5W , Al_4W and Al_9Co_2 phases are well marked by different symbols.

Fig.5 (d) illustrates the BSE image of A4 alloy ($\text{Al}_{78}\text{-Co}_{19}\text{-W}_3$), in which the brightest phase is Al_4W . Small grey $\text{Al}_{13}\text{Co}_4$ blocks exist within Al_9Co_2 matrix. Since the proportion of $\text{Al}_{13}\text{Co}_4$ in A4 alloy is low, the characteristic peaks of the $\text{Al}_{13}\text{Co}_4$ phase in Fig.6 (d) is not so obvious compared to that of the Al_9Co_2 phase or the Al_4W phase.

Alloy A5 ($\text{Al}_{75}\text{-Co}_{22}\text{-W}_3$) is located in the three-phase region of $\text{Al}_{13}\text{Co}_4+\text{Al}_4\text{W}+\text{Al}_3\text{Co}$, as shown in Fig.5 (e), in which the dark gray matrix phase is $\text{Al}_{13}\text{Co}_4$, the gray block phase is the Al_3Co phase, and the light grey needle-like phase is Al_4W . Note from the BSE micrograph of alloy A6 ($\text{Al}_{73}\text{-Co}_{25}\text{-W}_2$) in Fig.5 (f), the Al_5Co_2 phase is in equilibrium with Al_4W and Al_3Co phases.

4.2 Phase relationship in the W-rich corner

In the **W**-rich part, the (W) phase is in equilibrium with all the nearby binary phases (Al_4W , Al_9Co_2 , AlCo , Co_7W_6) and a new ternary phase T.

Alloy A7 ($\text{Al}_{65}\text{-Co}_{17}\text{-W}_{18}$) is located in the three-phase region of $\text{Al}_5\text{Co}_2+\text{Al}_4\text{W}+(\text{W})$, as shown in Fig.5 (g), in which the dark gray matrix phase is Al_5Co_2 , the gray phase is the Al_4W phase, and the phase on Al_4W is (W). According to the BSE image of alloy A8 ($\text{Al}_{58}\text{-Co}_{35}\text{-W}_7$) in Fig.5 (h), the (W) phase is also in equilibrium with AlCo and Al_5Co_2 phases. Its XRD pattern is exhibited in Fig.7 (a), where the characteristics peaks of the above three phases are evidenced.

The new ternary phase T is in equilibrium with AlCo and (W) in A9 alloy ($\text{Al}_{30}\text{-Co}_{55}\text{-W}_{15}$), as shown in Fig.5 (i), in which the matrix phase is AlCo , the brightest phase is the (W) phase, and the phase located along the grain boundary of AlCo is the ternary phase T. Seen from the BSE image of alloy A10 ($\text{Al}_{16}\text{-Co}_{61}\text{-W}_{23}$) in Fig.5 (j), the T phase is also in equilibrium with Co_7W_6 and (W) phases. XRD patterns of alloy A9 and alloy A10 are compared in Fig.7 (b). Most of the characteristic peaks of the T phase marked in alloy A9 ($\text{Al}_{30}\text{-Co}_{55}\text{-W}_{15}$) can be found in alloy A10 ($\text{Al}_{16}\text{-Co}_{61}\text{-W}_{23}$).

4.3 Phase relationship in the Co-rich corner

Regarding to the Co-rich part of the triangle, five three-phase regions, including (11) $\text{T}+\text{Co}_7\text{W}_6+\text{Co}_3\text{W}$, (12) $\text{T}+\gamma'+\text{Co}_3\text{W}$, (13) $(\text{Co})+\gamma'+\text{Co}_3\text{W}$ and (14) $(\text{Co})+\gamma'+\text{T}$ are defined from the micrographs of alloys A11-16 (see Fig.5 (k-n)) and typical XRD patterns shown in Fig.8.

Figure 5k illustrates the microstructure image of A11 alloy, which clearly contains three phases T, Co_7W_6 and Co_3W . The Co_7W_6 phase is wrapped by a thin layer of Co_3W . BSE image of A 12 alloy is illustrated in Fig.5 (l). As seen, three phases with different shapes exist in the alloy. According to EDS result, the matrix large block phase corresponds to T, the irregular shaped block phase is γ' , and the white phase distributed along the boundary of γ' is Co_3W .

The A13 alloy exhibited a $(\text{Co})+\gamma'+\text{Co}_3\text{W}$ microstructure which consists of mostly strip shaped Co_3W phase with blocky γ' and smaller black blocky (Co) phase, as shown in Fig.5 (m). The microstructure of A14 alloy is shown in Fig.5 (n). The microstructure consists of compact blocky γ' phase, loose needle-like phase and the T phase. The T phase distributed around γ' and (Co) phases. The phase makeup of the loose needle-like has been analyzed with XRD. As shown in Fig.8, characteristic peaks of (Co) and T are evidenced, and the γ' phase is well indexed with an L1_2 structure ($a=0.3607\text{nm}$), indicating loose needle-like phase should be composed of (Co), and A14

locates in the ternary region consisting of the above three phases. In addition, as the all A12-14 alloys contains the γ' phase, their XRD patterns have been compared in Fig.8, it can be seen that the phases in the A12-14 alloys determined from EDS results are evidenced. In addition, since the T phase is in equilibrium with (Co) or AlCo as illustrated by the sample A14-16 or A9 alloy, according to the phase rule, it is believed that ternary phase region of T+AlCo+(Co) at 600 °C should be existing.

4.4 Ternary phases in this system

As reviewed earlier, stability of the ternary phase γ' is controversial. So only few researchers have reported the composition of this dispute phase. As listed in Table 3, the composition of the γ' ternary phase at 600 °C is slightly richer in Al, and leaner in W and Co comparing to the compositions at 900 °C [1, 11, 18, 30, 31]. The deviation of the composition might be contributed to the uncertainty in the EDS instrument or the effect of temperature.

The average composition of the T phase is 22.6 at.% Al, 67.0 at.% Co and W in balance. As the composition of the T phase is around Co_2X ($\text{X}=\text{Al}, \text{W}$), which is close to typical structures, such as Laves phase, we have tried to index them with the three polytypes of the Laves phases-hexagonal C14 and C36 and cubic C15, none of their XRD patterns matched with that of the T phase. So the XRD pattern of the T phase was refined using Jade software. The peaks were indexed to the cubic system, resulting in a figure of merit of $F(13) = 32.5(20)$. The lattice parameters of the crystal were $a = b = c = 1.051941 \text{ nm}$. In addition, the WCoAl compound (prototype MgZn_2) [31] was not found in this system at 600 °C.

Seen from the phase relationship (Fig.3) calculated from thermodynamic dataset [18], both the γ' and T are not existing in the Al-rich region, and the AlCo phase is in equilibrium with the Al_4W phase in this section. The calculated results are not consistent with the phase relationship determined in this study (shown in Fig.4), so the results of the present work should be included in the evaluation of this Al-Co-W ternary system in future.

5. Conclusion

Based on SEM-EDS analyses and XRD studies, phase relations in the Al-Co-W ternary system in the entire composition range at 600°C have been constructed in the present work. The following results are obtained:

- 1) Isothermal section of this system consists of 15 three-phase regions and 28 two-phase

regions.

2) Ten binary phases, namely Al_9Co_2 , $\text{Al}_{13}\text{Co}_4$, Al_3Co , Al_5Co_2 , AlCo , Co_3W , Co_7W_6 , Al_4W , Al_5W and Al_{12}W , are stable at 600°C . The solubility of W in AlCo is 3.0 at%, the solubility of Al in Co_3W and Co_7W_6 are both 3.1 at%, and the solubility of Co in Al_4W reaches 3.6 at%. Solubility of the third component in the other binary phases are limited.

3) Besides the $\text{L1}_2\text{-}\gamma'$ phase, a new ternary phase T (prototype Y_3BO_6) has been found. The average composition of the T phase is 22.6 at.% Al, 67.0 at.% Co and W in balance.

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Figure captions:

Fig. 1 Constituent binary phase diagrams in the Al-Co-W ternary system [22, 23, 25]

Fig. 2 The isothermal section of phase diagram of Al-Co-W system at (a) 1173 K and (b) 1273 K determined by Sato et al. [1]

Fig. 3 Nominal compositions of designed alloys marked in the calculated phase diagram with data from Zhu et al. [18]

Fig. 4 Phase relations in the ternary Al-Co-W system, constructed from samples annealed at 600°C

Fig. 5 Microstructure images of alloys annealed at 600 °C, in back scattered electrons (BSE), (a) A1: (Al)+Al₁₂W+Al₉Co₂, (b) A2: Al₅W+Al₁₂W+Al₉Co₂, (c) A3: Al₅W+Al₄W+Al₉Co₂, (d) A4: Al₁₃Co₄+Al₄W+Al₉Co₂, (e) A5: Al₁₃Co₄+Al₄W+Al₃Co; (f) A6: Al₅Co₂+Al₄W+Al₃Co; (g) A7: Al₅Co₂+Al₄W+(W), (h) A8: AlCo+Al₅Co₂+(W), (i) A9: AlCo+(W)+T, (j) A10: Co₇W₆+(W)+T, (k) A11: T+Co₇W₆+Co₃W, (l) A12: T+γ'+Co₃W, (m) A13: (Co)+γ'+Co₃W and (n) A14: γ'+(Co)+T

Fig. 6 XRD patterns of the alloys (a) A1, (b) A2, (c) A3 and (d) A4 which were annealed at 600 °C for 90 days

Fig. 7 XRD patterns of the alloys (a) A8, (b) A9 and A10 which were annealed at 600 °C for 120 days

Fig. 8 XRD patterns of the alloys A12, A13 and A14 which were annealed at 600 °C for 120 days

Table captions:

Table 1 Crystal structure data for the phases in the Al-Co-W system at 600 °C

Table 2 Equilibrium compositions of the Al-Co-W ternary system determined in the present work

Table 3 Ternary phases in the Al-Co-W system

Fig.1

Fig.2(a)

Fig.2(b)

(b) $T=1273\text{K}$

Fig.3

Fig.4

Fig.5(a)

Fig.5(b)

Fig.5(c)

Fig.5(d)

Fig.5(e)

Fig.5(f)

Fig.5(g)

Fig.5(h)

Fig.5(i)

Fig.5(j)

Fig.5(k)

Fig.5(l)

Fig.5(m)

Fig.5(n)

Fig.6(a)

Fig.6(b)

Fig.6(c)

Fig.6(d)

Fig.7(a)

Fig.7(b)

Fig.8

Table 1 Crystal structure data for the phases in the Al-Co-W system at 600 °C

	Phase	Pearson symbol	Space group	Prototype	Strukturbericht designation	Ref.
Al-Co	(Al)	<i>cF4</i>	<i>Fm-3m</i>	A1	Cu	[22]
	(Co)	<i>cF4</i>	<i>Fm-3m</i>	A1	Cu	[22]
	Al ₉ Co ₂	<i>mP22</i>	<i>P2₁/a</i>	---	---	[22]
	Al ₁₃ Co ₄	<i>oP102</i>	<i>Pmn2₁</i>	---	---	[22]
	Al ₃ Co	---	---	---	---	[22]
	Al ₅ Co ₂	<i>Hp28</i>	<i>P6₃/mmc</i>	---	---	[22]
	AlCo	<i>cP2</i>	<i>Pm-3m</i>	B2	CsCl	[22]
Al-W	(W)	<i>cF4</i>	<i>Fm-3m</i>	A2	W	[23]
	γ-Al ₁₂ W	<i>cI26</i>	<i>Im-3</i>	---	---	[23]
	δ-Al ₅ W	<i>hP12</i>	<i>P6₃</i>	---	Al ₅ Mo	[23]
	ε-Al ₄ W	<i>mC30</i>	<i>Cm</i>	---	---	[23]
Co-W	Co ₃ W	<i>hP8</i>	<i>P6₃/mmc</i>	D0 ₁₉	Ni ₃ Sn	[24]
	Co ₇ W ₆	<i>hR13</i>	<i>R-3mH</i>	D8 ₅	Fe ₇ W ₆	[24]

Table 2 Equilibrium compositions of the Al-Co-W ternary system determined in the present work

No.	Nominal composition (at.%)	Phases	Composition (at.%)		
			Al	Co	W
A1	Al91-Co6-W3	(Al)	99.5	0.4	0.1
		Al ₁₂ W	91.2	0.1	8.7
		Al ₉ Co ₂	81.8	18.1	0.1
A2	Al86-Co5-W9	Al ₉ Co ₂	81.8	18.0	0.2
		Al ₁₂ W	90.9	0.3	8.7
		Al ₅ W	81.2	0.1	18.7
A3	Al80-Co5-W15	Al ₉ Co ₂	81.5	18.2	0.3
		Al ₅ W	81.5	0.7	17.8
		Al ₄ W	77.7	0.5	21.8
A4	Al78-Co19-W3	Al ₉ Co ₂	81.3	17.9	0.8
		Al ₁₃ Co ₄	75.8	23.4	0.8
		Al ₄ W	77.1	2.1	20.8
A5	Al75-Co22-W3	Al ₁₃ Co ₄	75.6	23.8	0.6
		Al ₃ Co	72.8	25.3	1.9
		Al ₄ W	74.6	3.6	21.8
A6	Al73-Co25-W2	Al ₃ Co	74.8	24.4	0.8
		Al ₅ Co ₂	72.1	27.4	0.5
		Al ₄ W	73.3	3.4	22.3
A7	Al65-Co17-W18	Al ₅ Co ₂	70.2	27.1	2.7
		Al ₄ W	73.1	2.3	23.6
		(W)	8.1	1.2	90.7
A8	Al58-Co35-W7	Al ₅ Co ₂	69.1	28.3	2.6
		AlCo	52.5	44.9	2.1
		(W)	6.2	3.1	90.7
A9	Al30-Co55-W15	AlCo	40.7	57.2	2.1
		T	24.3	66.2	9.5
		(W)	2.6	4.2	93.2
A10	Al18-Co60-W22	T	23.1	65.1	11.8
		Co ₇ W ₆	3.1	52.8	44.1
		(W)	1.4	2.1	96.5
A11	Al17-Co65-W18	Co ₃ W	2.7	72.1	25.2
		T	22.5	67.4	10.1
		Co ₇ W ₆	2.3	51.9	45.8
A12	Al11-Co73-W16	Co ₃ W	3.1	74.2	22.7
		γ'	13.8	73.1	13.1
		T	22.8	67.8	9.4
A13	Al5-Co79-W16	γ'	11.5	77.2	11.3
		Co ₃ W	2.2	74.1	23.7
		(Co)	6.7	91.5	1.8
A14	Al14-Co78-W8	γ'	13.1	75.8	11.1
		T	21.7	68.5	9.8
		(Co)	7.0	91.4	1.6
A15	Al18-Co70-W12	γ'	13.7	74.9	11.4
		T	20.4	68.8	10.8
A16	Al36-Co59-W5	AlCo	38.5	58.5	3.0
		T	23.2	65.6	11.2

Table 3 Ternary phases in the Al-Co-W system

Phase	Temperature (°C)	Composition (at.%)			Method	Refs.
		Al	Co	W		
γ'	600	13.1±0.9	75.2±1.9	11.7±1.0	EDS	This work
	900	10.03±0.09	77.5±0.11	12.48±0.02	APT ^a	[30]
	900	9.0	78.7	12.3	EPMA ^b	[1] ^c
	900	9.3±0.74	21.3±1.47	12.0±0.43	EDS	[11]
	900	9.2	78	12.8	EPMA	[18] ^c
T	600	22.6±1.6	67±2.6	10.4±1.0	EDS	This work
AlWCo	---	33.33	33.33	33.34	---	[31]

^a APT is the abbreviation of atom-probe tomography

^b EPMA is the abbreviation of electron probe micro-analyses

^c Data reported graphically in the phase diagram