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INVESTIGATING THE Al-Cr-La TERNARY SYSTEM: Al-RICH CORNER PHASE EQUILIBRIA AT 600 °C

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Abstract

The phase equilibria of the ternary Al-Cr-La system were investigated in the Al-rich corner at 600 °C, with a minimum Al content of 98.77 at.%. The formed phases, transformation temperatures (specifically liquidus and solidus), and microstructure evolution were experimentally determined by isothermal annealing at 600 °C for 600 hours and by Differential Scanning Calorimetry (DSC) analysis. A Scanning Electron Microscope (SEM) equipped with Energy-Dispersive X-ray Spectroscopy (EDXS) was used to fully characterize the samples. The equilibrium microstructure consists of (Al), the binary phase $Al_{45}Cr_7$, and the ternary phase $LaCr_2Al_{20}$ in samples with increased Cr content (from 0.03 up to 1.12 at.%), while it consists of (Al), the mixture (Al) + $Al_{11}La_3$, and the ternary $LaCr_2Al_{20}$ phase in samples with increased La content (from 0.03 up to 0.45 at.%). It was observed that even a small amount of alloying elements leads to the formation of the ternary phase.

Keywords: *Al-Cr-La; Ternary phase system; Phase equilibria; Microstructure*

1. Introduction

Aluminum alloys exhibit exceptional physical and mechanical properties, including high strength, good wear resistance, corrosion resistance, stiffness and elongation [1–6]. This unique combination makes them a widely used structural material [7–9] in various transport industries, such as automotive [10–16], rail [17] and aerospace [18–20], mainly due to their high strength-to-weight ratio. In the EU, transport is responsible for 20% of all greenhouse gas (GHG) emissions, with road transport alone contributing 72% [21–23]. In fact, transport has the largest impact on GHG emissions of all sectors, including agriculture, industry, trade, and electricity generation [24, 25]. More specifically, car transport contributes approximately 12% of total GHG emissions in the EU. Consequently, car manufacturers are obliged to reduce the average carbon emissions of their fleets by 37.5% between 2021 and 2030 [26]. A very effective strategy to achieve these reductions is to reduce vehicle weight, as lighter vehicles consume less fuel and therefore leave a smaller CO_2 footprint [23, 27, 28]. For this reason, as already mentioned aluminum alloys are already extensively utilized in the transport industry, and their application will continue to increase.

In order to improve the mechanical properties and suitability of aluminum alloys for the transport industry, they are often alloyed with rare earth elements (REE). In particular, the addition of La has been shown to refine the secondary dendrite arm spacing (SDAS) of the primary α-Al phase/grains [29–32]. Furthermore, previous studies [29–37] have consistently demonstrated that La additions improve both mechanical properties and corrosion resistance. In our previous work [38], we investigated the influence of La additions on a high-strength 7xxx Al-Zn-Mg-Cu alloy. This alloy typically contains small amounts of Cr. Surprisingly; La was found to form a ternary phase $LaCr_2Al_{20}$. This was unexpected as the CALPHAD calculations with Thermo-Calc [39], database TCAL9 (Al-Alloys v9.1) [40], did not show the phase and the ternary phase system Al-Cr-La is not included in the mentioned database and it is generally known that Cr and La do not normally form intermetallic phases with each other; this is explained in more detail in the literature review. The absence of this specific phase in the existing calculated ternary systems has motivated our current research on the Al-Cr-La ternary system. This ternary phase could be important for the development of the next generation of high-strength aluminum alloys of the 7xxx group, as it may potentially prevent excessive growth of the

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aluminum grain size. This would be beneficial in conjunction with the improvement of mechanical properties. As Cr has been added to most of these alloys, alloying with La leads to the formation of the ternary phase [38]. One of the objectives was to determine the minimum La and/or Cr content in the Al-rich corner at 600 °C to form a ternary phase $LaCr_2Al_{20}$ and also to study the evolution of the microstructure and phases present in the alloys.

In order to provide a better understanding of the phase equilibria in the ternary system Al-Cr-La, the three relevant binary phase diagrams described in the literature, Al-Cr, Al-La, and La-Cr, are briefly presented and the corresponding references are given. Limited experimental results for this ternary system are reviewed and the crystallographic information on its stable solid phases is presented in Table 3.

1.1. Binary systems

1.1.1. Al-Cr binary system

The binary Al-Cr phase diagram was analyzed by Murray [41], relying largely on experimental data from Köster et al. [42]. This phase system is widely recognized and has been studied in detail by numerous researchers over the years [43–56], with the most recent study being conducted by S. Cui et al. [57]. The phases present in this binary system, and their corresponding crystal structures are listed in Table 1.

Table 1. *Al-Cr crystal structure data*

Phase	Composition at.% Cr	Space group	Pearson symbol	Prototype	Reference
(Al)	0-0.37	$Fm\bar{3}m$	cF4	Cu	[43]
Al_7Cr	12.5-1	C2/m	mS104	$Al_{45}V_7$	[41, 43, 57, 58]
$Al_{11}Cr_2$	15.2-17	P2	mP48	-	[41, 43, 47, 54, 57]
Al_4Cr	18.5-20	P2/m	mP180	μ_Al_4Mn	[43, 56, 57]
$Al_{11}Cr_4$	25	$P\bar{1}$	aP30	-	[43, 48]
αAl_9Cr_4	30-42	$I\bar{4}3m$	cI52	-	[41, 43]
βAl_8Cr_5	30-42	-	-	-	[41, 43]
αAl_8Cr_5	30-42	$R\bar{3}m$	hR26	Al_8Cr_5	[41, 43]
AlCr	60.5-63	$Pm\bar{3}m$	cP2	CsCl	[43, 55]
$AlCr_2$	65.5-71.4	I4/mmm	tI6	$MoSi_2$	[41, 43, 57]
(Cr)	54.5-100	$Im\bar{3}m$	cI2	W	[43]

1.1.2. Al-La binary system

The binary Al-La phase diagram was analyzed by Gschneidner [59] mainly on the basis of Buschow's [60] investigation of the Al-La system. This binary system is also widely recognized and has been studied in detail by numerous researchers [61–72], with the most recent thermodynamic evaluation and optimization carried out by Jin et al. [65]. The phases present in this binary system and their corresponding crystal structures are listed in Table 2.

1.1.3. La-Cr binary system

The binary La-Cr phase diagram was redrawn by Massalski et al. [73] on the basis of the investigations by Barabash et al. [74]. This system has been studied less frequently compared to the two previously mentioned, although there are some studies [74–78]. The recent work by Chan et al. [78] was also included in the review by Okamoto [79]. As noted by Okamoto [79], there is a significant discrepancy regarding the maximum solubility of La in Cr. While earlier studies [75] suggested higher values, more recent work [76] indicates a much lower solubility of approximately 0.6 at.%. It is known that this system contains Cr, γLa, βLa and αLa phases. Since no binary intermetallic phases are formed in the La-Cr system, the crystal structure data for these constituent phases have already been presented in Table 1 and Table 2.

1.2. Al-Cr-La ternary phase diagram

The Al-Cr-La ternary system was first investigated by Kripyakevich et al. [80], who reported the existence of the ternary compound $LaCr_2Al_{20}$. Its existence and crystal structure were subsequently confirmed by Emes-Misenko [81] using X-ray diffraction (XRD) analysis. Emes-Misenko [81] identified three ternary phases (summarized in Table 3) and constructed the isothermal section at 500°C (Figure 1); however, the precise composition ranges for these phases remain largely undetermined.

In the Al-rich corner, $LaCr_2Al_{20}$ is known to exist. However, specific data on its minimum and maximum Cr and La content are still lacking in the literature. The 1971 study [81] remains the only comprehensive investigation of the phase equilibria in this system. Although more recent studies [84, 85] have examined $LnCr_2Al_{20}$ compounds (Ln = La, Gd, Yb), their primary focus was the interaction of conduction electrons with local magnetic moments. These works

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Table 2. *Al-La crystal structure data*

Phase	Composition at.% La	Space group	Pearson symbol	Prototype	Reference
$\alpha Al_{11}La_3$	0.01-21.4	Immm	oI28	$\alpha Al_{11}La_3$	[59, 65, 66, 72]
$\beta Al_{11}La_3$	0.01-21.4	I4/mmm	tI10	Al_4Ba	[59, 65, 66, 72]
Al_3La	21.4-25	$P6_3/mmc$	hP8	Ni_3Sn	[59, 60, 65, 66, 72]
Al_xLa or $La_{22}Al_{53}$	25-29.3	$P6_3/mmm$	hP3	AlB_2	[59, 65, 66]
Al_2La	29.3-33.3	$Fd\bar{3}m$	cF24	Cu_2Mg	[59, 60, 65, 66, 72]
AlLa	33.3-50	Cmc2 or Cmcm	oS16	AlCe	[59, 60, 65, 66, 72]
$AlLa_3$	50-75	$P6_3/mmc$	hP8	Ni_3Sn	[59, 60, 65, 66, 72]
(γLa)	75-100	$Im\bar{3}m$	cI2	W	[59, 65, 72]
(βLa)	75-100	$Fm\bar{3}m$	cF4	Cu	[59, 65, 72]
(αLa)	75-100	$P6_3/mmc$	hP4	αLa	[59, 65, 72]

Table 3. *Al-Cr-La crystal structure data*

Phase	Pearson symbol	Prototype	Reference
$LaCr_2Al_{20}$ or τ	cF184	$Mg_3Cr_2Al_{18}$	~4.5La-9Cr-86.5Al [81, 82]
$LaCr_{4-x}Al_{8+x}$ or ψ Or $LaCr_4Al_8$ Or $LaCr_3Al_9$	tI26	$ThMn_{12}$	not a homogeneity range, but two different compositions reported: x = 0 [82, 83] x = 1 [81, 82]
$La_2Cr_6Al_{11}$ or φ	hR19	Th_2Zn_{17}	[81, 82]

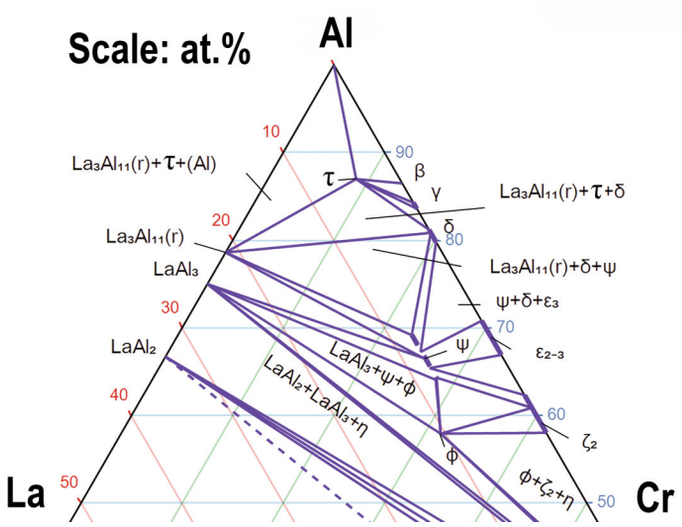

Figure 1. *Partial isothermal section through the ternary phase diagram of Al-Cr-La at 500 °C [82]*

are relevant as they confirm the structural stability of the $LnCr_2Al_{20}$-type phases, but they do not provide the thermodynamic or compositional data required for industrial alloy design.

2. Experimental methods

2.1. Sample preparation

Pure aluminum (99.99 wt.%, WAV AG "Kryal"), chromium (99.99 wt.%, Thermo Scientific Chemicals) and lanthanum (99.99 wt.%, JM Alfa Aesar) were used as starting materials for the alloy production. The alloys, each weighing 3 g, were produced as button-shaped castings with approximate dimensions of 20 mm in diameter and 5–10 mm in thickness. These were fabricated in a vacuum arc melting system (MTI SP-MSM208) using a non-consumable tungsten electrode on a water-cooled copper hearth. A high purity argon atmosphere (Ar 6.0, 99.999%) was maintained, which was further purified by melting a titanium getter (99.7 wt.%). The protective gas pressure in the furnace was 50 kPa at room temperature. Before the introduction of argon, the melting chamber was evacuated, and the residual

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pressure was monitored with a vacuum gauge. The alloys were remelted four times to ensure chemical homogeneity. Prior to annealing, the chemical composition of the samples was checked using a Thermo Fisher Scientific Quanta 650 scanning electron microscope (SEM) equipped with an Oxford Instruments AZtec Live, Ultim Max SDD 40 mm^2 system for energy-dispersive X-ray spectroscopy (EDXS). An accelerating voltage of 20 kV was used for all SEM/EDXS analyses to ensure accurate quantification and appropriate penetration depth. Homogenization was carried out in a Xiamen Tmax Battery Equipments Limited SK2-4-12TPB3 tube furnace under an inert argon (Ar 5.0, 99.999%) atmosphere. Before the protective gas was introduced, the tube was evacuated four times with a vacuum pump, and the residual pressure was continuously monitored with a vacuum gauge. To further purify the inert gas and prevent oxidation, magnesium crisps (99.99 wt.%) were added to the tube to act as an oxygen carrier. The samples were placed on the Al_2O_3 crucibles before homogenization, which was carried out at 600 °C for 600 hours. After the homogenization process, the samples were quenched in ice-cold water to maintain the equilibrium structure.

2.2. Differential scanning calorimetry (DSC)

The phase transformation temperatures were determined with a SETARAM Labsys EVO device equipped with a DSC rod. The DSC was calibrated with high purity standards of In (99.99%), Sn (99.99%), Al (99.99%) and Ag (99.99%) from the NETZSCH standard calibration set. A high-purity argon atmosphere (Ar, 99.9999%) was used as a protective gas. Prior to sample analysis, a baseline correction run was performed at a heating/cooling rate of 5 °C/min, ranging from 25 °C to 1100 °C and back to 25 °C. All samples were then analyzed using the temperature program mentioned above. Al_2O_3 crucibles with a lid were used for all runs, including calibration, correction, and sample analysis. To ensure accuracy in identifying the melting sequences, DSC heating curves were evaluated by determining the characteristic onset and peak temperatures. These were interpreted using the methodologies established by Boettinger et al. [86] for complex multicomponent systems, in which the sequence of endothermic events corresponds to the successive dissolution of phases until the liquidus is reached.

2.3. Microstructure analysis

The samples for microstructural analysis were ground on silicon carbide paper and then polished with a diamond-water suspension on cloth discs. Prior to SEM-EDXS (Energy-Dispersive X-ray Spectroscopy) analysis, all metallographic samples underwent quality control of the polished surface using a Leica DM4000 M optical microscope equipped with the AxioCam ERc 5s high-resolution digital camera. The microstructure was then analyzed using the Zeiss EVO 40 SEM with PentaFET EDXS detector (Oxford Instruments). The BSE (Backscattered Electron) mode was used to capture the images.

3. Results and Discussion

In order to analyze the aluminum-rich corner in the Al-Cr-La ternary phase diagram, 10 alloys with higher Cr (1-5) and La (6-10) content were produced. The global chemical composition is shown in Table 4 (compositions are calculated averages measured with EDXS); in addition to the chemical composition, the same table also lists the corresponding equilibrium phases at 600 °C for each alloy produced. The results show that a ternary $LaCr_2Al_{20}$ phase forms, even with the addition of La and/or Cr at concentrations as low as 0.03 at.%. The phases were determined by SEM-EDXS. As the ideal stoichiometry of the $LaCr_2Al_{20}$ phase is established in the literature, EDXS analysis was performed to confirm the presence of this phase and to determine its actual composition in the investigated samples. It should be noted that the $Al_{11}La_3$ phase (Table 4) is in the eutectic mixture with Al, this will be further discussed during the metallographic and DSC analysis. As the phases were only analyzed by EDXS, the phase assignments are estimates based on the chemical composition obtained.

Based on our results, we determined the phase equilibria at 600 °C in the Al-rich corner, see Figure 2. Since no data were available for the red dashed line, we took it from the ternary phase diagram drawn in the literature at 500 °C [81, 82].

Table 4. *Chemical composition of the samples with the corresponding equilibrium phases in the microstructure*

Sample	at.%			Detected phases		
	Al	Cr	La			
1	98.89	1.08	0.03	$Al_{45}Cr_7$	$LaCr_2Al_{20}$	(Al)
2	98.83	1.12	0.05	$Al_{45}Cr_7$	$LaCr_2Al_{20}$	(Al)
3	99.08	0.84	0.08	$Al_{45}Cr_7$	$LaCr_2Al_{20}$	(Al)
4	98.92	0.95	0.13	$Al_{45}Cr_7$	$LaCr_2Al_{20}$	(Al)
5	98.77	1	0.23	$Al_{45}Cr_7$	$LaCr_2Al_{20}$	(Al)
6	99.58	0.03	0.39	$Al_{11}La_3$	$LaCr_2Al_{20}$	(Al)
7	99.45	0.11	0.44	$Al_{11}La_3$	$LaCr_2Al_{20}$	(Al)
8	99.34	0.23	0.43	$Al_{11}La_3$	$LaCr_2Al_{20}$	(Al)
9	99.2	0.35	0.45	$Al_{11}La_3$	$LaCr_2Al_{20}$	(Al)
10	99.15	0.46	0.39	$Al_{11}La_3$	$LaCr_2Al_{20}$	(Al)

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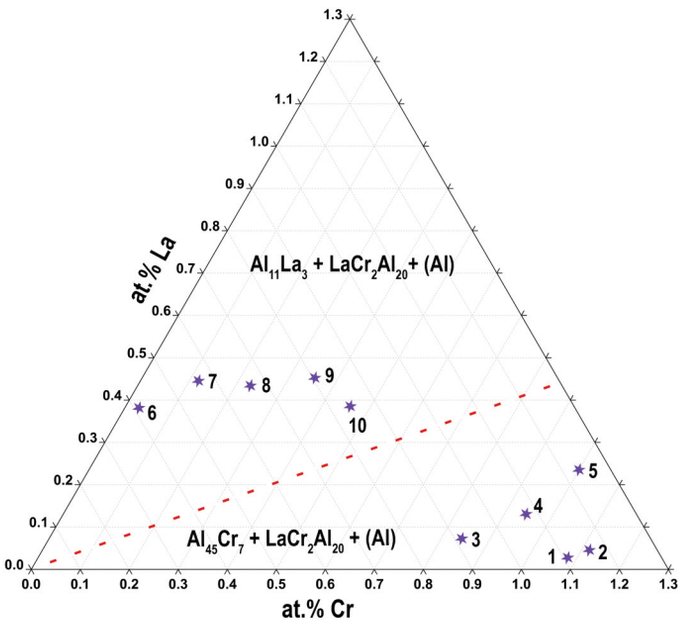

Figure 2. *Isothermal section through the diagram of the ternary phase Al-Cr-La at 600 °C*

3.1. DSC analysis

The DSC analysis was performed to determine the phase transformation temperatures. Based on the results, two different melting sequences can be recognized. For the samples with increased Cr content, we can recognize two peaks; the melting sequence for samples 1-5 is therefore as follows:

$$LaCr_2Al_{20} + (Al) + Al_{45}Cr_7 \leftrightarrow Al_{45}Cr_7 + L \leftrightarrow L \quad (1)$$

As an example, the representative part of the heating DSC curve of sample 3 is reported in Figure 3(a). We ascribe the low temperature large asymmetric peak to the melting of the ternary $LaCr_2Al_{20}$ phase and in the same peak the mixture $Al_{45}Cr_7$ + (Al) also melts. The second small peak (721±1 °C) belongs to the complete melting of the alloys.

The samples with increased La content (6-10) have three peaks; the melting sequence is as follows:

$$Al_{11}La_3 + (Al) + LaCr_2Al_{20} \leftrightarrow LaCr_2Al_{20} + Al_{45}Cr_7 + L \leftrightarrow Al_{45}Cr_7 + L \leftrightarrow L \quad (2)$$

The relevant part of the heating DSC curve of sample 10 is shown in Figure 3(b). In this case we were able to distinguish the lower temperature peaks: at 633±1 °C we have the melting of the mixture of $Al_{11}La_3$ + (Al) and at 645±1 °C the melting of the $LaCr_2Al_{20}$ ternary phase. The last peak at higher temperature (765±1 °C) fits the complete melting of the sample.

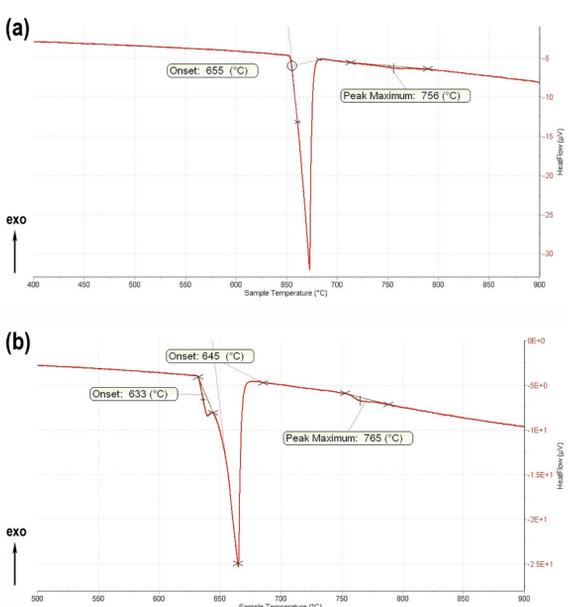

Figure 3. *DSC heating curves of sample 3 (a) and sample 10 (b)*

3.2. Metallography observations

The metallographic analysis of the annealed samples shows that the microstructure changes from that in Figure 4(a) (alloys 1–5, with higher Cr content) to that in Figure 4(b) (alloys 6–10, with higher La content). This difference can be clearly seen

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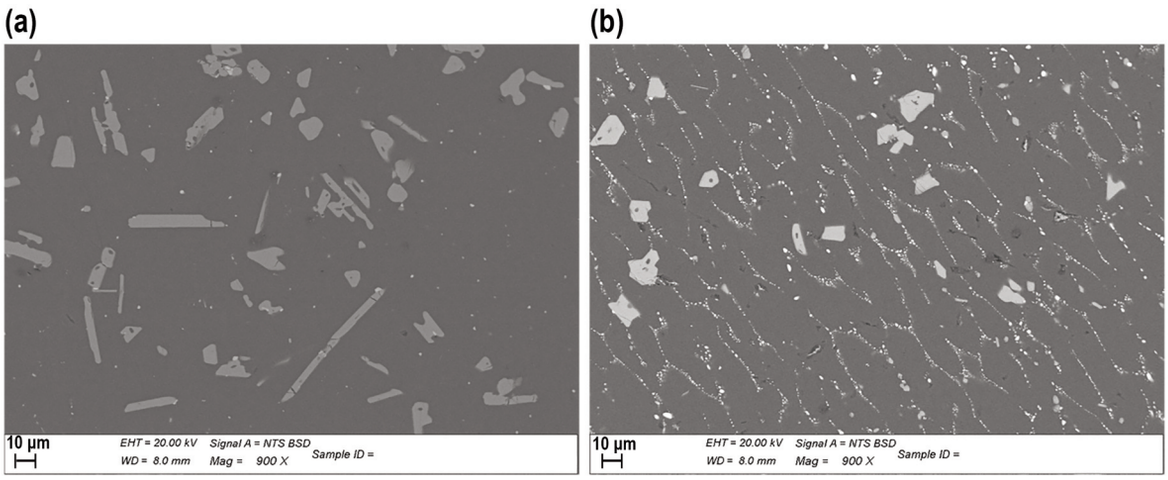
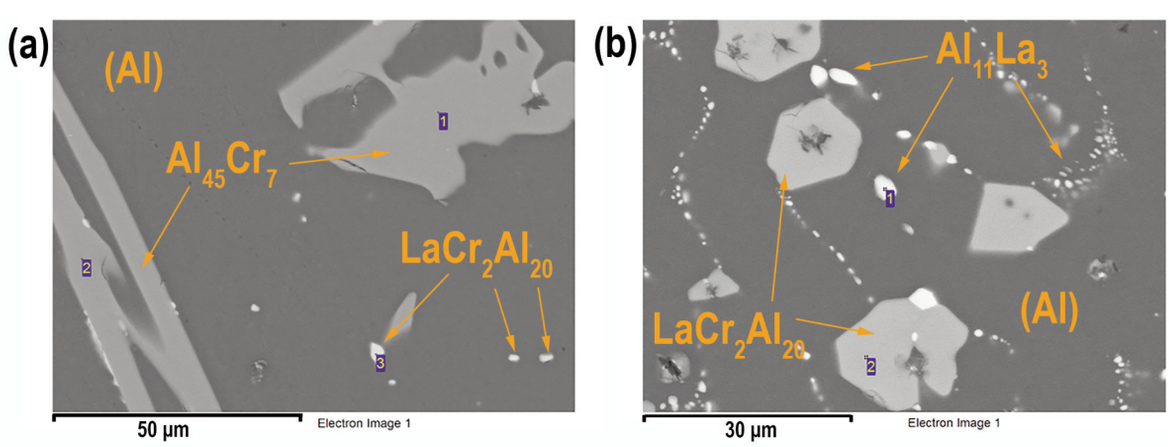


Figure 4. *SEM-BSE images of the microstructure of sample 1 (a) and sample 8 (b)*

in Figure 4, in which sample 1 (samples with higher Cr content, Figure 4(a)) is compared with sample 8 (samples with higher La content, Figure 4(b)). The main microstructural difference lies in the binary phase formed: alloys with higher Cr have an $Al_{45}Cr_7$ phase (large grey phases in Figure 4(a)), while alloys with higher La content contain the $Al_{11}La_3$ phase (small white phases along the grain boundaries in Figure 4(b)), which is mixed with (Al). All alloys analyzed also contain a (Al) phase and the ternary $LaCr_2Al_{20}$ phase (small white phases in Figure 4(a) and large grey phases in Figure 4(b)). In this section we present only the most representative results; the remaining ones can be found in the supplementary material.

To confirm the above estimates of the equilibrium phases, present in the samples (Table 4 and Figure 4), an EDXS analysis was performed. Figure 5 shows the EDXS analysis of sample 1 (Figure 5(a)) and sample 8 (Figure 5(b)). It is obvious that sample 1 (Figure 5(a)) consists of 3 phases, namely (Al), which is essentially the matrix, the binary phase $Al_{45}Cr_7$ (spectrum 1 and 2) and the ternary phase $LaCr_2Al_{20}$ (spectrum 3). On the other hand, sample 8 also consists of 3 phases, namely (Al), which is essentially the matrix, the binary phase $Al_{11}La_3$ (spectrum 1), which co-precipitate with (Al) and the ternary phase $LaCr_2Al_{20}$ (spectrum 2). One interesting thing that can be seen in Figure 5(a) is that the ternary phase $LaCr_2Al_{20}$ can be found around the $Al_{45}Cr_7$ phase. The



Spectrum	at.%		
	Al	Cr	La
1	86.4	13.6	
2	86.6	13.4	
3	88.9	7.5	3.6

Spectrum	at.%		
	Al	Cr	La
1	90.3		9.7
2	87.8	7.4	4.8

Figure 5. *SEM-BSE images with EDXS analysis of sample 1 (a) and sample 8 (b), with the corresponding chemical composition of the phases*

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morphology of the $LaCr_2Al_{20}$ phase, which frequently appears around $Al_{45}Cr_7$ particles, suggests that the ternary phase forms through a transformation involving the binary precursor.

In alloys with higher Cr content, the growth of $LaCr_2Al_{20}$ is constrained by the initial distribution of the $Al_{45}Cr_7$ phase, resulting in smaller ternary phase dimensions. Conversely, in alloys with lower Cr content, the smaller volume of the binary precursor is entirely consumed during the transformation, allowing the τ phase to develop a larger, less restricted morphology.

Regarding the solubility observed in the microstructures of the analyzed samples, there was a trend, i.e. in the samples with higher Cr content (1-5) only Cr was dissolved in the matrix, while in the samples with higher La content (6-10) only a small amount of La was dissolved (see supplementary material for data).

The observed microstructural differences, particularly the promotion of the τ phase by small La additions, are expected to affect the thermal stability and hardness of the alloys. From an industrial perspective, alloys with higher Cr content (alloys 1–5) appear more promising for the future development of Al-based materials, as they provide a balanced approach to improving properties while remaining economically viable.

4. Conclusions

Based on the results of this study, the following conclusions can be drawn:

1. The equilibria at 600 °C involving the ternary $LaCr_2Al_{20}$ phase have been determined. In alloys with higher Cr content (samples 1-5), together with $Al_{45}Cr_7$ phase and (Al) and, the alloys with higher La content (sample 6-10), consists of a $Al_{11}La_3$ + (Al). This is in agreement with the literature [80, 81], although we do not have information about the composition or the microstructure of the samples.
2. The study indicates that the ternary $LaCr_2Al_{20}$ (τ) phase forms immediately, even with a small (0.03 at.%) addition of La and/or Cr.
3. The DSC investigation revealed the characteristic temperatures of Al-rich alloys, which can be used to plan effective heat treatments for potentially newly developed aluminum alloys.
4. Since it was found that a small amount of La promotes the formation of the τ phase, positive effects on the future development of aluminum alloys are foreseeable from an economic perspective. In this regard, samples with higher Cr content appear more promising for the future development of aluminum-based materials.

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Authors' contributions

Tilen Balaško: Conceptualization, Methodology, Investigation, Formal analysis, Writing & editing – original draft. Adam Zaky: Methodology, Investigation. Simona Delsante: Methodology, Formal analysis, Investigation, Writing - review & editing – original draft.

Data availability

The data supporting the results of this study are available upon reasonable request from the corresponding author, Tilen Balaško.

Conflicts of interest

The authors declare no conflict of interest.

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ISPITIVANJE TROKOMPONENTNOG SISTEMA Al-Cr-La: FAZNE RAVNOTEŽE U Al-BOGATOM UGLU PRI 600 °C

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Apstrakt

Fazne ravnoteže trokomponentnog sistema Al-Cr-La ispitivane su u Al-bogatom uglu pri temperaturi od 600 °C, uz minimalni sadržaj Al od 98,77 at.%. Formirane faze, temperature transformacije (posebno likvidus i solidus temperature), kao i evolucija mikrostrukture eksperimentalno su određeni izotermskim žarenjem na 600 °C tokom 600 časova i analizom diferencijalne skenirajuće kalorimetrije (DSC). Za potpunu karakterizaciju uzoraka korišćen je skenirajući elektronski mikroskop (SEM) opremljen energetski disperzionom rendgenskom spektroskopijom (EDXS). Ravnotežna mikrostruktura sastoji se od faze (Al), binarne faze $Al_{45}Cr_7$ i trojne faze $LaCr_2Al_{20}$ kod uzoraka sa povećanim sadržajem Cr (od 0,03 do 1,12 at.%), dok se kod uzoraka sa povećanim sadržajem La (od 0,03 do 0,45 at.%) sastoji od faze (Al), mešavine (Al) + $Al_{11}La_3$ i trojne faze $LaCr_2Al_{20}$. Uočeno je da čak i mala količina legirajućih elemenata dovodi do formiranja trojne faze.

Ključne reči: *Al-Cr-La; Trokomponentni fazni sistem; Fazne ravnoteže; Mikrostruktura*

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