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Non-equilibrium solute partitioning in a laser re-melted Al–Li–Cu alloy

David W. Heard, Raynald Gauvin, Mathieu Brochu *

Department of Mining and Materials Engineering, McGill University, 3610 University Street, Wong Building, Montreal, Quebec H3A 2B2, Canada

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Abstract

Aluminum–lithium alloy AA2199 was rapidly solidified through the application of a laser re-melting process to determine the relationship between laser pulse energy and microsegregation during solidification. It was determined that laser pulse energies of the order of 0.125–0.5 J s resulted in a fine cellular solidification structure. Through comparison of the measured cell spacing with that predicted by the Kurz–Giovanola–Trivedi (KGT) model it was possible to estimate that solidification front velocities (SFV) of between 3 and 25 cm s^{-1} occurred during solidification. The SFV calculated from the KGT model was then input into the continuous growth model for solute trapping developed by Aziz to predict the deviation from equilibrium partitioning during solidification for all pulse energy levels employed. The chemical profile of lithium within the re-melted samples was measured using X-ray photoelectron spectroscopy and compared with that expected for equilibrium segregation. Measurement of the lattice parameter via X-ray diffraction revealed that the solute trapping phenomenon resulted in the formation of a super-saturated solid solution, as is evident through a reduction of the lattice parameter from 4.0485 Å for the starting material to 4.0399 Å in the material re-melted with a pulse energy of 0.125 J.

Keywords: Aluminum alloys; Rapid solidification; Solute segregation; Laser re-melting

1. Introduction

Recent developments in aluminum–lithium alloys have resulted in the development of third generation Al–Li alloys which include copper as an alloying element, such as the Al–Li–Cu alloy AA2199 developed by Alcoa [1]. The alloying of Al with 1 wt.% lithium results in a 3% reduction in density and a 6% increase in the Young's modulus of the alloy [2], resulting in a low density alloy with improved specific strength and stiffness [3]. This unique combination of properties makes Al–Li alloys desirable in applications where a reduction in vehicle weight is of the utmost importance, such as the aerospace and defense industries [4]. The replacement of traditional aerospace joining processes such as riveting or mechanical fastening by fusion welding processes creates the potential for further vehicle weight reductions [5]. One drawback of Al–Li alloys is difficulties associated with fusion welding of the material. The segregation of lithium towards grain boundaries (GB) during traditional (slow) solidification has been shown to result in the formation of lithium-bearing precipitates at GBs [6]. These lithium-rich precipitates then homogenize slip during deformation and lower the toughness of the alloy [7–9]. While this segregation may be reversed during cast-house production through thermo-mechanical homogenization (TMH) processes [10,11], when performing joining processes on large-scale components in situ TMH is not always possible. This constraint limits the widespread implementation of Al–Li alloys in applications in which fusion welding is required.

Rapid solidification processing (RSP) has previously been investigated as a method of circumnavigating the necessity of a TMH process [3,12]. RSP involves progressing the solidification front velocity (SFV) at high rates and has been shown to result in the formation of non-equilibrium structures, including metastable structures [13,14], and micro-segregation-free solidification [15] via the solute trapping phenomenon [16–19].

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* Corresponding author. Tel.: +1 514 398 2354; fax: +1 514 398 4492.
E-mail address: mathieu.brochu@mcgill.ca (M. Brochu).

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The application of a laser beam to induce surface re-melting and ultimately rapid solidification has been employed in various material systems [20–23]. Aziz and Smith have shown that the application of laser re-melting to various dilute aluminum binary alloys (Al–Sn, Al–Cu, Al–Ge, and Al–In) can result in deviations from equilibrium partitioning [18,19]. The authors also reported that the continuous growth model (CGM) for solute trapping can accurately describe this phenomenon in aluminum alloys.

The objective of this study was to investigate the ability of pulsed laser re-melting (LRM) to induce the solute trapping phenomenon within a commercially available next generation Al–Li alloy (AA2199). Therefore, preventing the formation of dendrites or cells which could serve as heterogeneous nucleation sites for strengthening precipitates such as the T_1 phase (Al_2CuLi) [24].

2. Experimental methods

The material re-melted during these experiments was an ~3 mm thick sheet of T3 temper (solution heat treated and then cold worked, naturally aged) AA2199. The composition of the AA2199 alloy used throughout this study is given in Table 1.

The as-received AA2199 sheet was analyzed alongside the laser re-melted material, and will hereafter be referred to as the "control sample".

Laser re-melting was performed using a Miyacki LW25 Nd:YAG ($\lambda = 1064$ nm) pulsed micro-laser welding system, focused on the surface of the AA2199 sheet to be re-melted, resulting in a theoretical spot size of ~150 μm. The laser system was mounted on a Machitech XYZ automated table, controlled using DeskCNC software. Laser re-melting was performed in an argon environmental chamber. Re-melting was performed on a 12.5 × 7.0 mm area, with a travel speed of ~127 mm min^{-1}. The conditions employed to fabricate the LRM samples of AA2199 are displayed in Table 2. The heat input (E) of the pulsed laser was calculated using the following equation:

$$E = \frac{\eta P_{av}}{v} \tag{1}$$

where η is the heat source efficiency (taken to be 0.85 in this work) [25], P_{av} is the average power, and v is the travel speed. The average power was calculated by multiplying the pulse energy by the pulse frequency.

Scanning electron microscopy (SEM) was performed using a Hitachi SU-8000 and a Phillips XL30 electron microscope. Samples for microscopic analysis were mounted in Bakelite and then ground using 320 grit SiC paper, with polishing then performed using 9, 3, and 1 μm diamond pastes, finished with 0.05 μm colloidal silica.

Table 2
Experimental parameters employed during the laser re-melting trials.

Parameter	Condition			
	1	2	3	4
Pulse energy (J)	0.125	0.25	0.375	0.5
Pulse duration (ms)	0.5	0.5	0.5	0.5
Pulse frequency (pulse s^{-1})	30	30	30	30
Peak power (W)	250	500	750	1000
Heat input (J mm^{-1})	1.51	3.01	4.52	6.02

X-ray photoelectron spectroscopy (XPS) was performed using a Thermal Scientific K-Alpha XPS system equipped with Avantage analytical software. Depth profile analysis was completed using an argon ion laser with an ion energy of 3000 eV, resulting in a Ta_20_5 equivalent sputtering rate of ~2.69 nm s^{-1}. Analysis was performed with a beam spot size of 400 μm at 10 depths (surface and nine subsurface), with 10 s sputtering between analyses.

X-ray diffraction (XRD) was performed using a Phillips PW1070 diffractometer (Cu Kα $\lambda = 1.54056$ Å). Scans were acquired from 20° to 100°, at a scan rate of 1° s^{-1}. The lattice parameter was calculated using a silicon reference standard and the XLat analytical software.

3. Results

3.1. Microstructural analysis

Microstructural analysis revealed a fine cellular morphology within the laser re-melted AA2199 samples. Furthermore, it was noted that an increase in pulse energy (i.e. heat input) resulted in a larger cell width. Fig. 1 displays SEM images of samples produced using 0.5 (Fig. 1a), 0.375 (Fig. 1b), 0.25 (Fig. 1c), and 0.125 J per pulse (Fig. 1d), respectively. As all samples were produced using a constant laser travel speed (~127 mm min^{-1}) and spot size (~150 μm) it is evident that as the pulse energy of the laser is reduced the resulting structure becomes more refined, due to the lower heat input. The samples re-melted with pulse energies of 0.5 (Fig. 1a) and 0.375 (Fig. 1b) Joules per pulse show similar structural evolutions. Both samples reveal an initial planar growth region followed by a morphological change to a cellular structure. The cellular structure then remains consistent throughout the re-melted and solidified material. The sample re-melted with a pulse energy of 0.25 J per pulse (Fig. 1c) reveals an initial epitaxial growth region, before transitioning into a further refined cellular structure. A further decrease in pulse energy

Table 1
Composition of AA2199 used throughout this study (at.%).

Al	Li	Cu	Zn	Mg	Mn	Zr	Fe	Si
5.3–6.8	1.0–1.2	0.1–0.4	0.05–0.4	0.1–0.5	0.1–0.4	0.03 max	0.05 max	Balance