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LASER CONSOLIDATION OF AL 4047 ALLOY

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Abstract

Laser consolidation (LC) is a novel manufacturing process that produces net-shape functional and metallurgically sound components by adding material based on a CAD model. In this paper, laser consolidation of Al 4047 alloy is demonstrated. The LC process successfully built metallurgically sound Al 4047 alloy samples on Al 6061 substrate. The microstructure of LC Al 4047 material was examined in detail using optical microscope, scanning electron microscope (SEM) and x-ray diffraction (XRD) techniques, while its chemical composition was analyzed by X-ray energy dispersive spectroscopy (EDS). The tensile properties of the LC Al 4047 material were evaluated and compared with similar wrought and cast aluminum alloys. In addition, several LC Al 4047 samples were produced to demonstrate the capability of the process. Laser consolidation of Al-alloys has many potential applications in aerospace, mold making and other industries for rapid tooling, small quantity production, and repair of expensive components.

Introduction

Laser consolidation (LC) is an innovative one-step manufacturing process that produces net-shape functional and metallurgically sound components layer by layer directly from a CAD model without any mould or die [1]. A focused laser beam is used to melt a controlled amount of injected metallic powder on a base plate to deposit the first layer and on previous passes for the subsequent layers. As compared to conventional machining processes, this computer-aided manufacturing (CAM) technology builds complete functional net-shape parts or features on an existing component by adding instead of removing material.

Some previous work has been reported by authors on laser consolidation of various industrial alloys and steels, such as Ni-base superalloys, Co-base alloys, Ti-base alloys, stainless steels and tool steels [1-4]. The LC samples show very good surface finish and dimensional accuracy. Laser consolidation offers unique opportunities to reduce manufacturing time and cost in many potential applications such as complex 3D shapes, aero engine components, and molds/dies [4-9].

There are several groups working in the same area of the laser powder deposition and made many impressive achievements through the development of materials, processes and systems [10-13]. However, there is very limited information available regarding laser powder deposition of aluminum alloys [14].

Aluminum is the second most plentiful metallic element on earth. With its unique features such as light weight, good strength and corrosion resistance, Aluminum and its alloys are widely used in aerospace, automotive, food packaging, construction and other industries. Al-Si alloys, one of the most important aluminum alloy systems, can be divided into wrought 4xxx alloys and cast 4xx alloys. The wrought 4xxx Al-Si alloys possess medium strength, good flow characteristics, low melting point and narrow freeze range. The 4xxx Al alloys can be forged and welded. As the most important industrial cast aluminum alloys, the 4xx Al-Si alloys (such as Al 413 and Al 443 alloys) are used for making sand castings, permanent mold castings and die castings for various thin-walled and intricate components that require moderate strength and ductility, good pressure tightness, and excellent corrosion resistance.

In this paper, laser consolidation of commercially available Al 4047 alloy powder to build metallurgically sound samples is reported. The mechanical properties and microstructure of the laser-consolidated Al 4047 alloy are evaluated, and the laser consolidation using multi-axis motion system to build complex shapes is described. In addition, the possibility of using the LC Al 4047 alloy to make functional net-shape components for rapid tooling and small quantity production is also discussed.

Experimental Details

The atomized Al 4047 powders used for the laser consolidation investigation were produced by Valimet. The powders are spherical in shape (Figure 1) with a size range of –48.5 μm/+8.5 μm. Annealed wrought Al 6061 plates were used as the base material. The aluminium plates were machined into coupons and ground to a consistent surface finish for the laser consolidation experiments. Chemical compositions of the powder and substrate are listed in Table 1.

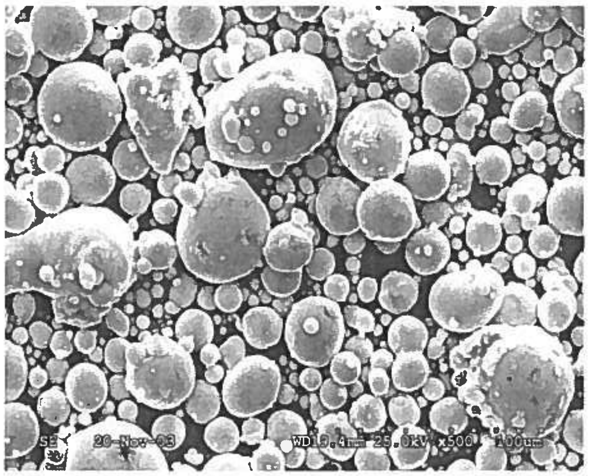


Figure 1: SEM micrograph of commercial Al 4047 powder.

Table 1: Nominal composition of experimental materials (wt. %)

Element	Al 4047 Powder	Al 6061 Substrate
Si	11.41	0.6
Fe	0.17	-
Cu	0.01	0.28
Mg	0.02	1.0
Cr	-	0.2
Al	Bal.	Bal.

A Nd:YAG laser coupled with a fiber-optic processing head was used for all the laser consolidation experiments. The laser was operated in a pulse mode with an average power ranging from 20 to 300 W. A powder feeder was used to simultaneously deliver metallic powder into the melt pool through a nozzle with a powder feed rate ranging from 1 to 30 g/min. During the laser consolidation, the laser beam and the powder delivery nozzle were kept stationary, while the sample was moved using a computer numerical controlled (CNC) motion system. All laser consolidation work was conducted in a glove box and at room temperature, in which the oxygen content was maintained below 50 ppm during the process.

The LC Al 4047 alloy was examined metallurgically using an optical microscope as well as a Hitachi S-3500N Scanning Electron Microscope (SEM). For optical microscope observation, the microstructure of the LC Al 4047 samples was revealed by swabbing the polished specimens for 15 - 30 sec. with Keller's etchant (2.5 ml HNO_3, 1.5 ml HCl, 1.0 ml HF and 95 ml H_2O). For SEM observation, a modified Murakami / Klemm chemical etchant (10 g NaOH, 5g $K_3Fe(CN)_6$ and 60 ml H_2O) was used. A Philips X'Pert X-ray diffraction system was used to identify the phases of the LC samples. A 100 kN Instron Mechanical Testing System was used to evaluate the tensile properties of the LC Al 4047 samples.

Results and Discussion

Laser Consolidation of Al 4047 Alloy

Laser consolidation processing parameters were developed to build Al 4047 alloy samples with good repeatability and high integrity. With the optimised parameters, metallurgically sound Al 4047 alloy specimens were successfully built on the wrought Al 6061 alloy substrate. Both optical microscope and SEM observations on the polished cross-section along build-up direction (Figure 2) indicate that LC Al 4047 thin wall sample as well as the bonding area between the LC Al 4047 and the wrought Al 6061 substrate are fully dense, free of cracks or porosity. The LC Al 4047 thin wall is metallurgically bonded to the substrate with a penetration depth in the range of around 150 μm.

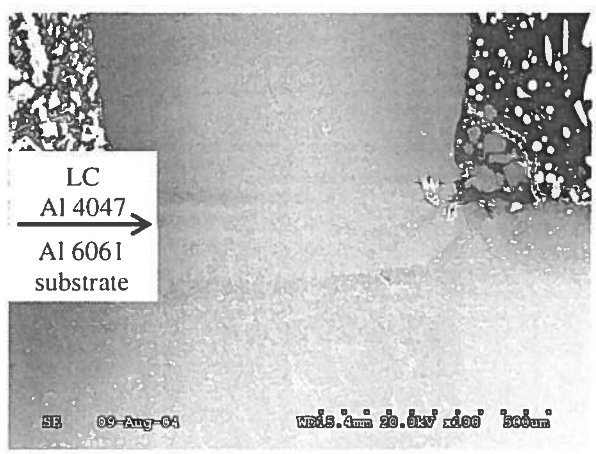


Figure 2: Cross-sectional view of LC Al 4047 thin wall on wrought Al 6061 substrate.

Layered Features

The polished LC Al 4047 specimen shows a dense and uniform cross-section along build-up direction (Figure 2). However, after chemical etching, layered features are revealed on the cross-section of the LC Al 4047 (Figure 3), which can be attributed to the laser consolidation process itself. Laser consolidation process builds samples layer by layer. When depositing a new layer, a surface portion of the previous layer will be re-melted by a focused laser beam along with injected Al 4047 powder to form a molten pool. When the laser beam moves away, the newly deposited layer starts to solidify through solid phase nucleation, dendrite growth, to final eutectic reaction. Since the new layer grows from the previous layer, each layer has a thin nucleation zone and a relatively large dendritic growth zone. Surface polishing does not reveal the microstructural details so only a dense and uniform LC Al 4047 cross-section can be observed. Chemical etching reveals the difference between the nucleation zone and dendritic growth zone and the layered feature appears on the cross-section of the LC Al 4047 sample. The layered feature reflects the solidification feature of the laser consolidation process itself, which, by no means, shows any indication of potential weakness of the LC Al 4047 material along layers.

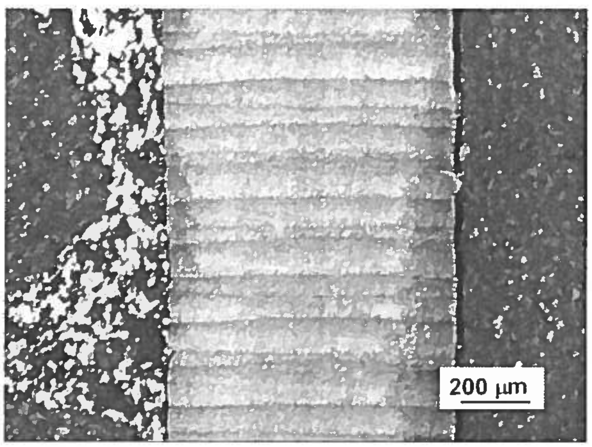
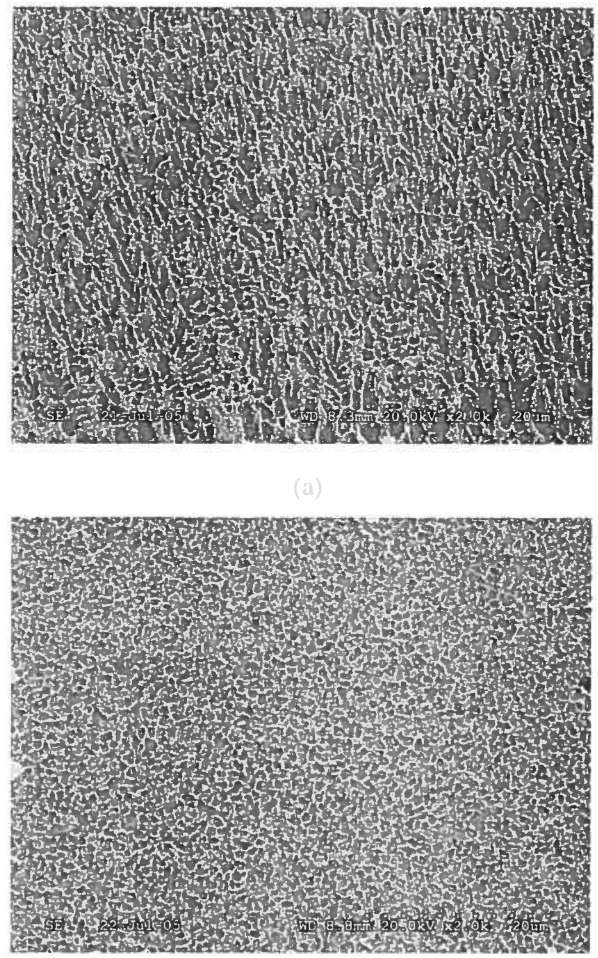


Figure 3: Layer features observed in a cross-sectional view of LC Al 4047 thin wall sample.

Microstructure

The good mechanical properties of LC Al 4047 material can be attributed to its unique microstructure. Figure 3 shows an optical microstructure photo of LC Al 4047 material along vertical cross-section. The LC Al 4047 material shows a rapidly solidified microstructure with layered features: very fine columnar dendrites growing almost parallel to the direction of build (vertical). The details of the dendrite structure along the vertical and horizontal cross-sections are revealed by two high resolution SEM micrographs (Figure 4). The dark regions are dendrite arms, while the interdendritic regions appear white. It is obvious that, along the vertical direction (Figure 4a), LC Al 4047 material shows very fine, directional growth dendritic structures with an average secondary dendrite arm spacing (DAS) of around 1-2 μm. Very fine cellular features have also been observed along the transverse cross-section (Figure 4b).



(a)

(b)

Figure 4: SEM observation of LC Al 4047 microstructure, (a) along build up (vertical) direction, ×2000, (b) along horizontal direction, ×2000,

Phase Identification

Phase identification of LC Al 4047 was conducted by the X-ray diffraction (XRD) technique. A Philips X'Pert X-ray diffraction system with mono chromatic Cu*Ka* radiation was used. The operating voltage and current of the X-ray tube were 40 kV and 45 mA, respectively.

The XRD results (Figure 5) show that LC Al 4047 material has the same XRD patterns as the Al 4047 powder: majority of α(Al) phase plus small amount of Si. However, after laser consolidation, the α(Al) matrix exhibits a preferred orientation along (100), which is consistent with the optical microscope observation (Figure 3).

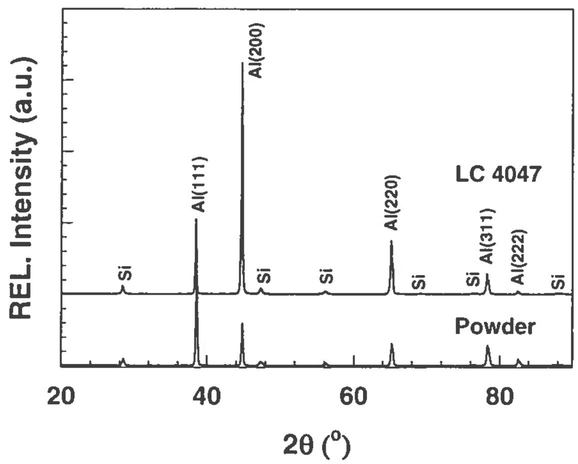


Figure 5: X-ray diffraction patterns of powder and LC Al 4047 alloy.

EDS Analysis

A Hitachi S-3500N Scanning Electron Microscope (SEM) equipped with an X-ray energy dispersive spectroscopy (EDS) was used to analyze the chemical distribution within LC Al 4047 alloy (Table 2). Each data represents the average of at least 5 measuring points. The EDS results show that Silicon is enriched in the interdendritic regions: about 26 % in the interdendritic region as compared to about only 17 % in the dendrite region.

Table 2: EDS analysis of LC Al 4047 alloy

Location	Elements (wt%)			
	Al	Si	Ca	Fe
Dendrites	83.03	16.93	0.05	-
Inter-dendrites	74.3	25.63	-	0.08

Tensile Properties

The laser consolidated (LC) Al 4047 alloy shows very good tensile properties (Table 3). The average yield and ultimate tensile strengths of the as-consolidated LC Al 4047 are about 139±12 MPa and 317±12 MPa, respectively, while the elongation is about 8.7±2.1 % and the elastic modulus is about 74±6 GPa. All tensile test readings have very small scatter, which indicates that the laser consolidation process has very good reproducibility.

Table 4 lists tensile properties of similar cast and wrought aluminum alloys. As compared to tempered Al 4047 sheet material, as-consolidated LC Al 4047 shows about 70% higher tensile strength and about 3 times improved elongation, although its yield strength is about 24% lower.

Table 3: Tensile properties of LC Al 4047 alloy

Sample No.	σ_y (MPa)	σ_{UTS} (MPa)	δ (%)	E (GPa)
LC #1	143	322		76
LC #2	155	326	10.2	66
LC #3	128	300	6.3	75
LC #4	131	320	9.6	80
Average LC Al 4047	**139 ±12**	**317 ±12**	**8.7 ±2.1**	**74±6**

Table 4: Comparison of tensile properties of LC Al 4047 alloy with similar cast and wrought materials

Sample No.	σ_y (MPa)	σ_{UTS} (MPa)	δ (%)	E (GPa)
LC Al 4047 (as-consolidated)	139	317	8.7	74
Al 4047 sheet (tempered)[15]	184	197	3	-
Cast Al 413 (as-cast)[16]	145	300	2.5	-
Cast Al 443 (sand casting)[16]	55	130	8	71
Cast Al 443 (die-casting)[16]	110	230	9	71

Al 443 and Al 413 are two most important industrial cast Al-Si alloys. Al 443 contains 5.3% Si and is mainly used for sand castings and permanent mold castings. Al 413 is very similar to cast Al 4047 alloy, containing similar Si (11-13 %) but higher Fe (2 %). Al 413 is used to make various thin-walled and intricately designed castings.

As-consolidated LC Al 4047 shows tensile and yield strengths very similar to as-cast Al 413, but with substantially improved elongation (8.7% vs. 2.5%). Compared to both sand cast and die cast Al 443 alloys, as-consolidated LC Al 4047 shows much better yield and tensile strengths and comparable elongation. The elastic modulus of LC Al 4047 (74 GPa) is about the same as cast Al 443 (71 GPa). Unfortunately, elastic modulus of cast Al 413 can not be found for comparison.

Aluminum and Silicon form a simple eutectic system. The eutectic point is at 12.5 % Si and 577 °C. Al 4047 is a hypo-eutectic alloy containing about 11.5-12.0 % Si. Under the equilibrium conditions, during the solidification of Al 4047 alloy, small amount of Al-enriched α dendrites will solidify first, while interdendritic regions will be filled with Al-Si eutectic (α phase + Si) when reaching to the eutectic temperature. The α phase contains about 1.65 % Si at the eutectic temperature. The solubility of the α phase decreases significantly with the decreased temperature, for example, only about 0.05% Si at 250°C. At the room temperature, there is practically no solubility of Si in α phase, so that an (Al + Si) structure will form. Under the equilibrium condition, the eutectic Si should be uniformly distributed within α matrix.

When the hypo-eutectic alloy is slowly cooled (such as sand casting), a degenerated form of eutectic is possible. In stead of a fine, well defined and uniformly distributed eutectic, a structure containing large plate-like and acicular Silicon crystals will be obtained. This leads to very brittle behavior and low strengths. With permanent mould casting or die casting, the chilling effect of the mould prevents degeneration of the eutectic. As a result, the tensile and yield strengths are improved substantially.

However, laser consolidation is a rapid solidification process that is far from equilibrium conditions. During the laser consolidation, a focused laser beam melted the pre-deposited Al 4047 layer (or Al 6061 substrate for the first pass) along with injected Al 4047 powder to create the deposit in a form of molten pool. As soon as the laser beam moves away from the location, Al 4047 melt starts to cool down rapidly. When its local temperature falls below the solidus temperature, Al-enriched α phase starts to solidify on the preferred seeds (usually on the surface of previous layer) into dendrites and grow along the build up direction due to the maximum temperature gradient. Due to the rapid solidification conditions, Si content in the α phase may be substantially higher than that under the equilibrium conditions. With the further growth of the Al-enriched α dendrites, the Si content in the remaining melt gets enriched. When the local temperature reaches the eutectic temperature, inter-dendritic regions will be frozen with Al-Si eutectic, which contains higher Si content compared to the pre-solidified α dendrites, as revealed by the EDS analysis (Table 2). Because of the rapid solidification inherent to the laser consolidation process, α dendrites in LC Al 4047 alloy are very fine, which results in the designed fine, well defined and uniformly distributed eutectic at inter-dendritic regions. Consequently, the LC Al 4047 alloy shows very good tensile properties: comparable tensile and yield strength and much better elongation than die-cast Al 413 alloy, and substantially improved strengths compared to sand-cast and die-cast Al 443 alloy.

LC Al 4047 Samples

Figure 6 shows several LC Al 4047 samples. It is evident that laser consolidated Al 4047 shows very good surface finish. Preliminary results indicate that, after using Scotch-Brite™ pad to remove loose particles and clean the surface, the surface roughness of the LC Al 4047 samples can reach up to about Ra = 1.9 μm.

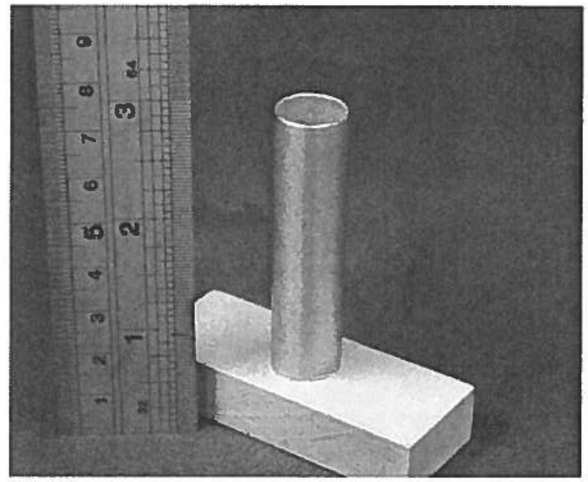


Figure 6: Some LC Al 4047 demonstration samples.

Potential Applications

As shown by the above experimental results, laser consolidation has the capability to build metallurgically sound Al 4047 components directly from a CAD model without moulds or dies. Unlike other similar laser powder deposition processes that produce near-net-shape component, the laser consolidation process has the unique capability to build net-shape Al 4047 components.

Since the LC Al 4047 alloy shows tensile properties comparable to die cast Al 413 and much better than sand cast or die cast Al 443 alloy, laser consolidation can be used to build thin-walled and intricate Al 4047 alloy components for prototype or small quantity production that otherwise require expensive moulds/dies to make Al 413 or Al 443 castings. As a result, the production cost and lead time can be reduced substantially.

Conclusions

(1) The laser consolidation process has been successfully used to build metallurgically sound Al 4047 alloy samples.
(2) The tensile and yield strengths of the as-consolidated Al 4047 alloy are substantially

higher than that of the sand cast and die cast Al 443 and comparable to the die cast Al 413 alloy.

(3) Laser consolidation of Al 4047 alloy provides many unique advantages for manufacturing thin wall, intricate components for rapid tooling and small quantity production without the expensive moulds and dies.

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Meet the Author(s)

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Andre Theriault is a Research Officer working in the areas of laser path planning for the laser consolidation process and the evaluation of mechanical properties of laser-consolidated materials. He obtained his Masters degree in Mechanical Engineering in 2003 from the University of Western Ontario.