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# The influence of the laser scan strategy on grain structure and cracking behaviour in SLM powder-bed fabricated nickel superalloy

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ABSTRACT

During the development of a processing route for the Selective Laser Melting (SLM) powder-bed fabrication of the nickel superalloy CM247LC it has been observed that the 'island' scan-strategy used as standard by the Concept Laser M2 SLM powder-bed system strongly influences the grain structure of the material.

Optical and SEM micrographs are presented to show the observed grain structure in the SLM fabricated and Hot Isostatically Pressed (HIPped) material. The repeating pattern shown in the grain structure has been linked to the overlapping of the 'island' pattern used as standard in the Concept Laser M2 powder-bed facility. It is suggested that the formation of this bi-modal grain structure can be linked to the heat transfer away from the solidifying melt pool. The concept of a 'band' heating effect across each 'island' rather than 'moving point' heating has been suggested and has been supported by Electron Back Scattered Diffraction (EBSD) evidence. For comparison an EBSD map from a sample formed using a simple 'back-and-forth' strategy has also been presented and reveals a dramatically different grain structure and crystallographic orientation.

MicroCT evidence, supported by SEM microscopy, shows that in the as-fabricated material the bimodal structure caused by the 'island' scan-strategy translates directly into the macroscopic pattern for the regions of extensive weld cracking associated with the SLM fabrication of $\gamma'$ hardenable materials. Similar microCT data has shown that HIPping can effectively close the internal cracks to provide a retro-fix solution.



## 1. Introduction

The aerospace industry has become increasingly interested in the potential use of Additive Layer Manufacturing (ALM) methods for the production of high-temperature components. Key drivers for this include the ability to produce complex netshape components without the same restrictions imposed by traditional machining and the ability to rapidly produce small batches of complex components without the prohibitive setup costs of traditional casting techniques. Reviews of the various ALM technologies can be found elsewhere [1–5].

The Concept Laser M2 Cusing system located at the University of Birmingham utilises an 'island' scan-strategy as standard; this strategy is reported to reduce overall residual stress within the final component [6]. Recent work has highlighted the influence of this scan strategy and is presented here in terms of grain structure; crystallographic orientation and distribution of cracks within the as fabricated material. This study forms part of a larger project aimed at establishing a processing route to produce fully-dense and netshaped aerospace components from the nickel superalloy, CM247LC, via a Selective Laser Melting (SLM) powder-bed route.

### 1.1. SLM process overview

SLM powder-bed fabrication is an ALM technology where components can be netshape formed directly from metal powder. A schematic representation of a typical powder-bed system is shown in Fig. 1. Preparation involves virtually slicing a three-dimensional shape, in the form of a CAD file, into a sequence of two-dimensional slices. For each slice fabricated the following sequence of events occurs:

– The powder platform is raised, presenting a small amount of powder proud of the bed.

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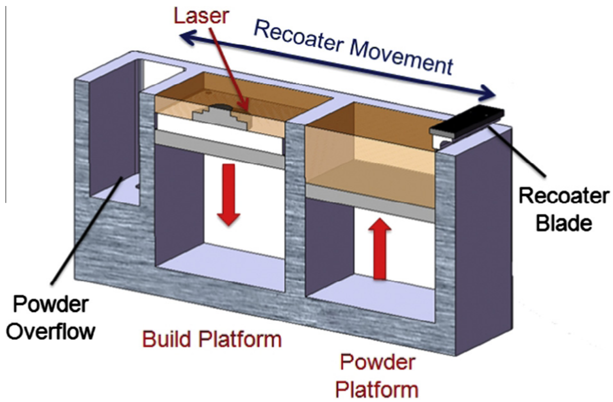


**Fig. 1.** Schematic cross-section of the Concept Laser M2 powder-bed system.

– The flexible rubber recoater blade is moved across the bed spreading a thin layer of powder across the previously built layers (or build-plate in the case of the first layer).
– The computer controlled laser scans the surface of the bed to selectively melt the current two-dimensional slice of the CAD file.
– The laser scanning remelts some of the previously built layer to ensure good bonding between layers and a fully dense component overall.
– The build platform is lowered by the thickness of a single slice and the recoater is returned to the start point.

This sequence is repeated until the final three-dimensional component has been constructed by the selective melting of the 'two-dimensional' layers.

### *1.2. Material: CM247LC*

The material selected for this study is the nickel base superalloy CM247LC. The alloy was developed for high-temperature directionally solidified (DS) turbine blade application and is a low carbon derivative of the more traditional material MAR-M247 with tighter controls on the detrimental elements Si and S [7]. Table 1 shows the nominal composition of CM247LC [8].

CM247LC exhibits a typical microstructure for this type of alloy consisting of a $\gamma$ nickel matrix which can be further strengthened by the precipitation of the $\gamma'$ phase ($Ni_3Al$). Through careful heat treatment the $\gamma'$ phase can be refined into a regular cuboidal form resulting in the optimum mechanical properties [9]. Grain boundary strengthening is achieved through the precipitation of particulate carbides at the grain boundaries facilitated by the inclusion of Hf [10].

Nickel superalloys display a face-centered cubic (FCC) structure in both the nickel $\gamma$ phase and the coherent secondary $\gamma'$ phase. As with all FCC alloys, nickel alloys exhibit preferential solidification in the {001} direction [11]; this been exploited in turbine blade manufacture with the production of DS castings and subsequently in single crystal castings where very low-angle grain boundaries significantly improve mechanical properties [11].

**Table 1**
Nominal chemical composition of CM247LC (wt.%) [8].

| C | Cr | Ni | Co | Mo | W | Ta | Ti | Al | B |
|---|---|---|---|---|---|---|---|---|---|
| 0.07 | 8 | Bal | 9 | 0.5 | 10 | 3.2 | 0.7 | 5.6 | 0.015 |
| Zr | Hf | Si | S [9] | | | | | | |
| 0.01 | 1.4 | ⩽0.03 | ⩽15 ppm | | | | | | |

### *1.3. Grain structure in laser fabricated materials*

It has been reported that due to the remelting of the previous layers (or substrate in the case of the first layer) there exists a strong trend of epitaxial growth of grains from one layer to the next [12]. In addition to this tendency for epitaxy between layers, the nature of the heat flow via conduction through the previous build layers and substrate in the '$-Z$' direction (as defined in Fig. 2) encourages the formation of large elongated or 'columnar' grains similar to those observed in the DS casting.

These columnar grains have been observed in both SLM powder-bed [13] and blown-powder laser fabricated [14–18] materials. The results presented by Liu et al. [15] are of particular interest as they show not only the columnar grains within the blown-powder laser fabricated material, but also fine grained regions formed due to the scan spacing.

### *1.4. Weld cracking*

It is known that the material CM247LC is particularly susceptible to weld-cracking in the as-fabricated state. This is typical of high-volume fraction $\gamma'$ strengthened nickel superalloys where the 'weldability' of a material can be linked to the content of the $\gamma'$ forming elements: Al and Ti [19].

It has been suggested that ductility-dip cracking (DDC) is one of the key mechanisms by which these cracks are formed during fabrication. This mechanism occurs from the reduction in ductility of the material at intermediate temperatures (700 °C–900 °C as reported by Kim et al. [20]). Under residual stress within the material, the DDC mechanism is reported to form grain boundary cracks [21,22]. The exact microstructural mechanism for the occurrence of DDC is outside the scope of this study, however it should be noted that two distinct schools of thought have emerged on the subject: That of Lippold et al. [22–26] and Young et al. [27]. A significant result however is that of Lippold et al. [23] which states that the occurrence of DDC is increased with the presence of high-angle grain boundaries.

The previous parametric study by Carter et al. [28] has investigated the character and mechanisms of cracking in SLM fabricated CM247LC and established processing parameters where cracking is minimised but not eliminated.

## 2. Experimental

### *2.1. CM247LC powder*

CM247LC powder was supplied by LPW Technology Ltd. in the size fraction +15–53 μm and showed smooth/even spreading within the powder-bed during processing. Two samples of the powder were examined using SEM microscopy: one was ground and polished to show the particles in cross-section, whilst the

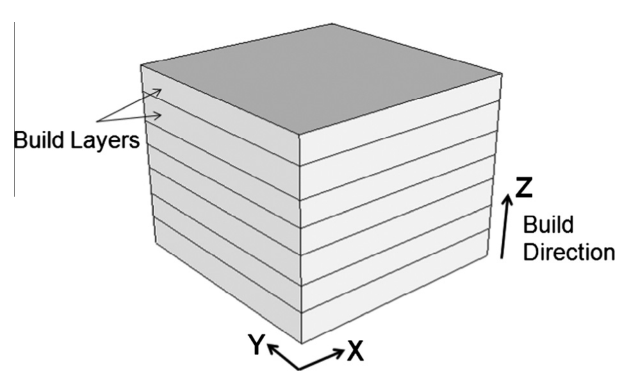


**Fig. 2.** Definitions of the axes and planes discussed within SLM fabrication with respect to the build layers.