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Reviewed Paper

A DIRECT METAL LASER MELTING SYSTEM USING A CONTINUOUSLY ROTATING POWDER BED

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Abstract

The aircraft engine industry manufactures many metal parts of large diameter, but small cross-sectional area. Designers of these parts require increasingly complex geometries for improved aerodynamic efficiency and cooling. The combination of large diameter and complex geometric features inspired the development of a new Direct Metal Laser Melting (DMLM) architecture with a rotating powder bed. The system coordinates the rotational motion of a powder bed with an ascending laser scanner and recoater to build in a helical fashion. A single-point powder feeder delivers metal powder near the inner radius of an annular build volume, and the recoater spreads the powder to the outer radius in a “snow plow” fashion. Because the recoater and laser scanner are installed at different angular positions, they operate independently and simultaneously. A prototype system was built to demonstrate this concept for an aircraft engine combustor liner (600-mm dia. x 150-mm ht.) and showed continuous laser utilization exceeding 97%.

1 Introduction

Multiple reviews of Additive Manufacturing technology [1-7] report that commercial Direct Metal Laser Melting (DMLM) machines of today share a common Cartesian architecture based on linear actuators arranged on three orthogonal axes. The part is built along one axis, the recoater motion is along another, and the gas flow is along the third axis (though it is sometimes parallel to the recoater motion). An inherent disadvantage with this arrangement is a requirement of sequential operation: the laser is idle during motion of the axes and the axes are idle during lasing. Laser utilization, defined as the ratio of laser fusing time divided by the total build time, is an important metric in system productivity and investigators have devised various schemes to improve this ratio [8-11] while working within the Cartesian architecture. High laser utilization is difficult to achieve for large parts of small cross sectional area, such as thin-walled tubes, because lasing time is low and recoating time is relatively high. Multiple lasers are required when the part dimensions exceed the field of view of a single scanner, a fact that further decreases laser utilization because laser exposure time is further reduced relative to recoating time.

This paper discusses a DMLM system architecture based on a polar coordinate system where the rotational and vertical axes are increased monotonically throughout a build without reversal. The approach was first explored by researchers at the University of Liverpool and published in 2005 [12,13]. Powder dispensing, recoating, and lasing occur at different angular positions, allowing these operations to occur simultaneously and continuously, thus maximizing laser utilization as the part is built in a helical fashion. Geometries well-suited to the polar arrangement are of large diameter and small cross-section. Parts meeting these characteristics are common in the aerospace industry where additive manufacturing is increasingly important as an enabler of performance improvements and cost reductions, achieved through innovative design and part-count reduction [14,15]. The cross-sectional area of a typical aircraft engine part (e.g., combustor liners, and engine casings) is approximately 1% - 5% of the powder bed area, so maximizing laser utilization is particularly important.

2 The Rotary DMLM Concept

A schematic of the rotary system is shown in Figure 1 [16-19]. A build plate is mounted on a rotational stage, which is rotated at a rate that is synchronized with a laser scanner. As in conventional DMLM [20], the laser scanner directs rapid motion of a laser beam onto the layer of powder, causing it to melt and fuse to prior layers. At an angular position that differs from that of the scanner, a powder feeder deposits powder and a recoater arm levels each layer of powder. The scanner, powder feeder, and recoater are elevated as the part grows in height allowing the part to be built in a helical fashion.

The primary benefits of the new architecture include:

- Continuous operation of the laser scanner
- Simultaneous powder recoating and lasing
- Scalability to large parts of small cross section
- Ability to build large parts with a single laser scanner
- Precise dosing and economical use of powder
- Local gas flow management
- Straight-forward implementation of multiple laser scanners

The first four benefits in the list above play key roles in enabling high laser utilization and result in high build speed. The last three items are added benefits over Cartesian machine geometries in terms of both process cost and product quality.

The geometry of parts built on the rotating system need not be axisymmetric; the scan pattern is adjusted for any local features as the build plate is rotated. As will be described below, the speed of the rotating stage is continuously adjusted as the bed rotates to maximize laser utilization. Simultaneously, the powder feed rate is adjusted to minimize powder use. In an extreme case of non-axisymmetry, the rotational system can be used to build multiple individual parts that fit within the annulus between the inner to outer radii on the build plate. No restrictions on part geometry beyond standard DMLM restrictions apply to parts built in this manner.

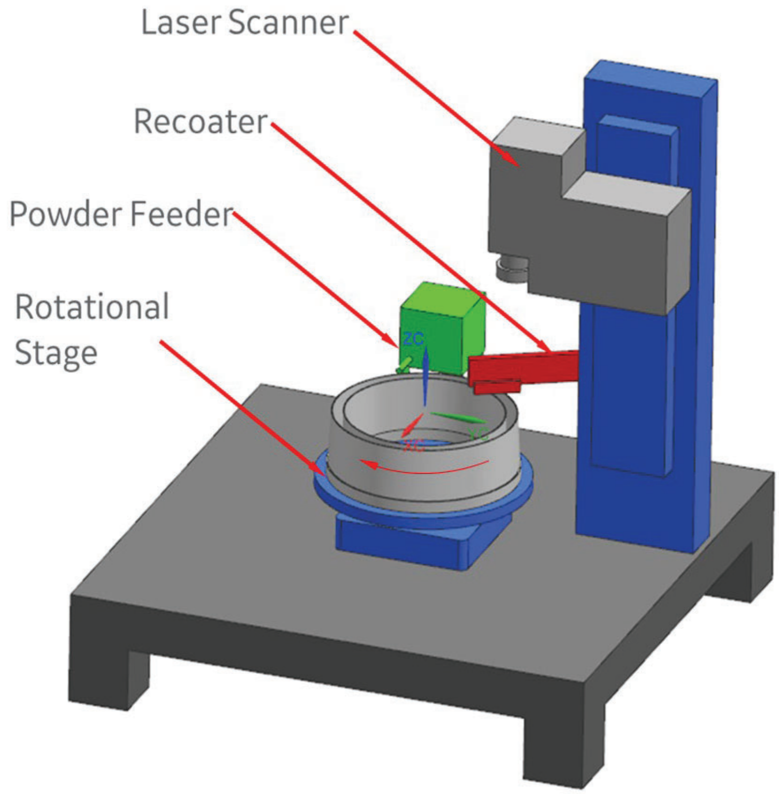

Figure 1. Rotational System Components. The scanner, powder feeder, and recoater ascend as the part is rotated, building the part in a helical fashion.

3 Scan Strategy

Several scan strategies are under development. For the initial trial, the part to be built is divided into vertical layers and angular sectors as shown in Figure 2. Though not a requirement in the general case, each of the angular sectors spans an equal angle and the angle is chosen to allow an integer multiple of sectors per revolution; this ensures that all sector boundaries aligned on top of each other throughout the building of the part. This simplification will be abandoned in future work, where staggering of sector boundaries may be desirable. Scan path files defining mark and move operations for the laser scanner are generated for each of these sectors before building the part.

Since the time requirement for scanning each sector is different, the rotation rate must be updated for each sector to maximize utilization. To accomplish this, each scan file includes an accurate estimate of the time required for completion of the sector [21,22]. A synchronization pulse is sent to the supervisory controller when a sector is completely within the view of the scanner.

The required modification to the rotational speed is computed, and the rotary stage is appropriately accelerated or decelerated to ensure that the sector is completed before it leaves the field of view of the laser. The scanner is controlled by a card that receives encoder feedback from both galvanometer positions and the rotary stage, so relative motion between the laser and powder are independent of the rotational speed. This approach works well as long as roundoff error in the sector timing calculation does not lead to a case where the sector cannot be completed in time. A small safety factor has shown to be satisfactory, leading to laser-on time less than 100%, but still greater than 97%. It is worth noting that synchronization between the scanner and rotation stage is maintained during all transitions of the rotational rate, so scanning is continued as the stage is accelerated or decelerated.

Because the scanner is not centered above the build plate, the coordinate system of the scanner must be calibrated with respect to the coordinate system of the rotating part. The calibration is specific to the machine geometry and configuration and, once applied, the scanner controller transforms the laser marking pattern to the specified location on the build plate as each sector passes through the scanner's field of view [23].

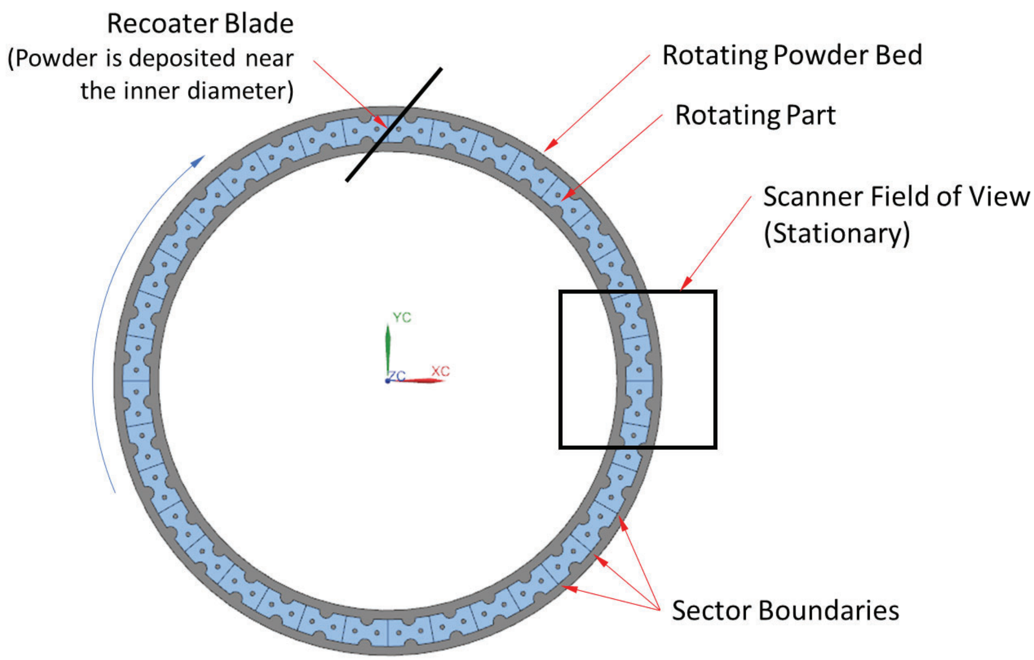

Figure 2. Scan Strategy. Powder dispensing and recoating are performed continuously as the build plate is rotated. Laser scanning of each sector starts when it is fully within the scanner field of view and the rotation rate is adjusted to minimize laser idle time between sectors.

4 System Prototype

Photographs of a prototype system that was built by the authors to demonstrate the rotary concept are shown in Figure 3. A laser-safe enclosure provides an inert gas environment for the process. A local gas plenum encloses the field of view of the laser and serves to sweep fumes out of the laser track and into a filtration system. (Many of the components of the gas plenum were 3D printed, allowing design creativity in the gas-handling system.) The photo shows a tall permanent inner wall inboard of the build plate; this wall prevents metal powder from pouring into the space at the inner diameter, saving substantial powder.

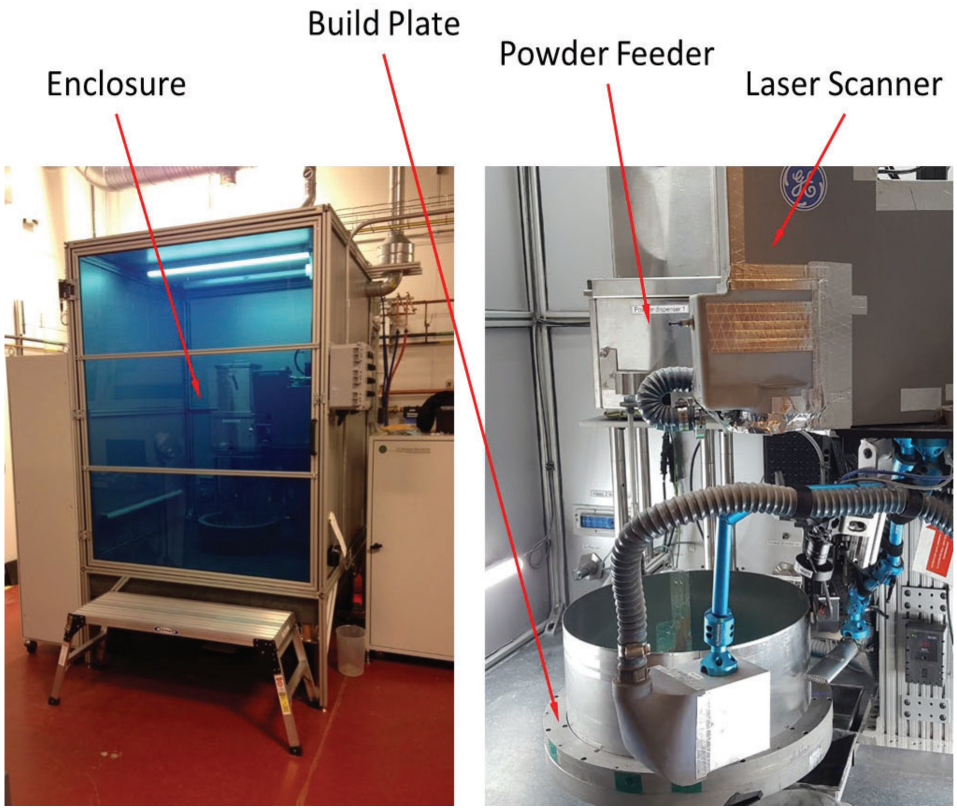

Figure 3. System Prototype. The demonstrator system can build parts to 24" diameter and 10" height.

4.1 System Control

The system control software is written in Visual C# and runs on a personal computer running Windows 7. Motion control of the rotational and vertical axes is done using an Aerotech A3200 device. Analog and digital I/O is controlled with a GE RSTi-EP remote I/O system fitted with various analog and digital I/O modules. The consolidation power source is a single-mode fiber laser Atla Prime 700W from nLight, Inc. The scanner used for the system is a custom-integrated system based on Scanlab GmbH hardware. The motion system is connected to the control computer via a dedicated Firewire port. The IO module and the laser use an ethernet connection for communication. The scanner is controlled via an RTC5 control board that is connected to the computer backplane through PCIe.

For modularity and scalability, the software is a multi-threaded architecture with each logical device having its own interface thread. An overall GUI thread takes user input, displays system information and controls system state including calibration, diagnostic and build. For post-build analysis, a low-priority "blackbox" thread periodically logs timestamped system conditions (e.g., temperature) as well as all changes to any hardware state (e.g., rotational velocity).

4.2 System Performance

An aircraft engine combustor liner (approximately 600-mm in diameter and 150-mm in height) was chosen as a demonstrator part (Figure 4). The part is thin-walled with a 20-mm thick flange and a 2-mm thick body. The part is complex, with a hole structure that includes large and small holes. Some of holes are too small to be seen in the photograph. The rotation rate was slowest (0.28 rpm) near the base of the part, where a thick flange required significant scanning time. The rate was fastest (2 rpm) at the mid-span where large horizontal holes were printed. Sector-to-sector variations in build time required rotation rate changes with an average of 0.2%, but sometime reached 30% at positions with rotationally asymmetric features and as high as 113% at the part thickness transitional section. All accelerations were accommodated within the rotary stage capabilities. A simple look-ahead algorithm was used to accommodate sudden acceleration/deceleration events to prevent missing a sector synchronization pulse. Laser utilization per sector varied between 75% and 99%, but the low-utilization excursions were brief resulting in an average utilization of 97.3% over the build duration (Figure 4). Though published data does not exist for conventional DMLM processing of a part of this size, the authors estimate that these systems would achieve approximately 30% utilization. Thus, the rotary system provides more than a 3x improvement in productivity.

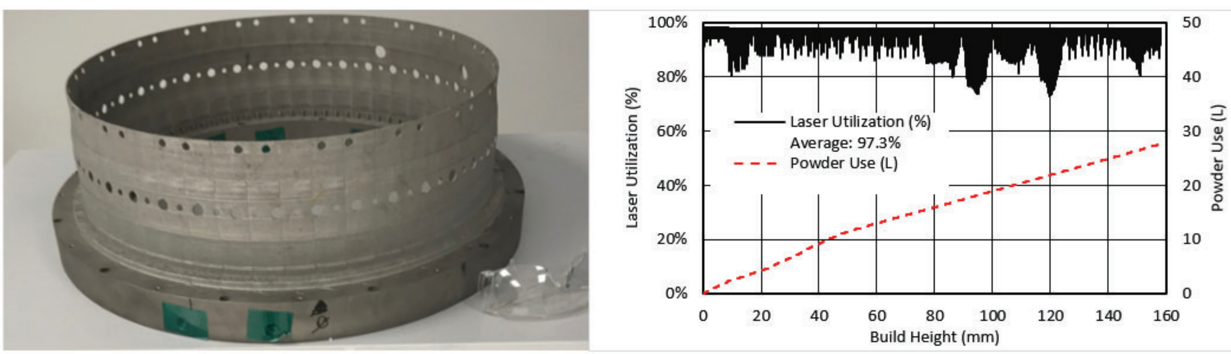

Figure 4. Combustor Liner. This demonstrator part was built using a CoCr Alloy. A single laser ran continuously with utilization per sector varying between 73% and 98%, averaging 97.3% over the entire build. Powder dispensed throughout the build totaled 27.6 L.

The powder feed rate, also shown in Figure 4, was adjusted in coordination with the rotational speed of the part. The total dispensed volume of powder was 27.6 liters, with nearly half of the amount being due to powder feeding overflow outside the annular powder bed. The volume of the consolidated part was 0.9 L, corresponding to 5% of total dispensed powder. For comparison, it would take 120 Liters of powder to fill a traditional rectangular powder bed for this part (including the typical overflow requirement). Thus the rotary system provides a 4x decrease in powder required.

5 Conclusions

A rotating powder bed DMLM system based on polar coordinates was shown to offer significant advantages in build time and powder use over conventional Cartesian DMLM machines for many parts of interest to the aircraft engine industry. These parts are characterized as generally axisymmetric, of large diameter, and of thin cross section. The authors showed that laser utilization exceeding 97% was easily achieved while building a 600-mm diameter combustor liner with the new architecture. As added benefits, the system was able to build parts larger than the field of view of a single laser, and the metal powder requirement was reduced by a factor of 4.

The authors are actively developing the rotary system to further increase productivity by adding lasers and increasing laser power. A larger system is under construction for building parts larger than 1-m in diameter and 1-m in height.

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