A Motion Planning Approach for Fabrication of Complex 3-D Shapes in a LENS™ Process

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Abstract

This paper discusses an approach for planning the motion of the laser deposition head relative to the part for fabrication of complex 3-D shapes such as parts with overhangs, branches, and internal cavities in direct metal deposition processes such as the LENS™ process. The proposed approach is based on slicing the solid model of the part into equal-thickness slices perpendicular to the normal build direction and formulating a motion planning strategy based on the properties of these slices. The paper discusses the four sub-approaches that are proposed to handle a variety of complex 3-D shapes parts.

Introduction

The Laser Engineered Net Shaping (LENS™) process developed at Sandia National Laboratories and commercialized by Optomec Design Company of Albuquerque, New Mexico, is one of the first successful techniques for direct metal deposition. A LENS™ machine delivers powder directly to the beam/powder interaction region on the substrate. A high-powered Nd:YAG laser melts the powder, solidifying it to the substrate. The LENS™ machine scans the entire x-y cross-sectional slice from the CAD model, steps in the z-axis, and then repeats the process over again until the part is fabricated.

An important problem in the LENS™ process is the development of general motion planning algorithms that plan the motion of the laser deposition head relative to the part for fabrication of complex 3-D shapes such as parts with overhangs, branches, and internal cavities and passages. Current methodology uses a computer model of the part to produce a tool path that guides the laser deposition system to form successive layers, building the part from bottom to top. The parts are built using a three-axis positioning system that moves the laser head relative to the part. As the part is formed, the powder delivery nozzle moves upward. This approach does not work for parts with complex features such as branches. For these parts, the parts need to be rotated to enable the laser head to be perpendicular to the part section while being fused.

This paper addresses the development of a general motion planning methodology that can work for arbitrary-shaped parts. The goal is to start with a solid model of the part to be manufactured as an input and to generate multi-axis laser scanning paths as an output. The proposed method assumes the LENS™ fabrication machine will be equipped with at least two additional axes to allow for two axes of part rotation. These axes can be either added to the laser deposition head, to the holder that the part is mounted to, or as a combination of the two. Any developed methodology need to be general enough to work with multi-axis configurations for both part manipulation or deposition head manipulation setups.

Very little work has been reported in the literature on motion planning of multi-axis LENS™ machines. In addition, no work has been reported yet to automatically control, based on the solid model alone, deposition for more than 3 axes of motion. Researchers at Sandia [1] have reported on the use of a six-axis robot to hold and manipulate a part during deposition. Optomec, the commercializer of the LENS™ technology, has sold machines which are equipped with 5-axes of motion. But, no software has yet been formulated which takes advantage of these axes in a generic and automatic way. The use of more than 3 axes of motion has always required significant operator intervention and programming to enable fabrication of complex geometries. Lockheed Martin, which owns an Optomec LENS™ machine, has reported on the use of a six-axis articulated robot [2] that carries the deposition head, but they too have been unable to successfully develop a methodology for using these additional axes without significant operator intervention.

Classification Procedure

In developing a methodology for conversion of a solid model CAD file into a motion file that drives the multi-axis LENS™ machine, our approach is based on slicing the solid model into equal-thickness slices perpendicular to the normal build direction. The first step in this approach is to develop a classification procedure that can classify the different types of parts based on the properties of these slices. We have categorized all solid parts into the following four categories:

Normal Build Parts: Are those parts that none of their slices has an overhang. Examples of such parts are shown in Figure 1.

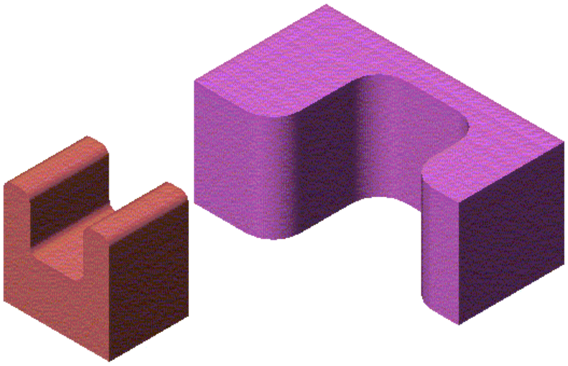

Fig. 1 Normal Build parts

Rotationally Symmetric Overhang Parts: Are those parts that are rotationally symmetric and also some of their slices have an overhang. Examples of such parts are shown in Figure 2.

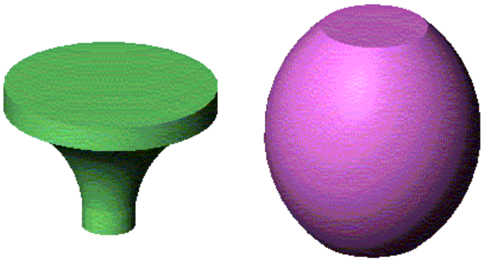

Fig. 2 Rotationally Symmetric Overhang parts

Regular Overhang parts: Are those parts that are non-rotationally symmetric, some of their slices have overhangs, and there are no closed branches or internal cavities. An example of such parts is shown in Figure 3.

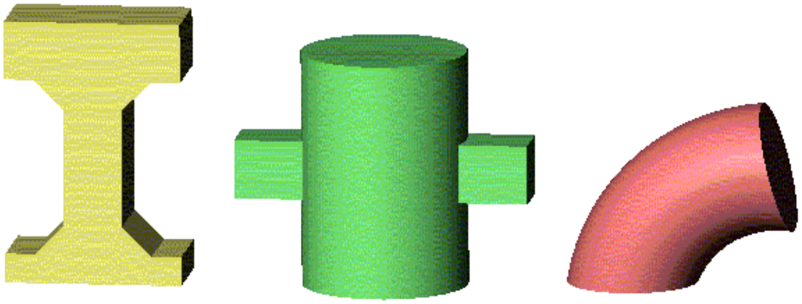

Fig. 3 Regular Overhang parts

Complex Overhang Parts: Are those parts that have either closed branches or internal cavities. Examples of such parts are shown in Figure 4.

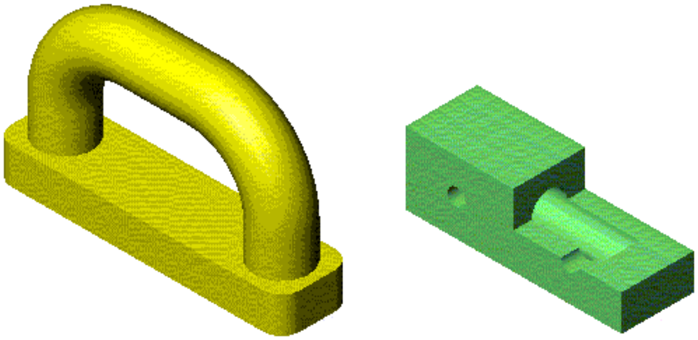

Fig. 4 Complex Overhang Parts

To aid in the classification procedure, we need to develop several algorithms. These include ones to compute if the current slice has an overhang relative to the lower slice, to compute if a slice has more than one closed contour, and to compute if the slices are rotationally symmetric.

Planning Approach

The second step in this approach is to develop a fabrication strategy for each of these categories. Parts of the first category can be fabricated with three axis machines and automatic approaches for their fabrication already exist. All parts in the remaining categories require more than three axes of motion to be fabricated, and will be discussed in this paper.

For Rotationally Symmetric Overhang parts, our approach is to fabricate the part in two stages. In the first stage, the no-overhang core of the part will be made. In the second stage, the core will be rotated 90 degrees and the reminder of the part fabricated similarly to a standard cylindrical cladding operation.

For the third category of parts, Regular Overhang parts, our approach is to start fabricating the part slice- by-slice starting from the lowermost slice until we reach a slice that has an overhang. At this point, the non-overhanging portion of the slice will be fabricated first, then the part will be rotated (typically 90 degrees) and the overhang portion will be fabricated as if it was a normal part. The approach will then be repeated for the remaining slices.

As an illustration of this approach, Figure 5 shows a simplified 2-D sequence for fabricating a part that has an overhang. The bottom two slices ("a" and "b") have no overhang so they are built using standard procedures. The third slice has an overhang, so it is split into two portions. Portion "c" is fabricated first on the top of the two previous slices. The part is then rotated 90 degrees, and then portion “d” is fabricated. The part is rotated back to its original orientation before fabricating the fourth slice. The fourth slice has an overhang relative to the third slice, so it is fabricated in two portions ("e" and "f") similar to the third slice. The last slice ("g") is fabricated last in the normal build orientation. In actual implementation, the slices will be thin (0.01" typically), so several slices will be combined together so that the overhanging portions will have sufficient strength.

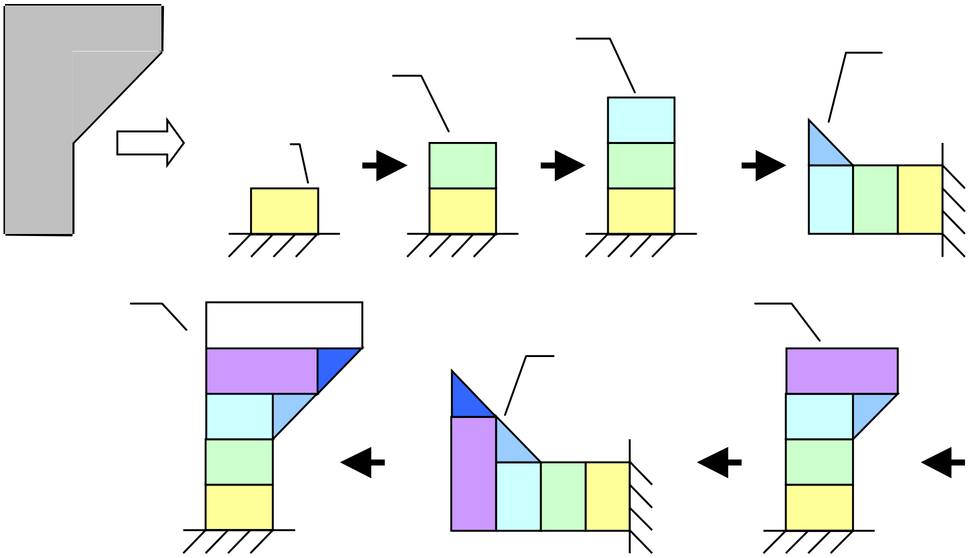

Fig. 5 Illustration of the build strategy

For the fourth category of parts, Complex Overhang parts, our approach will be similar to that of the third category with the exception that it may not be possible to fabricate the whole part using the above strategy alone due to limitations arising from interference between the laser head and the part or due to lack of powder support for certain portions of the parts. For these cases, a modified strategy is suggested which involves re-positioning of the part to enable part fabrication and building at angles that are not perpendicular to the build surface. Build angles ranging from 60-120 degrees are easily achievable using LENS™, and in some cases build angles from 45-135 degrees are achievable, thus there remains some flexibility for building parts whose geometry makes it impossible for the head to be exactly perpendicular to the deposition surface. For certain geometries it may be necessary to build "sacrificial" supports, which must be removed later. The removal of these supports will be greatly simplified by utilizing a sacrificial material that can either be chemically removed or simply melted out after fabrication. This is possible due to the multi-material deposition capabilities of LENS™.

Discussion

For the proposed approach, the following issues need to be addressed:

1. Sequencing of the fabrication procedure for parts with several branches, including identification of the initial build orientation.
2. Checking for interference between the part and the machine head
3. Generation of the needed geometrical information for fabrication when the part axis is rotated away from the normal build direction.

We believe that the proposed fabrication strategy is novel and has the following advantages:

1. Slicing is a standard feature available on most CAD packages that interface with rapid prototyping systems.
2. All the part characteristics are determined based on evaluating the properties of the slices, which are mathematically not difficult to evaluate.
3. The planning procedure is local and does not require decomposition of the part into different sub-volumes.

Currently work is underway to implement the above presented method. The successful implementation of such a 5-axis deposition control scheme will greatly enhance the ability of direct metal deposition processes to produce and repair real components with substantial geometric complexity.

References

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2. "Rapid Manufacturing Technologies". *Materials & Processes*, Vol. 159, Issue 5, May 2001.