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FREE FORM FABRICATION OF METALLIC COMPONENTS USING LASER ENGINEERED NET SHAPING (LENSTM)[#]

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INTRODUCTION

Solid free form fabrication is one of the fastest growing automated manufacturing technologies that has significantly impacted the length of time between initial concept and actual part fabrication^{1 2}. Starting with CAD renditions of new components, several techniques such as stereolithography³ and selective laser sintering⁴ are being used to fabricate highly accurate complex three-dimensional concept models using polymeric materials. Coupled with investment casting techniques, sacrificial polymeric objects are used to minimize costs and time to fabricate tooling used to make complex metal castings⁵.

This paper will describe recent developments in a new technology, known as LENSTM (Laser Engineered Net Shaping)^{6 7 8 9}, to fabricate metal components *directly* from CAD solid models and thus further reduce the lead times for metal part fabrication. In a manner analogous to stereolithography or selective sintering, the LENSTM process builds metal parts line by line and layer by layer. Metal particles are injected into a laser beam, where they are melted and deposited onto a substrate as a miniature weld pool. The trace of the laser beam on the substrate is driven by the definition of CAD models until the desired net-shaped densified metal component is produced.

EXPERIMENTAL

The system consists of a Nd:YAG laser, a controlled atmosphere glovebox, a 3-axis computer controlled positioning system, and a powder feed unit. The positioning stages are mounted inside a controlled atmosphere glove box, backfilled with argon, operating at a nominal oxygen level of 2-3 parts per million. The beam is brought into the glovebox through a window mounted on the top of the glovebox and directed to the deposition region using a six inch focal length plano-convex lens. The powder delivery nozzle is designed to inject the powder stream directly into the focused laser beam and the lens and powder nozzle move as an integral unit.

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A CAD solid model is sliced into a sequence of layers, and translated into a series of tool path patterns to build each layer. Each layer is fabricated by first generating an outline of the key component features and then filling the cross-section using a rastering technique. This file is used to drive the laser system to produce the desired component one layer at a time, starting from the bottom of the part. A schematic representation of the LENSTM fabrication process is shown in Figure 1. A solid substrate is used as a base for building the LENSTM object. The laser beam is focused onto the substrate to create a weld pool in which powder particles are simultaneously injected to build up each layer. The substrate is moved beneath the laser beam to deposit a thin cross section, thereby creating the desired geometry for each layer. After deposition of each layer, the powder delivery nozzle and focusing lens assembly is incremented in the positive Z-direction, building a three dimensional component layer additively. To insure that a uniform deposition was achieved for each layer independent of direction, a specialized powder delivery nozzle and powder feeder have been developed⁹.

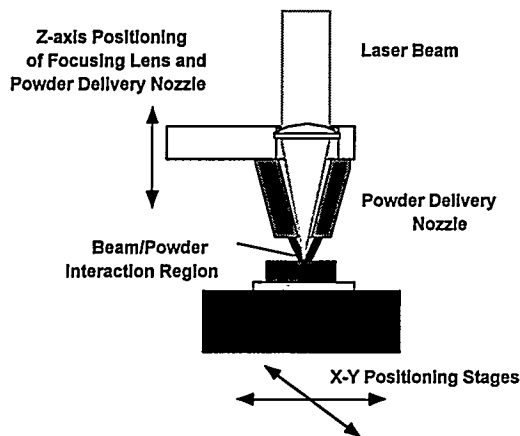


Figure 1: Schematic of the LENS process.

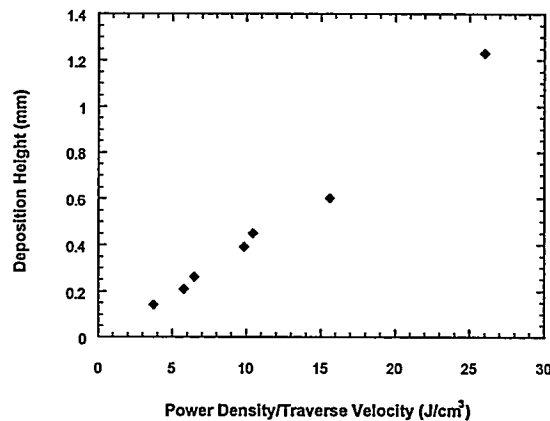


Figure 2: Build height as a function of the volumetric exposure.

RESULTS

A. Laser/Powder Interactions

(i) Process Parameters

Our initial research was to demonstrate the role of the processing parameters for thin walled geometries. Statistically designed experiments were done using Inconel 625 to identify significant process variables and to begin to understand the deposition process⁶. The process variables considered were: component velocity, laser irradiance, Z-axis increment, and powder volumetric flow rate. The response variables used in evaluating the experimental results were: the material build-up height, the melt depth into the previous layer, and the ratio of these two variables. The tests were performed by depositing ten layers of metal in a single wall for each of the experimental conditions, where the material was deposited in only one direction of travel. Metallographic analysis was used to measure the response variables and to evaluate the experiment results. Analysis of this data for the Ni-based super alloy 625 has shown that there is

a linear relationship between the layer build-up height and total volumetric exposure. The volumetric exposure is the ratio of the laser irradiance to the component travel speed. A graph of these experimental results is shown in Figure 2.

Complete melting of the powder occurred for all tests. In addition, textured growth of the deposited material occurred across the deposition layer boundary in nearly all cases for thin-walled parts. The build up height was measured from the original surface to the top of the deposited structure. Similarly, the melt depth was taken to be the depth of the dissolution region. Previous work^{6,8} shows there was little intergranular melting in the substrate region. The intergranular melting which has occurred was only a fraction of the substrate grain size. This suggests that for the conditions used in this testing the heat affected zone is relatively small.

For each new material processed by the LENS technique, test matrices are set up to determine the correct parameters to build near net parts. This has been done for a variety of materials: stainless steels, nickel-based alloys, H13 tool steel, and some tungsten. After thin-walled parts are built, solid block test matrices are performed to understand the inter- and intra-layer parameters needed to build fully dense parts.

(ii) Diagnostics

Several diagnostic techniques are used to monitor and to understand the LENS process. These include: laser Doppler velocimetry for powder flow and relative density of the powder entering the laser beam¹⁰, time resolved infrared imaging for thermal characteristics¹¹, high magnification, high speed digital imaging for process understanding⁶, and standard video imaging.

High speed, high magnification imaging allowed the LENSTM process to be effectively slowed down to visualize the molten metal/powder interaction region. It appears that particles do not become molten until they are, in fact, actually injected into the melted metal puddle in the deposition region. Two powder sizes were used to study the process and weld pool behavior. For the smaller particle size (-325 mesh), the melt puddle appear to be stable and well behaved. For the larger particle size distribution (-80 to +325 mesh), the molten puddle was very energetic and unstable. For the larger powder size distribution, the particle size was a significant fraction of the deposition region width. Directing the larger particles into the molten deposition region causes a larger displacement of the liquid metal thus adding more energy to the oscillations of the melt pool. Further studies are required to draw more quantitative conclusions for the effects of particle size on the powder deposition process.

B. Three-dimensional components

After determining the basic LENSTM parameters for a material, a hollow geometry is typically fabricated. Figure 3 is a picture of an H13 tool steel part. The tallest geometry we can build in the LENSTM platform is 6 inches. For this geometry and material, the dimensional variance along Z is only 0.002 inches for the wingspan section of the thunderbird. The surface finish on extruded shapes is typically 250 μ inch.

From our understanding of the LENS™ parameters, solid geometries are fabricated. With a solid geometry, understanding the hatch spacing (line by line spacing) is critical for building 100% dense components. Figure 4 shows a housing built out of 316 stainless steel (SS316). This part is very accurate in X and Y dimensions but the build height needs better control. The error in X and Y is less than ± 0.005 "; however, Z can vary by as much as ± 0.015 " where the substrate extracts the thermal energy from the first few layers. By understanding the thermal behavior along with the LENS™ parameters, we should be able to control the Z height.

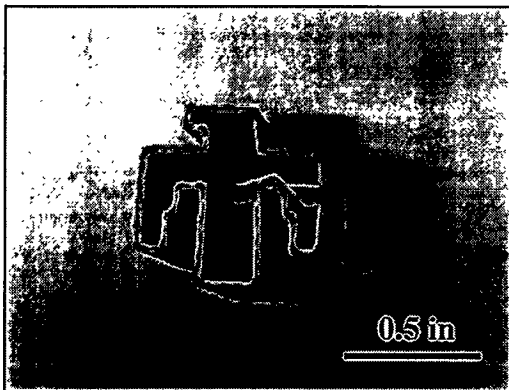


Figure 3: Thin-walled geometry fabricated from H13 tool steel.

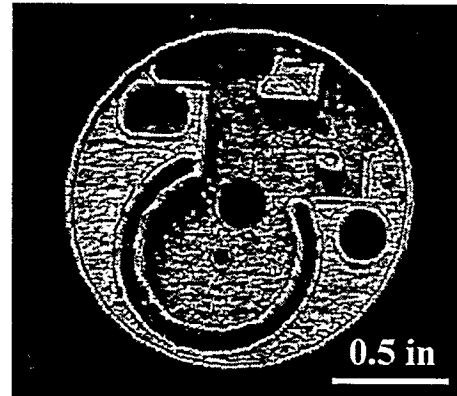


Figure 4: Solid geometry fabricated from 316 stainless steel.

Currently this process is being developed as a free-form fabrication process in which no support structures have been needed. Preliminary results from angle build studies suggest that the maximum angle which can be achieved in a single width deposition is approximately 30° and about 15° for solid parts. A horizontal rotation axis has been added to the LENS system and will expand the geometries which can be built.

Although visual analysis of sample cross-sections exhibited no obvious signs of porosity, helium pycnometry, Archimedes' method, and ultrasonic imaging were used to quantify the density for LENS processed materials. Both the pycnometry and Archimedes method showed the LENS processed materials to be fully dense. Ultrasonic imaging showed that the SS316 processed material had a few microvoids on the order of $1\text{--}5\text{ }\mu\text{m}$ in the interior of the solid. Electron microprobe analysis indicated that there was no apparent difference in composition between the deposited material and the original substrate (which is same material).

C. Accuracy

Photographs of tolerance test parts used to measure the dimensional accuracy of the LENS™ process are shown in Figures 5 and 6. In building these components, it was determined that the dimensions in the X-Y plane could be maintained to less than ± 0.002 inches (0.02 mm). The dimension in the Z or growth direction could only be maintained within ± 0.015 inches (0.4 mm). The angle in the pyramid of Figure 6 is maintain within ± 0.015 inches (0.4 mm). These results are extremely promising and further work will allow improvements in the dimensional accuracy to be achieved. The surface finish appears to be a strong function of the powder particle size with

the smaller powder particles giving a better surface finish. Although the surface finish of the “as built” component is somewhat rough, a small amount of finishing will produce an accurate, high polished surface.

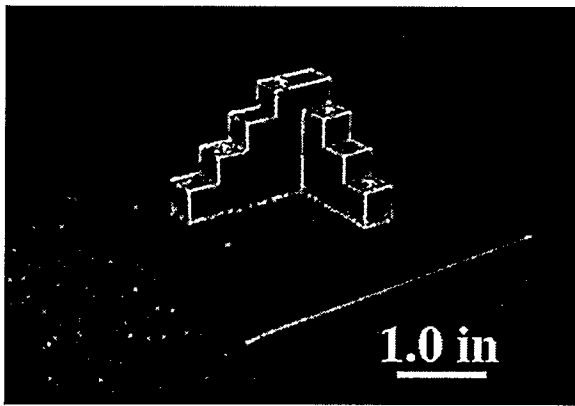


Figure 5: Accuracy test part with step geometry and cylindrical holes.

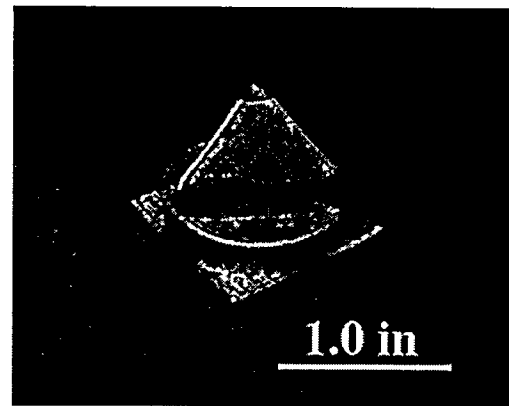


Figure 6: Square-circle-pyramid accuracy test part.

D. Mechanical Testing

Results from preliminary tensile testing of the deposited 316 stainless steel are given in Table 1. Eight bars have been tested to date, six with the layers perpendicular to the tensile pull direction, and two samples with the layers parallel to the tensile pull direction. A third set of data is given for conventionally processed, annealed 316 stainless steel¹². In all cases, the strength properties of the fabricated 316 stainless steel bars significantly exceeds that for the reported value of the annealed material. The elongation for the LENS fabricated have similar ductility where an elongation of 50% (in 1 inch) is achieved. Particle size did not effect the strength properties; but some of the early tensile samples were fabricated with a glove box oxygen content around 20-50 ppm, which lead to premature reduction in ductility. With low oxygen content (< 2 ppm), the ductility values were always greater than 50%.

Table 1: Mechanical tensile test results for LENS fabricated SS316 bars. Plane orientation represents the layer build style with respect to the tensile pull direction.

Plane Orientation (w.rt. tensile direction)	Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Elongation% (in 2.54 cm)
perpendicular (-325 mesh)	65	115	36-66
perpendicular (+100/-325 mesh)	65	115	51
parallel (-325 mesh)	86	117	33
annealed bar ¹²	35	85	50

Metallographic cross-sections of volumetric LENS fabricated parts exhibit no textured grain growth across the deposition layers. Moreover, Poisson’s ratio is isotropic, and the tensile results

do not show any preferred properties for specimens made with the layers perpendicular or parallel to the pull direction.

Preliminary work with H13 tool steel shows that it is readily possible to make components with a hardness value of 59.3 (Rockwell C).

SENSORS

Although this process has proven to be very robust, a significant amount of work remains to develop the LENSTM process for operation in a manufacturing environment. The current system operates as an open-loop system, where it depends solely on the reliability of the laser and other system components to reproduce a given result. Preliminary results from current experimentation suggests that improvements can be made in process reliability by implementation of sensors for monitoring the process and providing a response signal for closed-loop process control.

Research in the area of sensors to monitor the LENS process and for closed loop control is ongoing. Sensors being developed include: powder mass flow for accurate flow conditions¹⁰, thermal monitoring of the weld pool and the workpiece to obtain uniformity in fabrication and resulting material's properties¹¹, pyrometry to monitor characteristics of the weld pool for feedback control¹¹, and in-situ, z-height determination of the workpiece in relation to the nozzle to obtain accurate parts.

CONCLUSIONS

The feasibility of fabricating fully dense, solid metallic components directly from a CAD solid model has been demonstrated. The material properties obtained using alloys such as the Inconel 625 and 316 stainless steel are comparable to a conventionally processed wrought material, in some cases the material properties obtained in the LENSTM fabricated structure far exceed those for annealed materials. Dimensional studies have shown that very precise tolerances can be achieved in the horizontal build plane and the data generated from these studies has suggested ways to control and improve dimensional accuracy in the vertical fabrication direction. Further work is underway to continue to improve the material surface finish and modified fabrication techniques are being explored to overcome angular limitations imposed by the current fabrication approach.

ACKNOWLEDGMENT

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