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Using the Laser Engineered Net Shaping (LENSTM) Process to Produce Complex Components from a CAD Solid Model

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USING THE LASER ENGINEERED NET SHAPING (LENSTM)
PROCESS TO PRODUCE COMPLEX COMPONENTS
FROM A CAD SOLID MODEL

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ABSTRACT

The Laser Engineered Net Shaping (LENSTM) process, currently under development, has demonstrated the capability to produce near-net shape, fully dense metallic parts with reasonably complex geometrical features directly from a Computer-Aided Design (CAD) solid model. Using a highly localized laser beam, metal powders are used to produce very fine grain high strength structures. Results to date show that excellent mechanical properties can be achieved in alloys such as 316 stainless steel and Inconel 625. Significant increases in yield strength have been achieved with no loss in ductility. The current approach lends itself to produce components with a dimensional accuracy of ± 0.002 inches in the deposition plane and ± 0.015 inches in the growth direction. These results suggest that the LENSTM process will provide a viable means for direct fabrication of metallic hardware.

INTRODUCTION

Rapid Prototyping (RP) processes such as stereolithography¹ and selected laser sintering², have enabled component manufacturers to significantly reduce the time required to go from a conceptual design to a production piece of hardware. Although RP processes typically produce an intermediate prototype part from the CAD solid model in model materials such as plastics or plastic coated metal² rather than a finished part, RP processes have created a technology base for the development of a new process which can allow *direct fabrication of metallic hardware*. The Laser Engineered Net Shaping (LENSTM) process³⁻⁵, currently under development, is one process that uses these existing concepts to fabricate fully dense metallic structures directly from the CAD solid model.

The LENSTM process (described below) is a laser based technology that uses a high power Nd:YAG laser to fuse metal particles together as they are injected into the deposition region. Indeed, the concept of using metal powder or wire to fabricate an object is not new⁶. However, the continued development of faster, more powerful computers coupled with the existing level of the RP techniques has allowed this technology to be exploited to begin to fabricate reasonably complex geometrical features in metallic materials directly from the CAD solid model.

In it's current state, the LENSTM process is very much a research application. However, the results of current studies suggest that, with continued improvement, this process will indeed be feasible for direct fabrication applications. In fact, the material properties that can be obtained from the LENSTM process far exceed those for similar material processed using conventional techniques. Efforts are currently underway to improve surface finish and understand the interactions between the various process parameters so that process control methodologies may be developed for closed-loop process control. This article gives a brief description of the LENSTM process and the results that have been achieved to date.

PROCESS

The LENSTM process is currently being developed to satisfy the need to produce metallic hardware in small lot sizes and/or to enable frequent design changes at lower cost. The process operates in a fashion similar to existing rapid prototyping processes in that it uses a .STL stereolithography type file rendition of a CAD solid model for the component to be manufactured for direct fabrication of a mechanical part. The .STL file is dissected into thin layers using conventional slicing algorithms to create the slice file for generating a motion control file to deposit metal in regions defined by the CAD model. The slice file is converted to motion control using a second software driver. This conversion file produces a complete G-code file that dictates where material is to be deposited for each of the build layers. This motion conversion includes proper implementation of shutter response commands, programmed dwell sequences, positional information, etc.. These files can become quite large. For a relatively simple component geometry, the file length for the ASCII text file used in the motion control can be in excess of a thousand pages.

Once the motion control software is generated, the file is transferred to the LENSTM system control computer for fabricating the piece of hardware. The LENSTM system consists of a 1.5 kW continuous wave Nd:YAG laser, a controlled atmosphere glovebox, a powder delivery system and, of course, the motion control system. A schematic representation of the system is given in Figure 1. The laser is mounted on an overhead carriage and the beam is directed into the glove box through a window on top of the chamber. Conventional hard optics are used to deliver the beam to the work area. A six inch focal length, plano-convex lens is used to focus the beam at the work location. The beam spot diameter varies from 500 to about 650 μm , depending on the laser power.

Figure 1. Schematic representation of the LENSTM system developed for direct fabrication applications.

Powder delivery is a critical feature in this technology. Earlier attempts to deliver powder were plagued with non-uniform and non-steady powder delivery. The powder delivery system was developed to eliminate low frequency fluctuations in the powder flow stream and to provide uniform deposition independent of the travel direction. A schematic representation of the deposition process is depicted in Figure 2. Metal powder is directed by the nozzle into the laser

beam focus plane, where it is "consumed" in building up each layer. Powder is fed through multiple jets which converge to the same location as the focused beam. A substrate, typically the same material that being deposited, is required in order to begin to deposit the metal layers. The laser beam is directed onto the substrate to create a molten puddle into which the powder metal is then injected and subsequently melted. The beam is rastered across the substrate, or the previously deposited material, in straight line segments. The line segments are deposited side-by-side to create an entire layer. In this fashion the entire object is fabricated one layer at a time. The current process requires a layer of material to be present to successfully deposit each subsequent layer. Overhanging features are possible, but presently are limited to approximately 30° of overhang from the surface normal.

Figure 2. Schematic representation of powder deposition process used with the LENS™ system.

EXPERIMENTAL

A series of experiments has been performed to characterize the LENS™ process for direct fabrication of mechanical hardware. The primary objective of these experiments was to provide a basic understanding of the LENS™ process. Further experiments are now being performed to improve process characteristics. The majority of the work to date has focused on 316 stainless steel and the nickel based super alloy Inconel 625. Specimens were prepared to quantify the fabricated component surface finish, the material mechanical properties, and dimensional accuracy of the LENS™ process. The two test geometries which were created to evaluate dimensional properties of the LENS™ process are shown in Figure 3. One is a pair of stair-stepped thick walls joined at a right angle and has holes in several of the steps. The other is a relatively thick triangle on top of a circle on top of a square. Rectangular bars were fabricated using both the 316 stainless steel and the Inconel 625 alloys for mechanical testing of the LENS™ fabricated structures. Specimens were created such that the principal axis of the bars was either parallel or perpendicular to the deposition plane. Samples of both configurations were fabricated from each material to test the directional dependence of the material properties and to determine if delamination would occur. Surface finish measurements were performed on these samples using a commercially available perthometer to provide a quantitative measurement of the surface finish.

Figure 3. Photographs of test geometries used in performing accuracy analysis.

RESULTS AND DISCUSSION

The improvements in powder delivery equipment have provided uniform deposition independent of the travel direction of the translation stage. The powder delivery nozzle also provides improved consistency for deposition using powder feed systems which exhibit low frequency fluctuations in the volumetric flow rate. The depth of focus of the optical delivery system is approximately ± 0.05 inches and there appears to be a self-limiting phenomenon occurring in the growth direction. That is, if the laser parameters and z-axis increment are not matched exactly, then the layer thickness will be greater for the first several layers until the process reaches an equilibrium condition in which the layer thickness then matches the z-increment dimension. Thus far, this self-limiting behavior has only been observed when the laser parameters are such that excessive layer thickness is being achieved. Since the powder is injected into the deposition area at a relatively large angle with respect to the beam angle of incidence, the amount of powder available for the deposition process varies along the beam optical axis. Thus, as the deposition plane is moved closer to the nozzle, less powder is available for consumption into the molten puddle. This would suggest that the reduced powder available for consumption ultimately leads to this self-limiting behavior.

The array of experiments performed to characterize the LENSTM process has provided an

Figure 4. Relationship between layer height and processing parameters.

understanding of the controlling physics of the LENSTM process. A set of statistically designed methodology. The total volumetric exposure defined as the ratio of laser irradiance to translation velocity is a key parameter. A graph (Figure 4) of the material layer thickness as a function of the total volumetric exposure, demonstrates that there is a nearly linear relationship between the layer thickness and the volumetric exposure. This result is consistent with other results observed for existing RP systems such as stereolithography¹. In addition, the depth of penetration is constant over a broad range of deposition layer thickness. This suggests that layer thickness can be varied without significantly changing the heat affected zone in each subsequent layer.

Mechanical property data from tensile specimens prepared from 316 stainless steel and Inconel 625 powders with two different sizes (-325 mesh and -100+325 mesh) are given in Table 1. As can be seen from these data, the specimens produced using the LENSTM process exhibited excellent material properties and, in fact, in all but one of these cases the material properties tested were significantly higher than typical annealed wrought material. This was observed for both the 316 stainless steel and Inconel 625 materials. Metallographic examination verified the achievement of full density in the specimens. Transmission electron microscopy analysis of the 316 stainless steel specimens has shown that the grain size within the LENSTM fabricated structures is on the order of 5-10 μm whereas the grain size for the annealed 316 stainless steel is typically around 100 μm . This difference in grain size is believed to be the primary cause of the improved strengths for the LENSTM fabricated structures.

Table 1. Mechanical Test Data From LENSTM Manufactured Tensile Specimens.

Plane Orientation with Respect to Tensile Direction (mesh size)	Ultimate Strength (ksi)	Yield Strength (ksi)	Elongation (% in one inch)
316 SS Perpendicular (-325)	115	65	66
316 SS Perpendicular (100/325)	115	65	51
316 SS Parallel (-325)	117	86	33
<i>316 SS Anneal bar</i>	85	35	50
625 Parallel (100/325)	135	92	38
625 Perpendicular (100/325)	135	75	37
<i>625 Annealed bar</i>	121	58	30

The best surface finish achieved in LENSTM fabricated structures is approximately 250 μinches . It has been observed that the surface finish is a function of the powder particle size; however, little data has been collected at this time to quantify this result. Several alternative methods are currently being evaluated to provide improvements in the material surface finish. Post-processing procedures as well as variations in process parameters are being investigated to achieve the desired results.

CONCLUSIONS

1. We have demonstrated that the LENSTM process is feasible for direct fabrication of simple shapes in metallic alloys directly from the CAD solid model. These components can be produced with good dimensional accuracy and with reasonably complex features including limited overhanging structures.
2. The shapes are fully dense and exhibit enhanced mechanical properties over conventionally processed material for 316 stainless steel and Inconel 625.
3. The surface finish achieved to date is less than that required for most manufacturing operations; however, it is believed that significant progress can be made to provide the surface finish required for most manufacturing applications.
4. A process control methodology using total volumetric exposure, appears likely for controlling layer thickness.

ACKNOWLEDGMENTS

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