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Laser Engineered Net Shaping (LENS™): A Tool for Direct Fabrication of Metal Parts*

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Abstract

For many years, Sandia National Laboratories has been involved in the development and application of rapid prototyping and direct fabrication technologies to build prototype parts and patterns for investment casting. Sandia is currently developing a process called Laser Engineered Net Shaping (LENS™) to fabricate fully dense metal parts directly from computer-aided design (CAD) solid models. The process is similar to traditional laser-initiated rapid prototyping technologies such as stereolithography and selective laser sintering in that layer additive techniques are used to fabricate physical parts directly from CAD data. By using the coordinated delivery of metal particles into a focused laser beam, a part is generated. The laser beam creates a molten pool of metal on a substrate into which powder is injected. Concurrently, the substrate on which the deposition is occurring is moved under the beam/powder interaction zone to fabricate the desired cross-sectional geometry. Consecutive layers are additively deposited, thereby producing a three-dimensional part.

This process exhibits enormous potential to revolutionize the way in which metal parts, such as complex prototypes, tooling, and small-lot production parts, are produced. The result is a complex, fully dense, near-net-shape part. Parts have been fabricated from 316 stainless steel, nickel-based alloys, H13 tool steel, and titanium. This talk will provide a general overview of the LENS™ process, discuss potential applications, and display as-processed examples of parts.

Background

Sandia National Laboratories is a multi-program laboratory operated by the Lockheed Martin Corporation for the U.S. Department of Energy. As an engineering laboratory responsible for the design and manufacture of a variety of prototype electrical and electromechanical devices, a need continually exists for producing complex parts in a timely and more efficient manner. Over the years, Sandia's manufacturing processes have evolved from labor-intensive, manually operated machine tools to computer-aided machining centers and wire-feed electrical discharge machines. Despite advances in computer numerically controlled (CNC) machining, many components at Sandia still required extensive, time-consuming fabrication and assembly. Sandia is not alone in

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DISCLAIMER

the quest to reduce design and manufacturing costs. Global competition is forcing product manufacturers to look for new ways to reduce new product design time and manufacturing costs.

In 1986, a new process for fabricating complex prototype parts called stereolithography (SL) was patented. This process uses ultraviolet lasers to selectively cure photo polymer materials. In 1988, the first commercial Stereolithography Apparatus (SLA) was sold, and a new industry called rapid prototyping (RP) began. Stereolithography, Selective Laser Sintering (SLS), and other rapid prototyping systems give product developers the ability to quickly and accurately visualize, iterate, optimize, and fabricate new design prototypes directly from a three-dimensional CAD solid model. Rapid prototyping accelerates the product development cycle by as much as 80 percent and enhances product quality on everything from car engines and missile parts to cell phones and children's toys. Early on, Sandia engineers recognized the value of these processes for fabricating complex prototypes and patterns for investment casting. The Rapid Prototyping Laboratory (RPL) at Sandia was established in 1990 with the acquisition of a 3D Systems, Inc., Stereolithography SLA-250 system. This machine was initially utilized for production of polymer-based parts for design validation. In March 1992 a DTM Corporation Sinterstation 2000 Selective Laser Sintering Beta machine was installed in the RPL and was used exclusively to quickly fabricate patterns for investment casting. This began the era of using rapid prototype patterns for investment casting at Sandia. Advances in these RP technologies have led to the acquisition of more and newer models of SL and SLS equipment. The RPL now consists of an SLA-500, two SLA-250s, a SLS Sinterstation 2000 SLS production machine, and an Actua 2000 Multi-jet Modeler. These machines are used every day to fabricate complex parts for many applications. A big advantage of using RP machines is the transfer of machine operating data directly from three-dimensional computer models. The transfer is done automatically with little human intervention. Sandia's LENS™ technology is an extension of RP technologies into the direct fabrication of metal parts. Although this technology is relatively new, a promising application for the LENS™ direct metal fabrication process is the manufacture of production quality plastic injection mold tooling and other types of tooling made from high quality hardened tool steel. The development of the LENS™ technology began several years ago under a Cooperative Research and Development Agreement (CRADA) between Sandia and United Technologies Pratt & Whitney (UTPW). The objective of that CRADA was to develop a fundamental understanding of a component repair process previously developed at UTPW, known as laser spraying. During this program, Sandia developed improved methods of controlling laser powder deposition. The combination of that technology and our expertise in rapid prototyping led to the initial idea for the LENS™ process. Subsequent Sandia funding and the formation of a ten company LENS™ CRADA have led to significant improvements in the technology.

The LENS™ process

Conceptually, the LENS™ approach to near-net-shape component fabrication is derived from the approach used by rapid prototyping processes (e.g., SL and SLS) to create plastic prototypes and casting patterns. In both cases, a CAD solid model of a part is sliced into thin layers orthogonal to the z-axis. The slice data is then translated into laser scanning paths to fabricate a single layer. Each layer is fabricated by first generating an outline of each feature, then filling the cross section using a rastering technique. The process is repeated until the part is completed. The critical feature that distinguishes LENS™ from the other RP processes is that it can make components out of structural metals directly, and thus can be used not only as a RP process for fabricating near-net-shaped prototypes but also as a manufacturing process for fabricating production-quality metal parts and injection mold tooling.

The LENS™ system consists of a high-power Nd:YAG laser, a controlled atmosphere glove box, 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 3-5 parts per million. The laser beam is brought into the chamber through a window mounted on the top of the glove box and is 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.

A schematic representation of the LENS™ fabrication system is shown in Figure 1. A flat solid substrate usually made of the metal to be deposited is used as a base for building the LENS™ object. The laser beam is focused onto the substrate to create a weld pool into which powder particles are injected to build up each layer. The substrate is moved beneath the laser beam and a thin cross section of the geometry is deposited. After deposition of a single layer, the powder delivery nozzle and focusing lens assembly is incremented in the positive z-direction, and another layer is deposited. This process is repeated until the part is complete. To ensure uniform deposition and improve overall part quality, a specialized powder delivery nozzle and powder feeder has been developed.

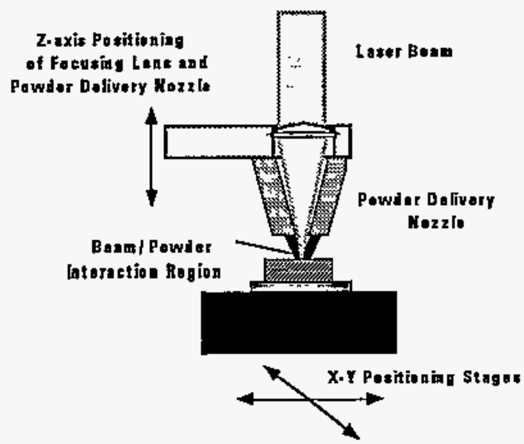

Figure 1: Schematic of the LENS™ process

Metal parts fabricated using LENS™

LENS™ is a unique processing system for fabricating metal parts. With fast localized cooling of the molten pool, parts with thin walls and high depth-to-diameter aspect ratios are easily fabricated. Parts have been fabricated with .014 inch (.356mm) diameter holes 1 inch (25.4mm) tall having a depth-to-diameter aspect ratio of more than 70 to 1. (Generally speaking, depth-to-diameter aspect ratios of up to 10:1 are achievable using CNC machining. Of course, gun drilling and other special machining processes can achieve higher aspect ratios.) Tall thin-walled parts, the thickness of one laser pass, are built rapidly using the LENS™ process. The part shown in Figure 2 is 6 inches tall and was built in less than 2 hours. Another unique processing feature of LENS™ is the capability of selectively applying metal to existing parts or repairing worn or broken parts while maintaining the integrity of the parent material. For many components, integration of the substrate will significantly reduce part build time. Figure 3 is an example where the substrate was used as the base of the part and the sides were added using the LENS™ process. Solid parts with complex internal and external features have been built to near-net-shape, then machined to final accuracy and surface finish requirements. The LENS™ housing in Figure 4 has small, fine features and was processed leaving .007 inch (.18mm) on each surface for final machining. Figure 5 is the LENS™ housing after final machining.

To date, most of the LENS™ research and development at Sandia has been accomplished using 3 axes motion control. A multi-axis system would allow for more complex shapes to be fabricated. In addition to the work at Sandia, similar direct metal fabrication systems are under development at Los Alamos National Laboratory and the University of Michigan, as well as in other laboratories.

LENS™ parts

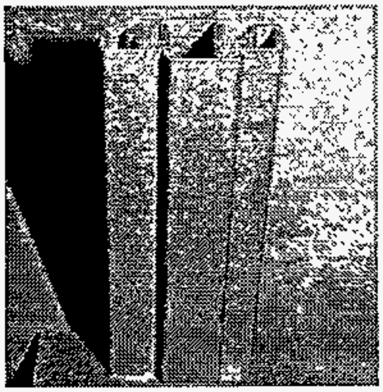

Figure 2: Six-inch tall thin walled part

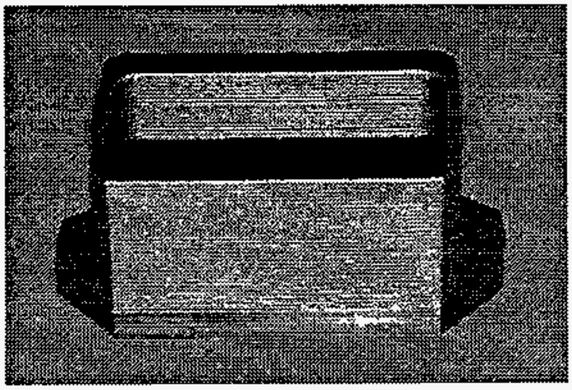

Figure 3: Substrate included in part

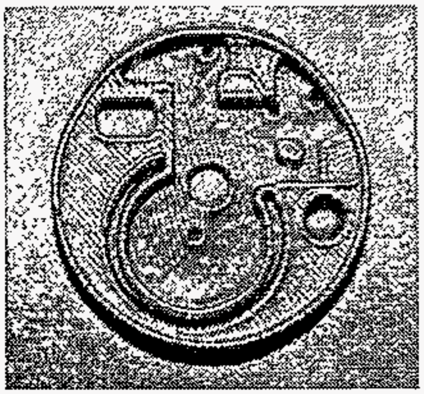

Figure 4: Housing

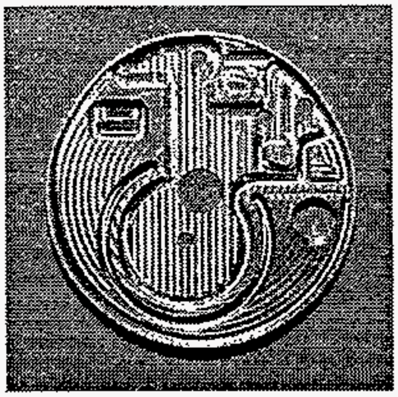

Figure 5: Finished Housing

LENS™ for tooling applications

One of the more promising applications for the LENS™ process is building production quality plastic injection molds and die cast tooling. As previously stated, LENS™ can build complex internal shapes for specific applications. Injection mold tools can be built with internal cooling channels that follow the contour of the mold core and cavity. Although it is a relatively new concept, conformal cooling has the potential to significantly reduce part cycle time by increasing the removal of heat from the mold, ultimately allowing the part to cool more rapidly and be ejected sooner. In addition, more rapid cooling of selected areas of the mold can reduce part distortion and improve part accuracy. The part in Figure 6 demonstrates the concept of an out-of-plane conformal channel. The channel in this part is roughly diamond shaped due to the limitations of a 3-axis system. Tooling experts have stated that the out-of-round shape may allow for more efficient cooling by causing more turbulence within the cooling channel.

Figures 7 and 8 are a core and cavity set of a plastic injection mold die as processed using LENS™. The unique features of these parts are the small diameter holes and deep narrow slots. The saw tooth shaped slots in Figure 8 are .030 inch (.76mm) wide and more that 1 inch (25.4mm) deep. Fabricating this mold set to a near-net shape significantly reduced the amount of EDM time and the number of electrodes required to finish the part.

LENS™ tooling parts

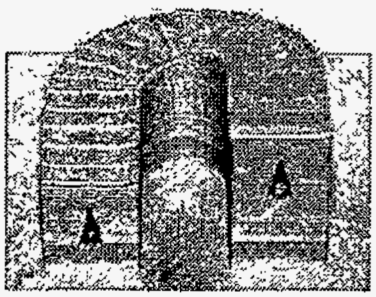

Figure 6: Conformal Cooling Channel

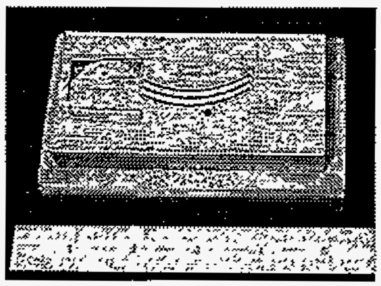

Figure 7: Injection Mold Core

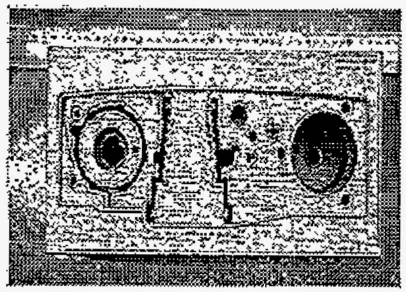

Figure 8: Injection Mold Cavity

Quality of parts fabricated

Traditionally, the overall quality of metal parts used in industry are gauged by accuracy, surface roughness, feature definition, and material properties. This paper will not go into detail regarding material properties of metal parts produced by the LENS™ process, but tests to date show that due to the fine microstructure created by the rapid solidification process, LENS™ parts have material properties that are equivalent or superior to that of wrought material.

With refined parameter selection and process control, the accuracy of LENS™ parts is rapidly improving. Figure 9 is a simple accuracy test part that was used to get a perspective of the dimensional accuracy of parts in the x, y, and z directions. Measurement taken in the x and y directions are within ±.002 inches (.05mm) of the nominal dimension. The accuracy of the z dimensions are typically within ±.015 inches (.38mm) from nominal. The accuracy in the z direction is dependent on the build layer thickness. The thinner the build layer, the more accurate the part. The ability to build a part with variable layer thickness would improve the accuracy in the z direction. The surface roughness of LENS™ parts is relatively rough compared to a machined surface. Surface roughness is a function of powder particle size, and the optimum particle size for the LENS™ process produces a surface between 200-300 microinch average roughness (Ra). Techniques for improving surface roughness are under development.

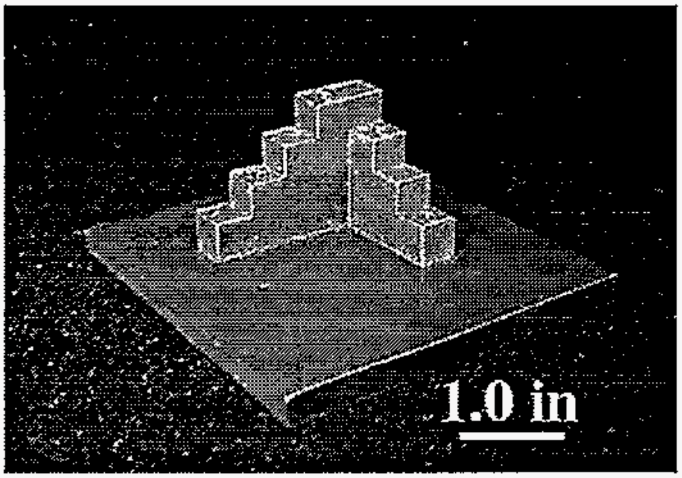

Figure 9: Accuracy Test Part

Conclusion

LENS™ is a new manufacturing process for fabricating complex production quality metal parts and tooling directly from three-dimensional CAD data. Recent advances in hardware and software development have had a significant impact on the overall quality of metal parts produced. Accuracy, feature definition, and surface roughness continue to improve. Further improvements in reliability will lead to unattended operation that will reduce concerns about build time. Injection mold tools have been fabricated with internal conformal cooling channels demonstrating the potential to significantly reduce manufacturing time and costs. By coupling the LENS™ process with CNC machining, parts have been fabricated to a near-net shape and easily finished. And finally, by using LENS™, the concept of art-to-part has now been extended from prototype plastic parts using rapid prototyping machines to fully dense production quality metal parts.

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Biography

Clint Atwood is a Senior Member of Technical Staff at Sandia National Laboratories where he has worked for 23 years, all in manufacturing. For the past nine years, he has worked to integrate and develop laser-assisted Rapid Prototyping and Direct Metal Fabrication technologies at Sandia. He is Chairman of the Rapid Prototyping Association of the Society of Manufacturing Engineers and Past Chairman of the 3D Systems North American Stereolithography Users Group and DTM Selective Laser Sintering Users Group.