MULTI-MATERIAL PROCESSING BY LENS^{TM}

Michelle L. Griffith, Lane D. Harwell, J. Tony Romero,
Eric Schlienger, Clint L. Atwood, and John E. Smugeresky*

Sandia National Laboratories
Albuquerque, NM 87185, *Livermore, CA 94551

INTRODUCTION

During the past few years, solid freeform fabrication has evolved into direct fabrication of metallic components using computer aided design (CAD) solid models. [1-4] Laser Engineered Net Shaping (LENS^{TM}) is one such technique [5-7] being developed at Sandia to fabricate high strength, near net shape metallic components. In the past two years a variety of components have been fabricated using LENS^{TM} for applications ranging from prototype parts to injection mold tooling. [8]

To advance direct fabrication capabilities, a process must be able to accommodate a wide range of materials, including alloys and composites. This is important for tailoring certain physical properties critical to component performance. Examples include graded deposition for matching coefficient of thermal expansion between dissimilar materials, layered fabrication for novel mechanical properties, and new alloy design where elemental constituents and/or alloys are blended to create new materials. In this paper, we will discuss the development of precise powder feeding capabilities for the LENS™ process to fabricate graded or layered material parts. We also present preliminary results from chemical and microstructural analysis.

EXPERIMENTAL

A. The LENS^{TM} Process

The LENS^{TM} system consists of a Nd:YAG laser, a controlled atmosphere glovebox, a 3-axis computer controlled positioning system, and multiple powder feed units. The positioning stages are mounted inside an argon-filled glove box (nominal oxygen level of 2-3 parts per million). The laser beam is brought into the glovebox through a window mounted on the top of the glovebox and directed to the deposition region using a focusing lens. The powder delivery nozzle is designed to inject the powder stream directly into the focused laser beam. The lens and powder nozzle move as an integral unit.

A CAD solid model is sliced into a sequence of cross sections and translated into a series of tool path patterns to build each layer. This file is used to drive the laser system to produce the desired component one layer at a time. A representation of the LENS™ fabrication process is shown in Figure 1. A solid substrate is used as a base for building the LENS™ object. The laser beam is focused onto the substrate to create a weld pool in which powder is simultaneously injected to build up each layer. The substrate is rastered beneath the laser beam to deposit 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 to build a three dimensional component, layer additively.

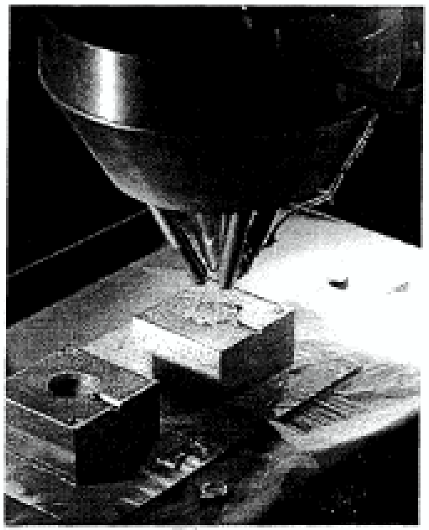

FIG. 1: LENS™ powder nozzle and fabricated parts.

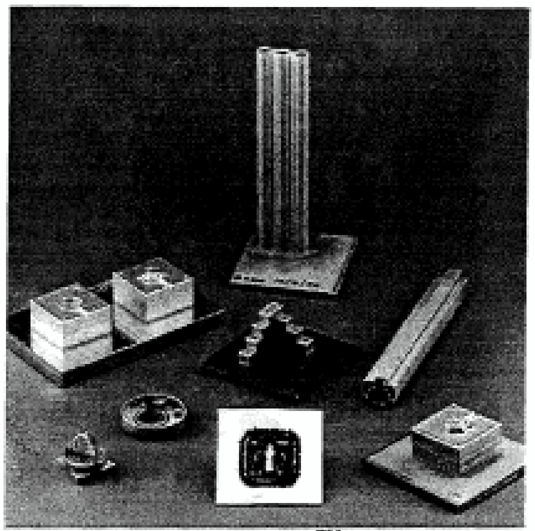

FIG. 2: Collection of LENS™ fabricated parts.

After determining the basic LENS™ parameters [laser power, powder feed rate, traverse velocity, layer thickness, hatch spacing] for a chosen material [5], extrusion or solid geometries are fabricated. Figure 2 shows a collection of components fabricated with LENS™. With an understanding of the LENS™ parameters, fully dense parts are repeatedly built with errors less than +0.005" in the X and Y dimensions and less than +0.015" in the Z dimension [1].

Near net shape components are fabricated with LENS™ having high strengths. Because of the rapid cooling of the weld pool, the as-processed material has a very fine grain structure (< 4 μm), which affects the mechanical properties. Results from room temperature tensile testing [1] of the as-deposited 316 stainless steel show high strength properties [$\sigma_y = 90$ ksi, $\sigma_{ult} = 120$ ksi] which significantly exceeds that for the reported value of annealed material [$\sigma_y = 35$ ksi, $\sigma_{ult} = 85$ ksi] [9]. Nevertheless, the ductility is retained in LENS™ fabricated parts, where elongation of 50% (in 1 inch gauge length) is typically achieved. Hardness testing of tool steel materials, such as H13, have values exceeding 59 R_c.

B. Multi-material Powder Feed

Development of accurate powder feeding capabilities was required for precise control of material placement. Previously, the LENS™ process fed powder into the molten pool for accurate control of line height over a narrow range of flow conditions. The powder feeder was redesigned for accurate flow conditions over a large range of flow rates. Moreover, computer control was integrated into the powder feed system for unattended operation during fabrication of parts. Diagnostic testing was used to test powder feeder designs and to study line heights to determine flow over a variety of feed conditions. Figure 3 shows a comparison between two powder feeders versus flow rates for a chosen laser power and traverse speed. The powder feeders correspond reasonably well, where both feeders show a linear change in line height for increasing powder flow rate. This linear change is beneficial for controlling powder blending or grading in multi-material fabrication.

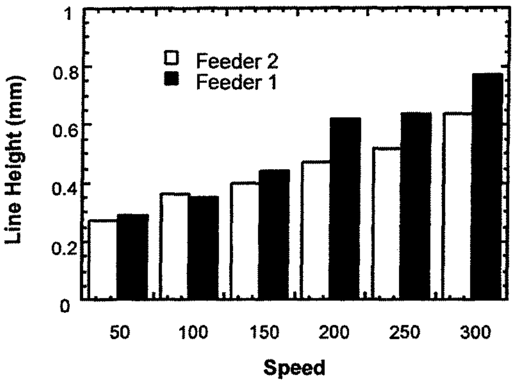

FIG. 3: Line build height versus powder flow rate for re-designed powder feeders 1 & 2.

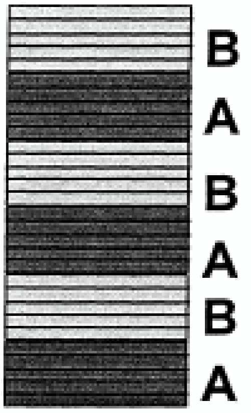

FIG. 4: Schematic of layered deposition. Each material region contains four layers of fabrication before alternating.

Two fabrication styles were used to test the powder feeders: (1) graded deposition and (2) layered deposition. Graded samples consisted of precise deposition where material A was homogeneously deposited, then material B was slowly blended into A from 0 to 100 volume percent (v/o), and lastly material B was fabricated on top. A schematic of layered deposition is shown in Figure 4. Layered samples consist of alternating regions of material, A and B, where each region is built with four layers of material. This paper will describe results for two material combinations: (1) stainless steel 316 (SS316) and Inconel 690 (In690), and (2) SS316 and a special tool steel grade Micromelt 10 (MM10) by Carpenter.

Samples were cross-sectioned, polished, and etched. Optical microscopy and scanning electron microscopy (SEM) were used to evaluate microstructure and porosity. Quantitative analysis of elemental constituents was determined with electron microprobe. Hardness was characterized by either Vickers or Rockwell techniques. Ferrite content in the microstructure was measured as Ferrite Number (FN) by a Magne gage and ferrrite scope.

RESULTS

A. Graded Structures

Figure 5 shows the quantitative elemental constituent results for blending In690 into SS316. As expected, the iron (Fe) content decreases as In690 is added, resulting in increasing nickel (Ni) content. The elemental constituents match with values calculated using a simple rule of mixtures model. Processing conditions were not optimized, but the density of the sample was greater than 98%.

Figure 6 shows the change in hardness over the graded sample. The hardness drops as small amounts of In690 are added to the SS316. At approximately 25 v/o In690, the hardness reaches a low value of 75 R_B. Beyond 25 v/o, the hardness increases until pure In690 is fabricated. This change in hardness at 25 v/o is due to a change in solidification mode. Pure SS316, as-processed by LENS^{TM}, begins solidifying as primary ferrite. Upon cooling, the primary ferrite undergoes a phase change to austenite with a small amount (< 5%) retained skeletal ferrite, referred to as the "ferritic-austenitic solidification mode". [10] In contrast, pure In690 solidifies by primary austenite solidification, with retained eutectic ferrite, otherwise known as the "austenitic-ferritic solidification mode". [10]

Figure 6 shows the change in the skeletal ferrite as measured by ferrite number (FN). In the pure SS316, the ferrite content is approximately 3 FN, and this decreases as In690 is graded into the mixture. In the range of 20-30 v/o In690, the skeletal ferrite disappears because of the changing solidification mode (ferritic-> austenitic) and FN = 0. Moreover, the decreasing iron content along with changes in the Cr/Ni equivalency ratio convert the solidification mode from the primary ferritic to the primary austenitic solidification mode. Beyond 25 v/o In690, the hardness increases linearly through solid solution of Ni and Cr additions.

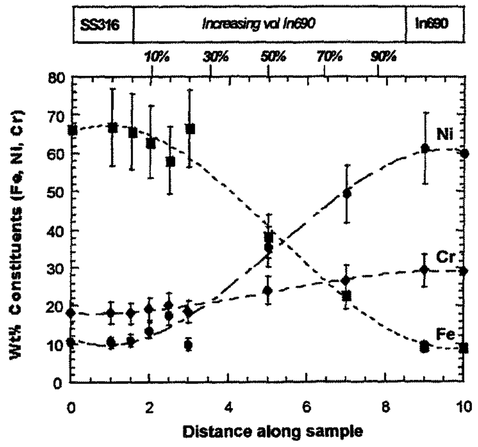

FIG. 5: Alloyed constituent results for blending In690 into SS316 from 0 -100 volume percent.

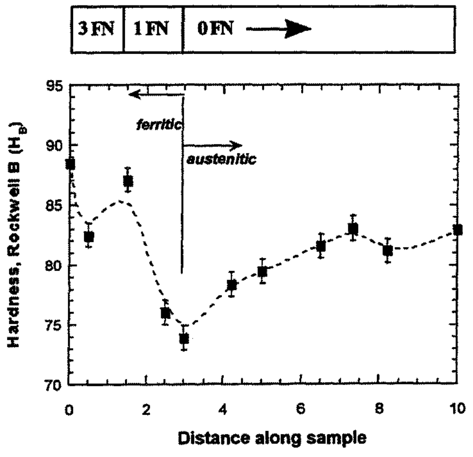

FIG. 6: Hardness values for graded structure from Fig. 5.

B. Layered Structures

(i) SS316/In690

Figure 7a is a SEM micrograph showing three layers in the alternating SS316/In690 part, where the darker shade material is SS316. During LENS^{TM} fabrication of each layer, a small fraction of the previous layer is melted to create the weld pool into which the new material powder is injected. Interestingly, as the stainless steel is deposited onto the Inconel, the weld pool wicks the In690 into the solidification structure as shown in Figure 7b. However, the In690 retains a sharp interface when deposited onto the stainless steel. Further studies are required to understand this effect.

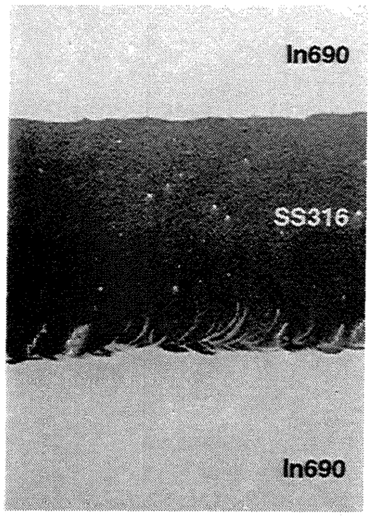

FIG. 7a: Layered structure of SS316 (Dark) and In690 (Light). Growth direction is vertical.

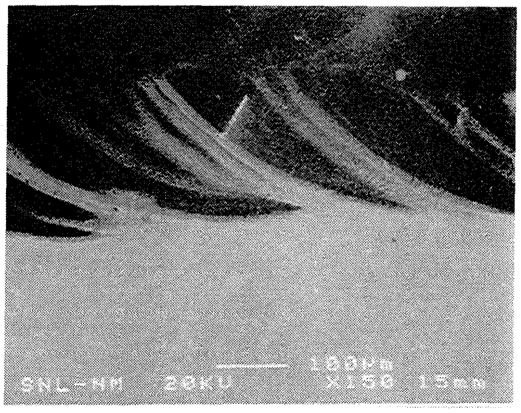

FIG. 7b: High magnification of interface region between SS316 and In690.

(i) SS316/MM10

Figures 8a and 8b show the layered structure for tool steel (MM10) and SS316. In contrast to the SS316/In690 layered sample, each interface is sharp. The fine precipitation of carbides in the tool steel results in high hardness, with a value of 62 R_c. The rapid solidification with fine grain size of the SS316 results in a hardness value of 22 R_c.

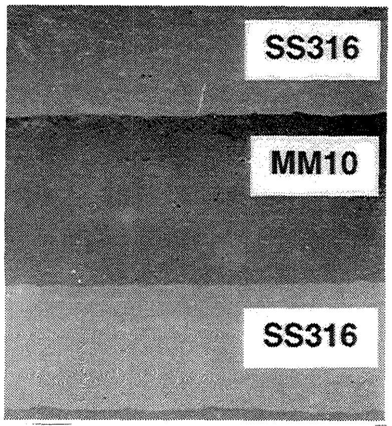

FIG. 8a: Layered structure of SS316 and MM10. Growth direction is vertical.

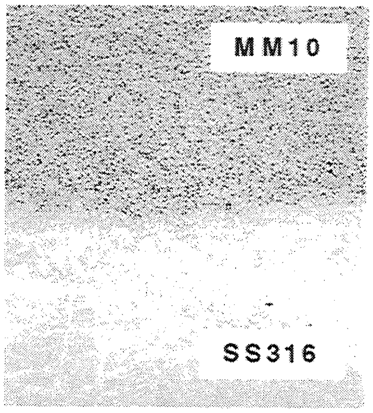

FIG. 8b: Interface between the tool steel MM10 and SS316.

CONCLUSIONS

In summary, a new powder feeder design allows for controlled flow, where dense parts were fabricated in either graded or layered structures. For graded structures, the microstructure and hardness could be tailored when blending In690 into stainless steel 316. Dense structures could be fabricated in a 4-layer composite for two materials, SS316 and In690, and SS316 and MM10.

With this initial work complete, studies of phase formation, microstructural development, and property tailoring have the potential for unique fabrication of components by LENS^{TM} processing. Future work will require further software development to control material placement during part fabrication.

ACKNOWLEDGMENTS

This work supported by the U. S. Department of Energy under contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

REFERENCES

[1] M. L. Griffith, D. M. Keicher, C. L. Atwood, J. A. Romero, J. E. Smugeresky, L. D. Harwell, D. L. Greene, *Free Form Fabrication of Metallic Components using Laser Engineered Net Shaping (LENS^{TM})*, proceedings of the Solid Freeform Fabrication Symposium, August 12-14, 1996, Austin, TX, p.125.

[2] J. R. Fessler, R. Merz, A. H. Nickel, F. B. Prinz, L. E. Weiss, *Laser Deposition of Metals for Shape Deposition Manufacturing*, proceedings of the Solid Freeform Fabrication Symposium, August 12-14, 1996, Austin, TX, p. 117.

[3] F. Klocke, H. Wirtz, W. Meiners, *Direct Manufacturing of Metal Prototypes and Prototype Tools*, proceedings of the Solid Freeform Fabrication Symposium, August 12-14, 1996, Austin, TX, p.141.

[4] J. Mazumder, K. Nagarathnam, J. Choi, J. Koch, D. Hetzner, *The Direct Metal Deposition of H13 Tool Steel for 3-D Components*, Journal of Materials, Vol 49, Number 5, May 1997, p. 55.

[5] D. M Keicher, J. L. Jellison, L. P. Schanwald, J. A. Romero, D. H. Abbott, *Towards a Reliable Laser Powder Deposition System through Process Characterization*, 27th International SAMPE Technical Conference, Vol. 27, Diversity into the Next Century, proceedings of SAMPE '95, Albuquerque, NM, October 12-14, 1995, p. 1029.

[6] D. M. Keicher, J. A. Romero, M. L. Griffith, C. L. Atwood, *Laser Metal Deposition of Alloy 625 for Free Form Fabrication*, proceedings of the World Congress on Powder Metallurgy and Particulate Materials, June 16-21, 1996, Washington, D.C.

[7] J. E. Smugeresky, D. M. Keicher, J. A. Romero, M. L. Griffith, L. D. Harwell, *Laser Engineered Net Shaping (LENS^{TM}) Process: Optimization of Surface Finish and Microstructural Properties*, proceedings of the World Congress on Powder Metallurgy and Particulate Materials, June, 1997, Chicago, IL.

[8] M. L. Griffith, C. L. Atwood, J. E. Smugeresky, L. D. Harwell, D. L. Greene, E. Schlienger, *Using Laser Engineered Net Shaping (LENS^{TM}) to Fabricate Metal Components*, proceedings of the Rapid Prototyping and Manufacturing Conference, April 22-24, 1997, Dearborn, MI.

[9] Alloy Digest Typical Value (gauge length of 5.8 cm), ASM International p. ss-114.

[10] J. A. Brooks, J. C. Lippold, *Selection of Wrought Austenitic Stainless Steels*, ASM Handbook Volume 6: Welding, Brazing, and Soldering, published by the American Society of Metals, 1993, p. 456.