SAND--97-8652C

Laser Engineered Net Shaping (LENS™) Process: Optimization of Surface Finish and Microstructural Properties

J. E. Smugeresky, D. M. Keicher[1], J. A. Romero[2]
M. L. Griffith[2], and L. D. Harwell[2]

Sandia National Laboratories
Livermore, California 94551-0969
[2]Albuquerque, New Mexico 87185-1411

[1]Optomec Design Company
Albuquerque, New Mexico 87123

RECEIVED
SEP 26 1997
OSTI

ABSTRACT

Rapid prototyping (RP) has revolutionized the approach to fabricating geometrically complex hardware from a CAD solid model . The various RP techniques allow component designers to directly fabricate conceptual models in plastics and polymer coated metals; however, each of the techniques requires additional processes, e.g. investment casting, to allow the fabrication of functional metallic hardware. This limitation has provided the impetus for further development of solid freeform fabrication technologies which enable fabrication of functional metallic hardware directly from the CAD solid model. The Laser Engineered Net Shaping (LENS™) process holds promise in satisfying this need. This newly emerging technology possesses the capability to fabricate fully dense components with good dimensional accuracy and with unique material properties. Relatively complex geometrical shapes have been fabricated using this technology. In continuing to develop the LENS™ process, further advancements are required. The functional dependence of the component surface finish and microstructural characteristics on process parameters including powder size and size distribution are being evaluated. A set of statistically designed experiments is being used to sort through the various process parameters and identify significant process variables for improving surface finish and achieving optimum material microstructural properties.

DISCLAIMER

DISCLAIMER

INTRODUCTION

The pressures of the changing world are leading manufacturers to develop novel approaches to stay competitive in the market place. The drivers for these new approaches are reductions in both time and cost to bring products from design to production with maximum flexibility. The first steps in reducing time and cost have come from advances in computers, motion control stages, materials, and laser technologies, which when coupled together facilitated the evolution of rapid prototyping capabilities. Stereolithography and selective laser sintering are examples of processes that have been developed for quickly making models of mechanical parts from polymer based materials. In addition to models, these processes provided patterns to be used in secondary processes such as investment casting. While this development brought about significant reductions in time for castings, these processes are not capable of producing structural metallic parts directly from the CAD files. Further developments at several institutions, including Sandia National Laboratories [1], have led to usage of the structural materials, in particular metals and metal alloys in direct fabrication processes. Examples of processes that include this advancement in technology are Laser Engineered Net Shaping (LENS™), [2-6], Directed Light Fabrication (DLF) [7-9], and Direct Metal Deposition [10]. Each of these processes is similar in that metal particles are fed into laser beams producing near net shape three dimensional parts.

Designers, starting with computer files can now use view techniques to see 3-D images on their desktop monitors, and when the desired part is achieved, can send those files to the laser based machines for fabrication of the part. While these things are possible today, additional development is required to improve on the surface finish of the parts. At this juncture, touch-up machining is still required to achieve the familiar values of surface finish attributable to conventional machining operations.

In this paper, we describe the LENS™ process, and a study to evaluate the impact of processing parameters on the surface finish and material properties. The study was limited to conditions expected to give full density and best dimensional tolerances achievable to date.

EXPERIMENTAL

The Process: The LENS™ apparatus[2] consists of an 1.8 kW continuous wave 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 the argon filled glovebox 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. A specially designed powder delivery nozzle [5] injects the powder stream directly into the focused laser beam and the lens and powder nozzle move as an integral unit. The laser beam creates a small molten pool on the substrate or previously deposited layers. The powder fed into this region is consumed in this puddle causing the height of the puddle to grow away from the substrate surface. A positioning stage on which the substrate is attached is simultaneously moved resulting in the deposition of a thin line of metal that is fully dense. The nominal width and height of this deposit are determined by the powder size, the laser power, the powder feed rate and the travel speed. The trace of the path is analogous to a miniature weld bead. As the bead is rastered back and forth in a plane, a cross-section layer of the shape is left behind. After each layer is deposited, the substrate is moved down away from the lens the distance equivalent to the height of the deposited metal layer and another layer is deposited. Repeating this process, each successive layer is built up until a three dimensional part is formed to net shape. The part is removed from the substrate and ready for testing. Alternatively, the substrate can be designed to be an undersized part of the LENS fabricated structure to expedite processing and reduce time to build the part.

The Experiments: While net shape parts are the ultimate goal for this technology, these experiments utilize simple coupons which are representative of the final shapes expected from this process. A full factorial statistically designed series of experiments was carried out to investigate the effect of process parameters on surface finish and microstructure. Input powder size, laser power, powder feed rate, and stage travel velocity were varied. The range of values is listed in Table I. Powder feed rates varied by changing the settings on the motorized drive. The resulting powder feed rate for these settings is estimated to be in the 1 to 5 g/min range Under this set of parameters, it was expected to get full metal density, based on our previous results [2-4, 6, 11]. The experiments consisted of building 25 mm long single pass samples consisting of 15 layers on 51 by 25 by 1.6 mm substrates. The stage was moved 250 micrometers vertically with each pass.

The material was 316 stainless steel powder sized by mesh sizes of 100/120, 170/200. and -270, corresponding to 149/125, 88/74 and <53 micrometers. These were gas atomized spherical powders with estimated average particle sizes of 137, 81, and 30 micrometers. Spherical powders are preferred because of their good flow characteristics.

The samples were measured for surface roughness on a Mahr perthometer. Selected samples were sectioned, mounted in epoxy, polished and electrolytically etched (10-20 sec) at 3V with 10% oxalic acid for metallographic examination. Knoop microhardness was measured on mounted samples with a LECO DM 400 hardness tester.

RESULTS AND DISCUSSION

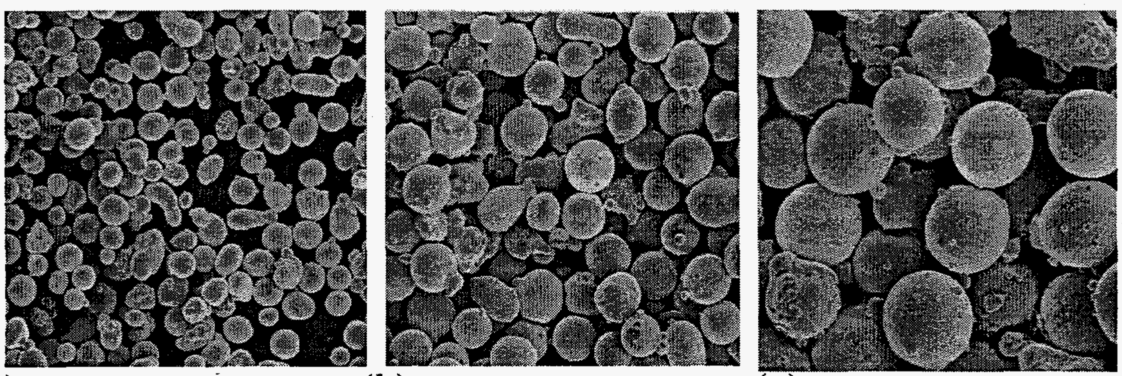
There was considerable variation in both the width and height of the line-builds. The width ranged from 580 to nearly 2500 micrometers, while the height ranged from 3000 to 8200 micrometers. Average layer height ranged from about 25 to 125 micrometers. The topmost layer height, on the other hand, ranged from 380 to 2000 micrometers, despite the step height being held constant at 250 micrometers, and each sample made with 15 layers. This is seen on figure 2, and is summarized in Table II. This suggests that some portion of the previous layer is remelted when each additional layer is deposited.

As expected the rapid solidification that occurs by this process[12] resulted in very fine as-solidified structures Both cellular and dendritic structures were observed, with cell sizes and secondary dendrite arm spacings in the range of 2 to 15 micrometers (see Figure 3). This is an indication that there is enough variation in processing conditions to select different microstructures and therefore engineer the properties of metal alloys with rapid solidification technology. All the benefits of rapid solidification developed to take advantage of metastable microstructures for powder processed materials could be exploited by this technique. In contrast, conventionally processed and annealed bar stock has grain sizes in the 40 to 80 micrometer size range, and no evidence of solidification structures (see Figure 4). TEM examination of the as-deposited structure revealed dislocation densities similar to annealed material (see Figure 5).

Hardness values ranged from 180 to 232 on the Knoop scale, equivalent to Rockwell B values of 85 to 96. Rockwell B values in the 80 to 85 range for stainless steels correspond to tensile yield strengths in annealed bar of about 240 MPa. In previous work[1, 4], which reported mechanical properties on similarly processed material, samples with Knoop hardnesses in the 230 to 240 range, (Rockwell B of 96) had tensile yield strengths greater than 480 Mpa. In that study, the

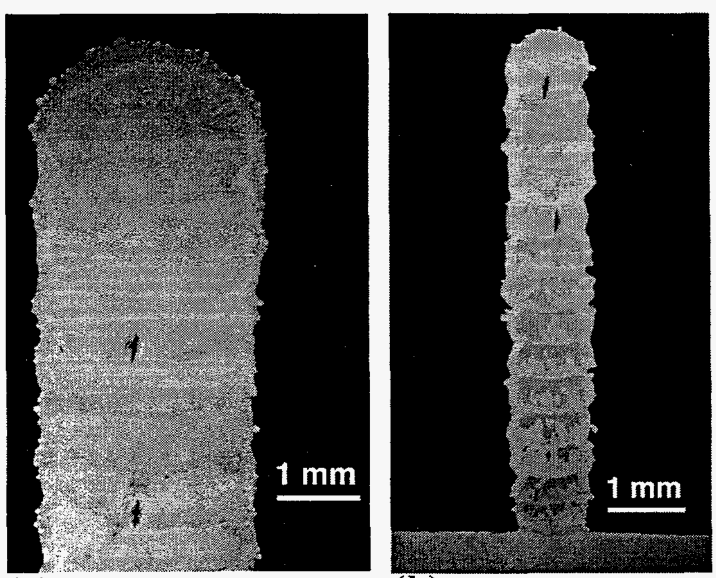
Table I Process Variables Considered For Statistically Designed Experiments.

Input Variable	Low	Medium	High
Powder Size (micrometers)	30	81	137
Laser Power (watts)	150	300	600
Beam diameter (micrometers)		600	
Travel Speed (mm/s)	4.2	8.5	16.9
Powder Feeder Setting	6	12	24
Z-Axis Increment (micrometers)		250	
No. of Layers		15	



(a) (b) (c)

Figure 1 Starting 316 stainless steel powder particle sizes: a) -53 micrometers, b) -88+74 micrometers, and (c) -149+125 micrometers

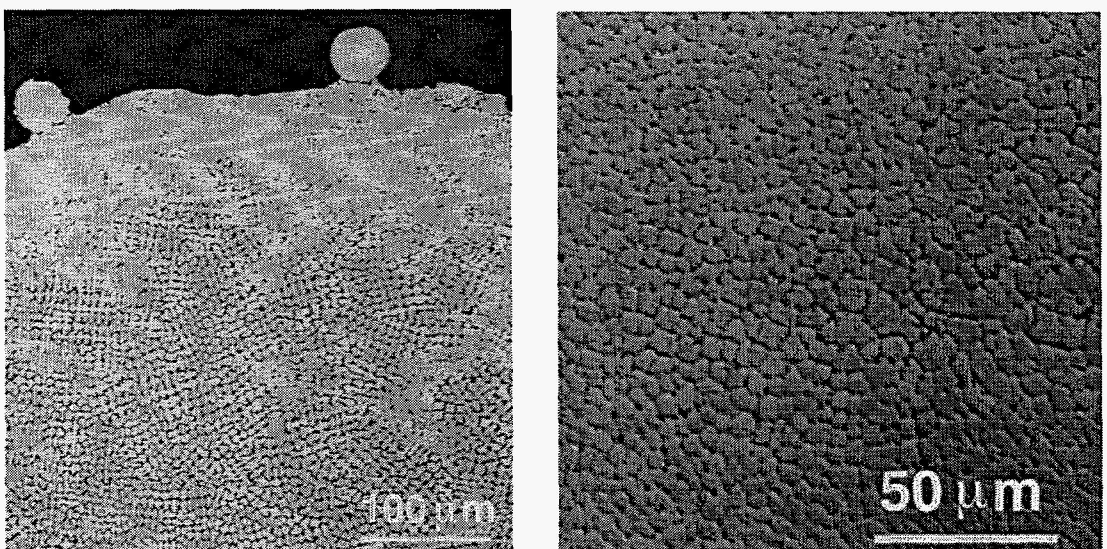


(a) (b)

Figure 2 Examples of variation in sample width and height with laser power, using smallest size particles and maximum speed and travel settings a) 600 Watts, b) 150 Watts.

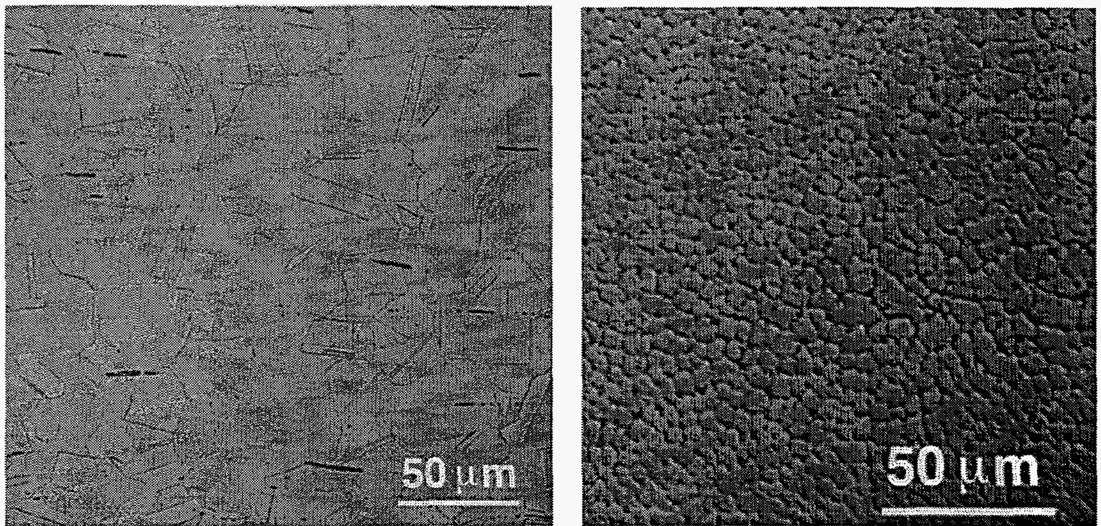
Table II Range of values observed for response variables from statistically designed experiments.

Measured Values	Low	High
Surface Finish (µm)	8	20
Total Height (mm)	0.48	8.18
Width (mm)	0.58	2.34
Top Layer Height (mm)	0.38	1.98
Height per Layer (mm)	0.025	0.132
Knoop Hardness	180	232
Rockwell B Hardness	85	96
Cell/Dendrite arm Size (µm)	2	15



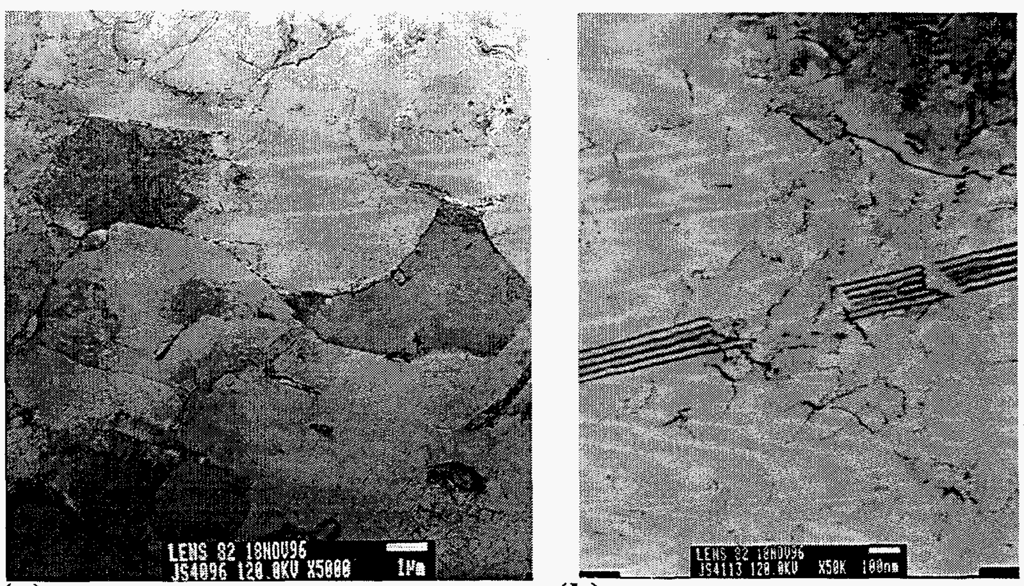
(a) (b)

Figure 3 Both Dendritic and Cellular Structures are Observed: a) secondary dendrite arm spacing is about 10 micrometers, b) cell size is about 7 micrometers.



(a) (b)

Figure 4 Significant refinement in grain size is obtained: a) conventional process, b) LENS™ process, large particles, low power, slow travel speed.



(a) (b)

Figure 5 TEM micrographs of a) fine grain structure and b) dislocations: observed in LENS™ processed sample.

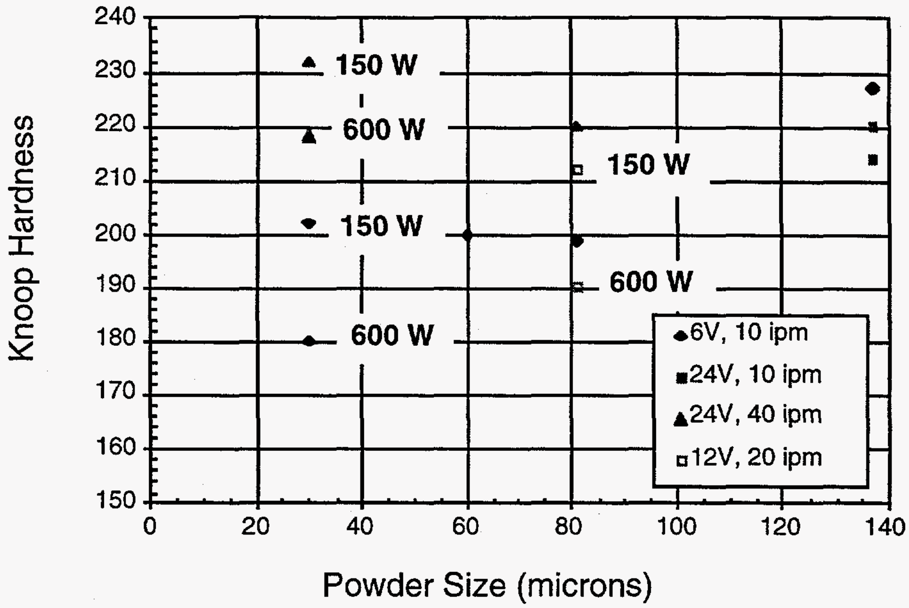


Figure 6 Hardness Depends on Laser Power and travel speed at a given Powder Size, with lower power and higher travel speed resulting in higher hardnesses.

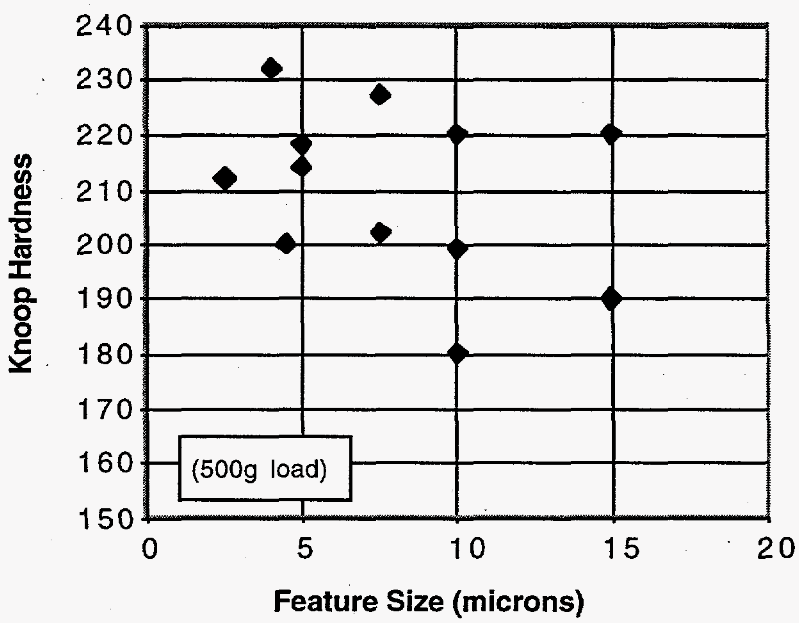


Figure 7 Hardness appears to be independent of microstructure size. Includes both dendritic and cellular structures.

grain size within the LENS™ fabricated structures was reported to be 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 LENS™ fabricated structures, and is consistent with the Hall-Petch relationship between yield strength and grain size. Consequently, full size parts can be made with a wide range of strengths. There does appear to be some relation between laser power and hardness for a given powder particle size as indicated in Figure 6. For the smallest powder size, a wide range of values can be obtained depending on power and travel speed. Higher travel speeds resulted in higher hardnesses, and at a given travel speed, lower power produced the higher hardness. While this trend seems to also apply to the intermediate powder size, it is more ambiguous for the larger particles.

The relation between hardness and microstructure feature is plotted in Figure 7. Here the feature size corresponds to either cell size or secondary dendrite arm spacing. While yield strengths reported for 316 are quite high for bulk samples, and reflect a dependence of grain size, it is hard to see any dependence of hardness on microstructure size for these line-built coupons. Additional studies are under way to examine this correlation in more detail.

Surface finishes ranged from 8 to 20 micrometers. The surface finish appears to be a function of powder particle size as indicated in Figure 8. While a range of surface finish is possible for each powder size, the smoothest finishes were obtained for the smallest particles size. Examination of the surface with the SEM indicates that a significant amount of unmelted particles have stuck to the surface and are contributing to the surface finish, as seen in Figure 9. Cross sections of the surfaces of some samples, reveal evidence of unmelted particles adjacent to solidification microstructures. This suggests that more than one mechanism for particle attachment is occurring, depending on processing parameters, while the deposit is still hot. In some cases, there are just

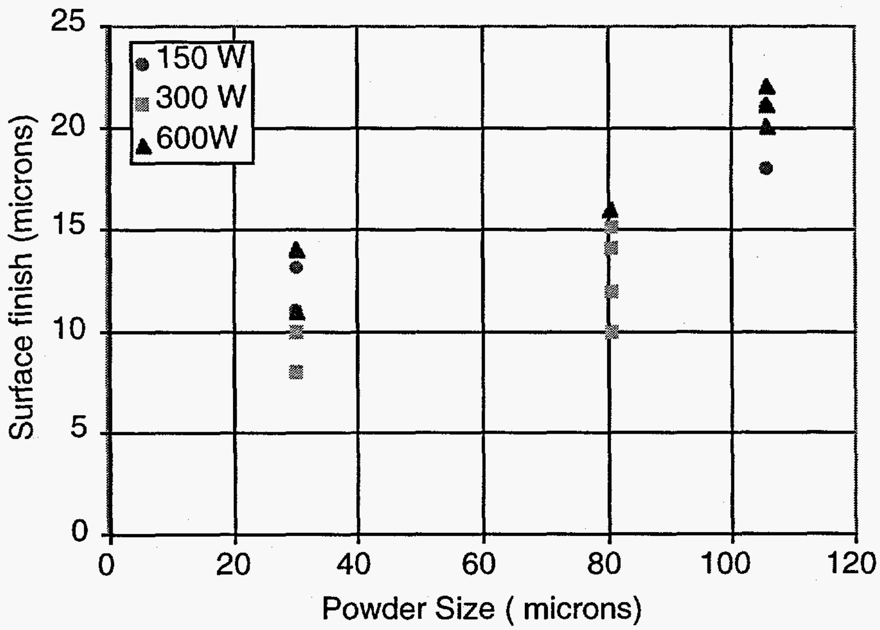
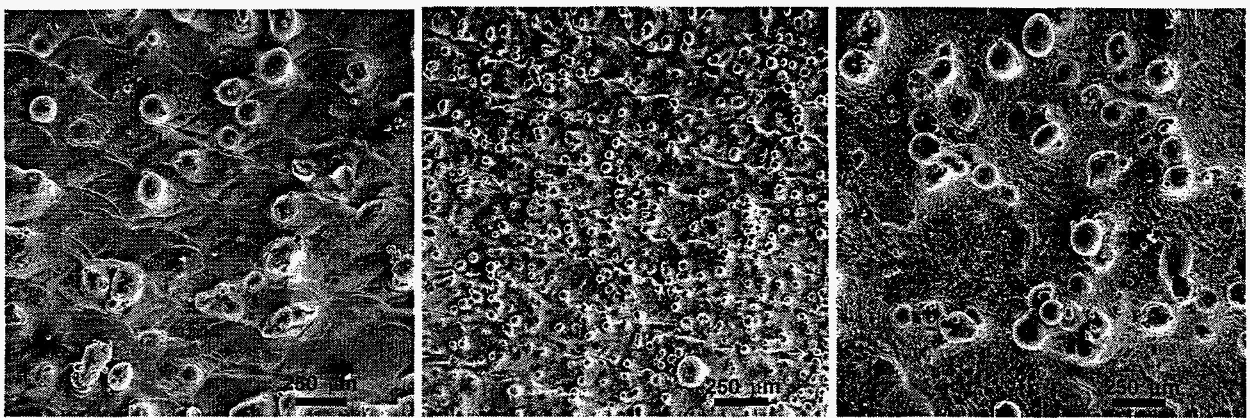


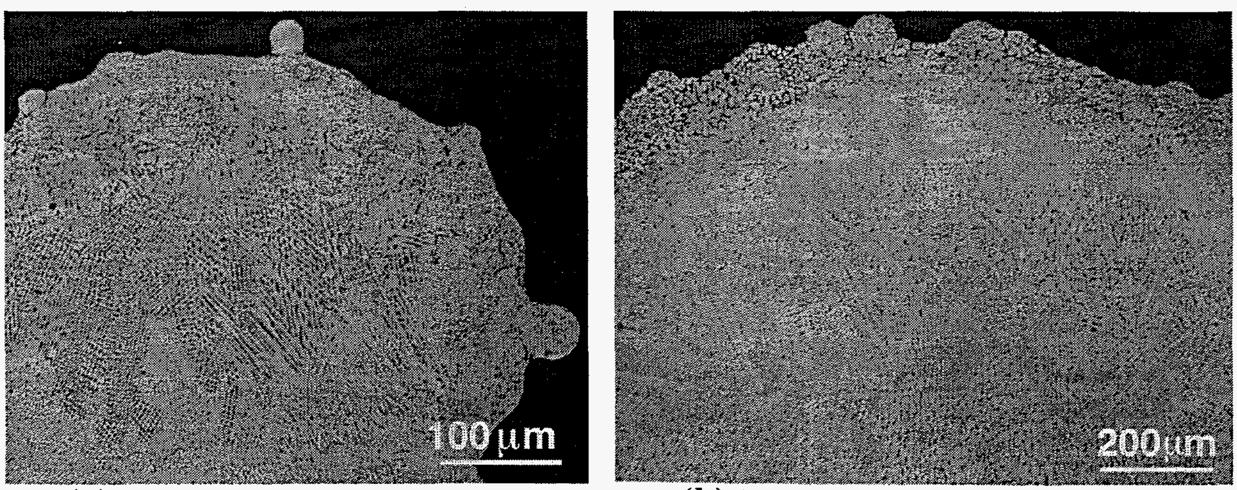
Figure 8 Effect of powder size and laser power on surface finish, showing that surface finish is best for smaller powder size.

individual particles as seen in Figure 10a, and in others, a larger concentration of particles appear as a partially sintered layer (Figure 10b).



(a) (b) (c)

Figure 9 Surface finish for three different conditions, a) Finish is 21 microns, particles are -149 + 125 microns, power is 150 W, feed is 6V, b) Finish is 10 microns, particles are - 53 microns, power is 600 W, feed is 24V, and (c) Finish is 22 , particles are -149 + 125 microns, power is 150 W, feed is 24V.



(a) (b)

Figure 10 Surface features contain a) unmelted but bonded powder particles, and b) partially sintered layer.

CONCLUSIONS

Selection of appropriate processing parameters for the LENS™ process does allow control of such features as surface finish, microstructure and hardness. There is some functional dependence of the LENS fabricated parts on powder size. However, these experimental results suggest that the optimal surface finish is principally a function of laser power and the powder volume. The results suggest that:

1) The best surface finish (8 micrometers) should be achieved at an intermediate power of 325 watts, an intermediate flow rate, and will be independent of travel speed.

2) Knoop hardness ranged from 180 to 232, with the best hardness for the smallest powder size and lowest laser power. The hardness depends on laser power and travel speed at a given powder size, with lower power and higher travel speed resulting in higher hardnesses. The effect is smaller for the larger powder particle size.

3) For 150 and 300 watts, the width of deposited material is approximately the same as the beam diameter, which is approximately 600 microns. At the highest power setting, the width of deposited material was about three times the beam width. The height of the deposited material also varied with laser power.

Work is in progress to further evaluate the relationship between process variables and surface finish and microstructure with support from the US Department of Energy SBIR and Technology Partnership programs.

ACKNOWLEDGMENTS

This work was supported by the US Department of Energy under contract DE-AC04-94AL85000. We would like to thank Mike Oliver for fabrication of samples, Andy Gardea for assistance in metallographic sample preparation and hardness measurements, Mike Tootle for assistance in mechanical property measurements and data analysis, Chris Rood and Nancy Yang for assistance with SEM observations.

REFERENCES

1 D. M. Keicher and J. E. Smugeresky, JOM , 51-54 (1997).

2 D. M. Keicher, J. L. Jellison, L. P. Schanwald, *et al.*, in *SAMPE 1995*, Albuquerque, NM, 1995), p. 1009 -1018.

3 D. M. Keicher, J. E. Smugeresky, J. A. Romero, *et al.*, in *SME Conference*, Dearborn, MI, 1996).

4 D. M. Keicher, J. A. Romero, C. L. Atwood, *et al.*, in *PM2TEC '96* (APMI, NJ, Washington, DC, 1996).

5 D. M. Keicher, J. A. Romero, F. P. Jeantette, *et al.*, (Sandia National Laboratories/DOE, USA, 1996).

6 M. L. Griffith, D. M. Keicher, C. L. Atwood, *et al.*, in *Solid Freeform Fabrication Symposium*, Austin, TX, 1996).

7 G. K. Lewis, R. Nemec, J. Milewski, *et al.*, in *ICALEO 1994*, Orlando, FL, 1994), p. 17.

8 G. K. Lewis, J. O. Milewski, R. B. Nemec, *et al.*, (Los Alamos Laboratory Publication, Los Alamos, NM, 1995).

9 G. K. Lewis, D. J. Thoma, R. B. Menec, *et al.*, in *PM2TEC 96* (MPIF, Princeton NJ, Washington, DC, 1996), Vol. Part 15, Intermetallics and Lasers, p. 11 total.

10 J. Mazumder, J. Choi, K. Nagarathnam, *et al.*, JOM , 55-60 (1997).

11 J. E. Smugeresky, D. M. Keicher, J. A. Romero, *et al.*, Submitted to MS&E (1997).

12 C. O. Brown, E. M. Breinan, and B. H. Kear, (United Technologies, 1982).