Solid Freeform Fabrication of Functional Ceramic Components Using a Laminated Object Manufacturing Technique

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ABSTRACT

Lone Peak Engineering (LPE) has demonstrated the feasibility of using solid freeform fabrication to prepare advanced structural ceramics using a laminated object manufacturing (LOM) technique. High purity, high density alumina ceramic components were successfully made using the LOM process. The properties of the laminated object manufactured (LOMed) components were very similar to the physical and mechanical properties of alumina ceramics that were prepared by a conventional pressing process. The LOMed ceramics were also very similar in properties to commercially available alumina ceramics.

INTRODUCTION

A variety of techniques have been developed to produce parts and prototypes directly from a computer-aided drawing (CAD). The overall process is called by a number of names, including desktop manufacturing, rapid prototyping, freeform fabrication and flexible manufacturing. Some of these techniques are being examined for structural ceramics. Lone Peak Engineering has successfully demonstrated the use of one technique, laminated object manufacturing (LOM), to manufacture advanced structural ceramics.

The LOM process and equipment were originally designed to produce parts from paper. Using a modified LOM machine[a], tape-cast ceramic sheets are being used by LPE to manufacture ceramic parts. The LOM machine uses a computer-controlled laser to cut the green ceramic tape. The cutting path of the laser is determined from a computer-generated solid model of the part being manufactured. The solid model is sliced into a number of cross-sections from the bottom of the part to the top. The laser cuts the ceramic tape to create each cross-section. A new layer of green tape is laminated to the previous layers and then the laser cuts the next sheet. The laser cuts only the new layer. The process is repeated layer-by-layer until the parts are finished. Excess material surrounding the part is removed and binder chemicals are removed thermally. The LOMed ceramic parts are then sintered to high density in a conventional sintering furnace.

Lone Peak Engineering has demonstrated that it is possible to produce parts in a matter of days as opposed to the weeks or months that are required by conventional ceramic processing methods. LPE's experience to date indicates that a print-to-part time of seven days is feasible. The process under development is flexible and suitable for ceramic material in virtually any configuration. The

[a] LOM-1015, Helisys, Inc., Torrance, CA.

ability to rapidly prototype ceramic components via the LOM process will expand the range of applications being considered for ceramic materials.

This paper describes a ceramic LOM process currently under development at LPE. The physical and mechanical properties of the LOMed ceramics are compared to ceramics prepared by a conventional pressing technique. The potential to manufacture complex-shaped components by the LOM process is also shown.

EXPERIMENTAL PROCEDURE

Two processes were used to prepare ceramic specimens for this demonstration. One set of specimens was prepared by the laminated object manufacturing process, while the other set was prepared by a conventional powder-pressing process. Most of the specimens prepared in this project were rectangular bars, however, some other more complicated parts were also prepared by the LOM process.

The only difference between the LOM and conventionally-prepared parts was the method used to form the green parts. The same alumina powder (Al_2O_3)[a] was used in both methods. Once the green specimens were formed by the different methods, the binder removal, sintering, and evaluation processes were identical for the LOMed and conventionally-formed specimens. Process steps specific to LOM and to the conventional processes are described in the next sections. Steps common to both processes, binder removal, sintering and evaluation, are described in later sections.

Laminated Object Manufacturing

Prior to manufacturing ceramic parts, CAD drawings of the parts were prepared. A solid model of the part was created and converted to the .STL format. The .STL file was used by the LOM software to control the LOM process.

Thin sheets of alumina were prepared by tape casting using a proprietary process. The alumina powder was mixed with an organic binder system using a ball mill. The resulting slurry was cast into thin tapes. A doctor blade was used to control the tape thickness to approximately 0.015mm. Squares, 10 x 15 cm, were cut from the tape-cast roll.

The LOM procedure to form ceramic parts consisted of several steps. The LOM process was originally developed to make components from paper and plastic. The process is shown schematically in Figure 1. The sheet material is rolled into place and adhered to the previous layer. During this demonstration, LPE used green ceramic tape-casts sheets that were initially placed by hand onto

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[a]Grade A-16SG, Alcoa, Inc., Pittsburgh, PA.

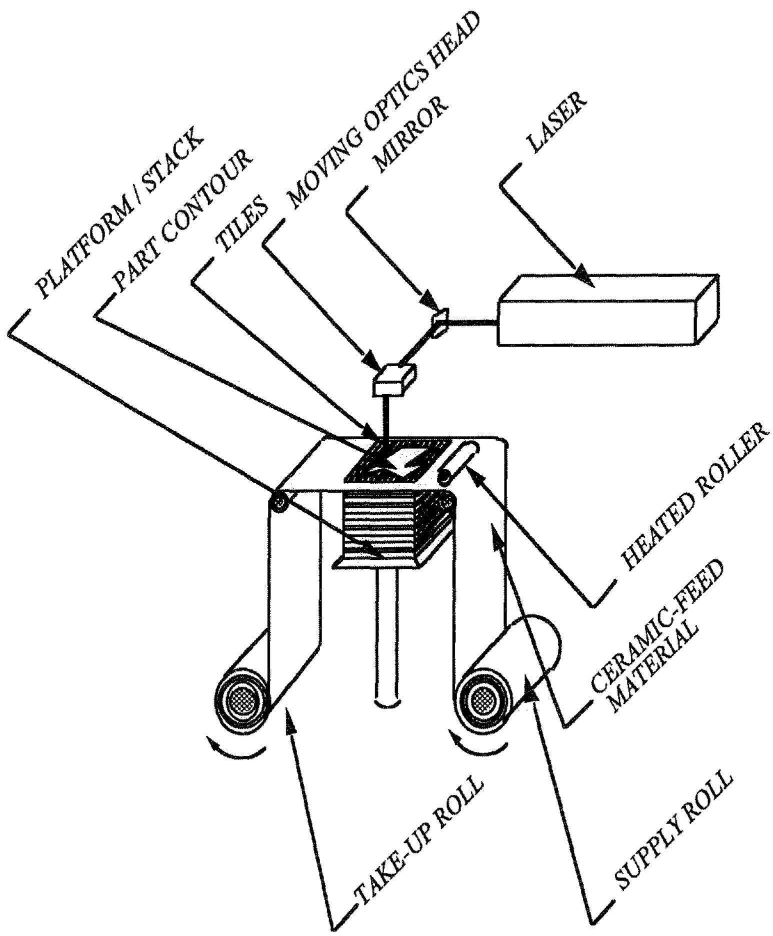

Figure 1. LOM Schematic

the previous layers[a]. The system was modified so that a heated plate and pressure could also be used to assist layer lamination. In the LOM process, a laser cuts only the top sheet material to outline the part. The laser is controlled by a sliced .STL file. "Tiles" are cut into the surplus material to help with removal of the finished component. The table containing the laminated layers is lowered slightly to accommodate the new feed sheet. The process repeats until the part is completed. Eventually, a continuous roll of ceramic tape will be used so that the process can be completely automated for ceramic components.

Excess material was removed from the LOMed parts. The green density of the LOMed parts was determined from the dimensions and mass of the parts when possible. Various alumina parts were made by the LOM process. Bars approximately 6 x 6 x 60 mm in size were prepared. Complex-shaped parts were also made.

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[a] The initial coated sheet was placed onto a glass plate, whereas subsequent sheets were placed onto the previous layers.

Conventional Processing

The alumina powder was milled in denatured ethyl alcohol with 3 wt% of a polyethylene glycol binder[a] to prepare it for pressing. The milling conditions were similar to the conditions used to mill the alumina slurry for tape casting. The milled alumina was dried and screened to -100 mesh.

Rectangular bars were prepared from the screened powder. The powder was first uniaxially-pressed in a cold steel die to form bars, approximately 6 x 6 x 60 mm. The cold-pressed bars were then isostatically-pressed at 207 MPa (30 Kpsi). The dimensions and weight of the pressed bars were measured.

Binder Removal and Sintering

The binder was removed by thermal degradation in air. The LOMed parts and pressed bars were placed together on alumina setter plates. The setter plates were placed inside a furnace and heated to 600°C to remove the binder. The parts were sintered at 1550°C for 2 hours in air.

Physical Property Evaluations

The density and open porosity of the sintered bars were determined by an immersion technique[b]. The weight loss and shrinkage were determined from the physical measurements of the sintered parts. The data are presented in the Results section.

Mechanical Property Evaluations

The sintered bars were ground using a 320-grit diamond wheel. The grinding was done parallel to the length of the bar. These ground bars were used to determine the flexure strength. Some of the ground bars were polished down to a 1 mm finish. These polished bars were used for the hardness and fracture toughness tests. Bars were prepared so that tests could be conducted either perpendicular or parallel to the direction of lamination or pressing.

The flexure strength was determined in 4-point bending. Outside and inside spans of 40 and 20 mm, respectively, were used. The same conditions were used to test the LOMed and pressed bars. The hardness was measured using a Vickers-type diamond indentor [1]. The hardness (H) was determined from the size of the indentation diagonal (a) and indentation load (P) using the following equation:

$$H = 2P/(2a)^2 \qquad (1)$$

The fracture toughness was determined using the indentation-strength method [1]. In this method, the polished bars were indented with the Vickers indentor and the hardness was determined.

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[a] Carbowax 20M, Union Carbide, Danbury, CT.

[b] ASTM-STD-C373-56.

The flexure strength (σ_f) of the indented bar was determined in bending. The fracture toughness (K_{ic}) was calculated from the measured hardness, elastic modulus (E), indentation load, and the flexure strength of the indented bar.

$$K_{ic} = 0.59(E/H)^{1/8}(\sigma_f P^{1/3})^{3/4} \qquad (2)$$

The elastic modulus used for these measurements was 375 GPa.

RESULTS AND DISCUSSION

Alumina ceramic components were successfully made by the laminated object manufacturing process described above. The LOMed components were very similar in physical and mechanical properties to alumina ceramics that were prepared by a conventional pressing process during this project. The LOMed ceramics were also very similar in properties to commercially-available sintered alumina ceramics.

Physical Properties

The physical properties of the LOMed and pressed parts are presented in Table 1. The LOMed and pressed parts sintered to very high densities. The sintered densities were about equal regardless of the forming process or the material used to form the parts. The sintered densities of the LOMed and pressed parts shown in Table 1 were similar to densities of a commercially-available 99.5% alumina, 3.89 g/cc [2].

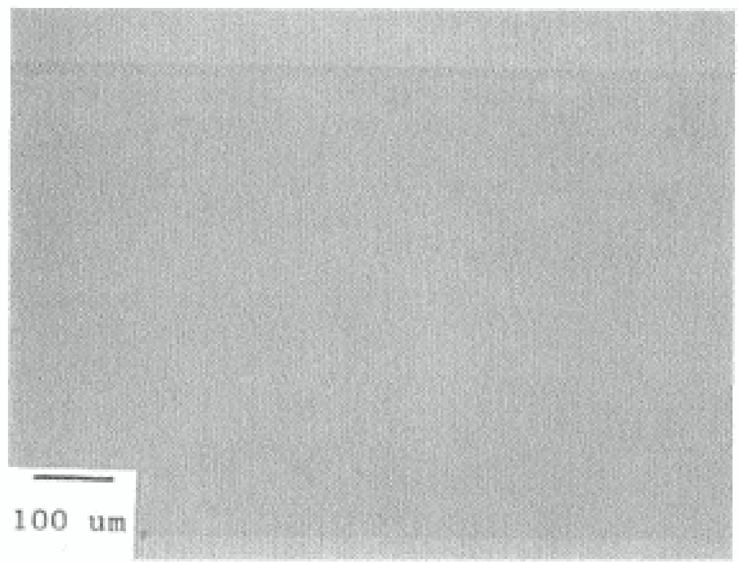
The other physical properties shown in Table 1 are different. The difference in green density, weight loss, and shrinkage can be attributed to the different forming methods. For example, the higher green density of the LOMed parts was due to the higher binder content in these parts, which also resulted in the higher weight loss when the LOMed parts were sintered.

Table 1. Physical Properties of Alumina Parts Made by Laminated Object Manufacturing and by Conventional Pressing.

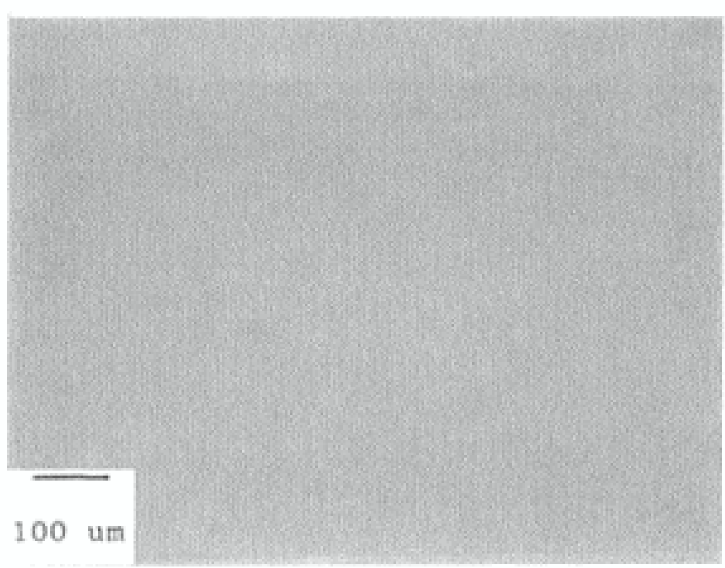
Forming Process	Material	Density Green g/cc	Density Sintered g/cc	Open Porosity, %	Weight Loss, %	Shrinkage
LOM	Tape	2.55	3.88	1.0	17.6	14.1
Pressed	Powder	2.34	3.89	0.4	3.6	15.8

The higher open porosity of the LOMed parts is probably due to small gaps that were observed at the ends of the bars where the laminating pressures were lower. These gaps have been eliminated in more recent parts by adjusting the lamination conditions.

The microstructure of the LOMed parts are shown in Figures 2. It is difficult to distinguish the individual laminated layers in the microstructure of the LOMed parts. The microstructures perpendicular and parallel to lamination were very similar. The microstructure of the LOMed and pressed parts were similar.



(a) Perpendicular



(b) Parallel

Figure 2. Microstructure of LOMed part

Mechanical Properties

The mechanical properties of the LOMed and pressed bars are summarized in Table 2. Tests were conducted in both the perpendicular and parallel direction to lamination or pressing. The mechanical properties were very similar regardless of the forming method used or the direction the test was conducted.

Table 2. Mechanical Properties of the LOMed and Pressed Alumina Bars.

Forming Process	Direction[1] of Test	Flexure Strength, MPa	Vickers Hardness, GPa	Fracture Toughness, MPa-√m
LOM	Parallel	314	20.2	4.3
LOM	Perpendicular	311	20.1	3.9
Pressed	Parallel	336	21.8	4.0
Pressed	Perpendicular	325	19.8	3.7
Commercial grade[2]		379	14.1[3]	4 to 5[4]

[1]The test direction was either parallel to the direction of lamination (pressing) or perpendicular to it.
[2]Data taken from product data sheet for AD995 (99.5%) Alumina, Data sheet 7164C FP 20K 2/89, Coors Ceramics Company, Golden, CO.
[3]Knoop hardness under a 1000 g load, whereas the other hardnesses shown in the table were measured using a Vickers indentor.
[4]Measured by the single edge notched beam technique.

The mechanical properties of a commercial-grade alumina are included in Table 2 for reference. The flexure strength of the LOMed parts was similar to the strength of commercially available alumina. The hardness of the LOMed parts is higher than the commercial alumina but this probably reflects the different test methods, Vickers versus Knoop. The fracture toughness of the LOMed parts was close to the lower limit of the commercial material. This again may be due to the different test methods used, indentation strength versus the single edge notched beam method, rather than an indication of significant material differences.

Complex-Shapes

The power of the ceramic LOM process comes from the potential to form complex shapes without molds or dies. More complex-shaped parts, such as illustrated in Figure 3, can be manufactured by the LOM process.

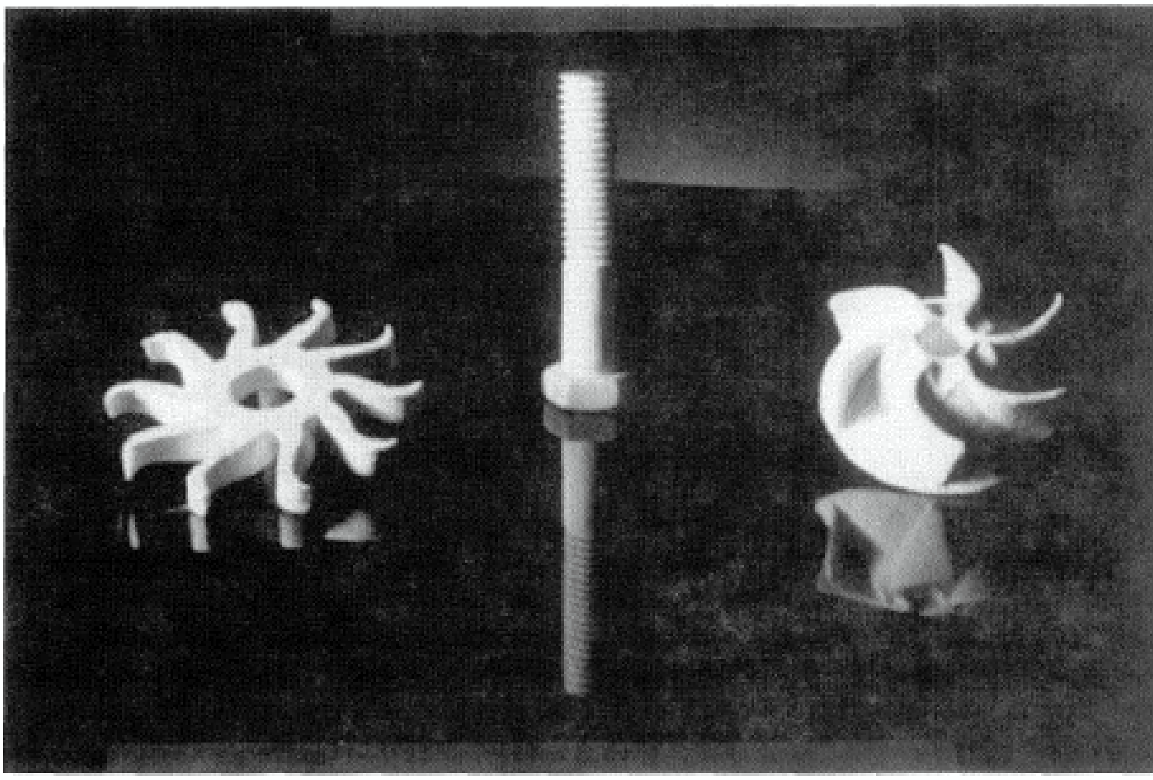


Figure 3. Complex-shaped ceramic components formed by the LOM process

CONCLUSIONS

Advanced structural ceramic parts can be formed by the LOM process. Simple bars and a few complex shapes have been produced. The resulting physical and mechanical properties of the sintered LOMed ceramic bars were similar to ceramics prepared by conventional powder pressing. The properties of the LOMed bars were similar to commercially available alumina.

FUTURE WORK

The ceramic LOM process is still being developed at Lone Peak. The chief goal is to completely automate the LOM process and improve surface finish characteristics.

ACKNOWLEDGMENTS

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REFERENCES

1. J. Am. Cer. Soc., 64[9]: 539-543, 1981.
2. Coors Ceramics Company, Golden, Colorado, Data Sheet 7164C FP20K, 2/89, 1989.