RAPID FABRICATION OF MATERIALS USING DIRECTED LIGHT FABRICATION

Author(s):
DAN J. THOMA, MST-6
GARY K. LEWIS, MST-6
JOHN O. MILEWSKI, MST-6
KATHERINE C. CHEN, MST-6
RONALD B. NEMEC, MST-6

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RAPID FABRICATION OF MATERIALS USING DIRECTED LIGHT FABRICATION


Los Alamos National Laboratory
Materials Science & Technology Division,
Los Alamos, New Mexico 87545 USA

Abstract

Directed light fabrication (DLF) is a rapid fabrication process that fuses gas delivered metal powders within a focal zone of a laser beam to produce fully dense, near-net shape, 3-dimensional metal components from a computer generated solid model. Computer controls dictate the metal deposition pathways, and no preforms or molds are required to generate complex sample geometries. The focal zone of the laser beam is programmed to move along or across a part cross-section, and coupled with a multi-axis sample stage, produces the desired part. By maintaining a constant molten puddle within the focal zone, a continuous liquid/solid interface is possible while achieving constant cooling rates that can be varied between 10 to $10^4$ K s$^{-1}$ and solidification growth rates (that scale with the beam velocity) ranging up to $10^2$ m s$^{-1}$. The DLF technique offers unique advantages over conventional thermomechanical processes in that many labor and equipment intensive steps can be avoided. Moreover, owing to the flexibility in power distributions of lasers, a variety of materials can be processed, ranging from aluminum alloys to rhenium, and including intermetallics such as Mo$_2$Si. As a result, the rapid fabrication of conventional and advanced materials are possible.

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Introduction

Conventional processing of metal components typically involves a multitude of processing steps. In addition, based upon the given design requirements for a desired part, a preform of the product is usually necessary. For example, a pattern, die, or mold is required depending upon whether casting, thermal spraying, forging, stamping, or hot-isostatic processing steps are available or are the most cost efficient. Furthermore, a combination of production methodologies may be required. With the requirement for a preform, steps associated with the production of the preform as well as the component becomes necessary, resulting in multiple handling steps, large production footprints, and waste streams of excess material coupled to the preform or part production. Finally, after a desired shape is produced, further finishing operations may be required, such as joining, machining, or grinding operations.

Rapid fabrication techniques are being developed to potentially overcome the inefficiencies and shortcomings of conventional processing techniques, particularly with difficult to process materials. Specifically, rapid fabrication technologies seek to improve upon conventional processing technologies through either a reduction of processing steps, reduced use of materials, an increase in processing speed, increased chemical homogeneity, or an improvement in process efficiency or safety [1].

This paper describes a near-net shape, rapid fabrication technique that utilizes computer controlled laser fusing of powders. The process, Directed Light Fabrication (DLF), will be defined in addition to the microstructural development experienced in the production technique. From the process definition, examples for the processing of refractory materials will be described, illustrating certain capabilities available with rapid manufacturing.

Experimental Procedure

Directed light fabrication (DLF) is a rapid fabrication process that fuses gas delivered metal powders within a focal zone of a laser beam to produce near-net shape, 3-dimensional metal components from a computer generated solid model [2-5]. Computer controls dictate the metal deposition pathways, and no preforms or molds are required to generate complex sample geometries. The focal zone of the laser beam is programmed to move along or across a part cross-section, and coupled with a multi-axis sample stage, produces the desired part (Figure 1).

Specifically, a solid model is developed, a tool path program is generated from the solid model information, and then a post processor is created to drive the laser beam and positioning system. DLF uses the energy of a high powered multi-kilowatt Nd:YAG laser to fuse powder particles which are precisely injected into the focal zone of the laser using an inert gas. The design of the powder head allows the focal zone of the powder and the laser to remain co-oriented, allowing deposition of material in any position without support structures. The five-axis DLF system enables the processing of three dimensional objects.

Figure 1 - Schematic diagram of the DLF process
consists of motion axes that move the deposit or part, as well as motion axes that index the laser beam focal spot upward an amount equal to the deposition depth after each layer is formed.

The deposition process is started on a metal base plate, and typically, the laser beam is rastered onto the base plate before powder feeding starts. The preheated base plate promotes better adhesion (and therefore better heat transport) for the initial deposited powder. Powders are then fed into the focal zone and the part is deposited in a continuous fashion through the constant feed of a molten puddle that is on the order of 1 mm in diameter. Spherical or angular powders can be used, ranging in size from 10 μm to 100 μm, and the powder can be elemental blends or pre-alloyed. Typical deposition rates can range up to ~10 g/min. (or 1 cm³/min.), resulting in deposition layers that are on the order of 200 μm. The entire process takes place in an inert gas glove box connected to a dry train that reduces the oxygen content to < 5 ppm. Finally, overflow can be recycled from the base plate area so that waste minimization is possible.

In this study, stainless steel samples were processed initially to demonstrate the flexibility of producing complex geometries. Next, for the purpose of evaluating the solidification behavior in DLF, 1-dimensional and 2-dimensional experimental studies were conducted. The 1-dimensional studies consisted of only z-direction growth of rods (~40 mm long and 3 mm in diameter). Plates (or walls) were produced for the 2-dimensional study by building up horizontal layers of continuously fused powder. The walls typically have dimensions of 25 mm x 40 mm x 3 mm (length x height x width). The materials explored were Ag-19wt%Cu and 316 stainless steel. Finally, to evaluate material flexibility, refractory materials (rhenium and Mo₂Si₃) were processed. All starting powders were commercially available.

Results

Process Geometry Capabilities

Owing to the multi-axis processing capability in DLF, complex geometries are possible. The rapid fabrication, near-net shape production of components with various features is shown in Figure 2. Plates, tubes, cones, angles, hemispheres, and cubes can be produced, illustrating such features as overhangs, straight sides, sharp corners and bulk deposits. In addition, in situ joining operations is demonstrated with the asymmetric cone attachment to the oval tube. The near-net shape components can be produced withing a 0.25 mm tolerance, and this tolerance is

![Figure 2 - Parts made by DLF to demonstrate the rapid fabrication of complex geometries.](image-url)
dictated by the surface finish of the process. For example, partially fused powder that is overflow from the process actually defines the surface finish, and a final finishing operation can be performed to meet desired accuracy requirements. However, the single step nature of the process is evident.

**Solidification Behavior**

**Solid/Liquid Interface.** A longitudinal cross-section of a Ag-19%Cu rod processed by DLF is shown in Figures 3a. The rod has continuous dendrites along the length of the sample. Since the microstructural development in the DLF processed sample displays continuous morphologies, a constant solid/liquid interface must be maintained. A schematic diagram of the rod growth process is shown in Figure 3b. Apparently, a molten layer of the alloy resides at the top of the rod, and the solid dendrites continuously grow (in the mushy zone) during the process. Of course, if the molten zone is too large or too small, the stability and integrity of the process decreases. Therefore, the processing variables, such as laser power, beam speed, and powder feed rate, are critical in producing uniform samples. Once these parameters are optimized, the continuous feeding of the molten puddle within the focal zone permits the production of fully dense components. Full density will optimize the properties of the metal.

![Image of Ag-19wt.%Cu dendrites and schematic diagram](image)

Figure 3 - (a) Cross-section micrograph of Ag-19wt.%Cu showing continuous dendrites, and (b) a schematic diagram of the processing of a rod

A longitudinal cross-section of a 316 stainless steel plate sample is shown in Figure 4a, and a schematic diagram of the plate growth is shown in Figure 4b. As with the rod, the dendritic structure is continuous in the sample. Strong evidence of epitaxial growth off of the prior solid interface can be observed with each beam pass, and the zig-zag growth orientation of the layers results from the alternate processing directions of the multiple laser beam passes. In addition, a thin, heat-affected zone (~2 μm) is evident with each beam pass. In the schematic drawing of the plate growth, the mushy zone exists continuously, even at the corners of the plate, to maintain a constant solid/liquid interface. The continuous microstructural development in the plate growth supports the existence of the continuous solid/liquid interface during processing.
Cooling and Growth Rates. Secondary arm spacing analysis is a common technique to experimentally evaluate cooling rates during solidification [3,4]. In fact, previous studies on DLF have documented, with both experiments [3] and computer simulations [4], that the cooling rate for 1-dimensional iron-based rods are on the order of 100 K/s. In addition, the cooling rates for 2-dimensional iron-based plates are approximately $1 \times 10^4$ K/s. The plates experience higher cooling rates because the prior substrate can cool before the next deposition layer is added, thus increasing the driving force for conduction cooling.

The solidification growth rate in the DLF processing of rods should scale with the z-direction growth of the 1-dimensional part. For example, laser speeds can vary between 1 to 50 mm/s. If the laser traverse speed does not match the solidification growth rate, then a stable rod will not be maintained. In fact, the most stable rods are grown when the balance of powder flow rate into the puddle, the laser power, and laser speed provide a rod growth velocity that scales linearly with the laser speed. Similar arguments have been shown to be valid plates using eutectic spacings as a basis for interpreting the solidification growth rates [3].

The cooling rate, $\varepsilon$, is related to growth velocities by the expression $\varepsilon = GV$, where $G$ is the temperature gradient at the solid/liquid interface (K/mm) and $V$ is the solidification growth velocity (mm/s). The Ag-19%Cu material was processed in rod form with various growth rates, and the plot of dendrite arm spacing vs. growth rate is shown in Figure 4. Despite the balance of parameters that are required to produce stable geometries, the cooling rate is rather constant as the growth velocities are changed. This implies that the gradient at the solid-liquid interface must change inversely to the growth rate, with an approximate value being on the order of $G = 1 \times 10^5$ K/m. This value is similar to computer simulation values [4].
Processing of Refractory Metals

The processing of refractory materials introduces production challenges related to the high melting temperature of the metals. For example, processing from the melt is often limited by crucible materials, and thermo-mechanical forming can be hindered by brittle tendencies, especially for intermetallics. As a result, powder processes are a common methodology to produce components, requiring consolidation techniques which may not result in full density.

Rhenium is an example of a refractory metal that displays unique features associated with fabrication. Many iterations of forging and annealing are necessary to form a part by conventional metal working techniques because of its high strain hardening characteristics. The metal may only be worked 10% to 15% before requiring a high temperature anneal of the microstructure. However, despite its high melting temperature \( T_m = 3180 \pm 1 \) °C, structures have been generated with DLF [5] owing to the flexibility in laser power distributions. The micrograph in Figure 5 shows a transverse cross-section of a rhenium rod. The random crystallographic nature of the microstructure is evident from the polarized light response in the micrograph.

Intermetallics offer similar yet different processing difficulties to refractory metals. In addition to high temperature requirements, the brittle nature of this class of materials introduces forming and machining problems. Laser rapid fabrication is being explored to produce quality specimens. Initial efforts on Mo\textsubscript{5}Si\textsubscript{3} \( T_m = 2180 \pm 1 \) °C are demonstrated in Figure 6. The micrograph in Figure 6a is an as-processed rod (transverse section), and the microstructure in Figure 6b was heat-treated at 1400°C for 120 hours. The second phase in the intergranular regions of each micrograph has been identified with x-ray diffraction and scanning electron microscopy techniques to be Mo\textsubscript{5}Si\textsubscript{3}. Apparently, loss of silicon occurred during processing as opposed to microsegregation resulting from non-equilibrium solidification (i.e., Scheil freezing). Nonetheless, the capability to process the brittle intermetallic was demonstrated.

Figure 5 - Cross-section of DLF processed Re.

Figure 6 - Micrographs of (a) as processed, and (b) heat-treated DLF rods (Mo\textsubscript{5}Si\textsubscript{3}).
Discussion

DLF is a rapid fabrication processing technique that can produce near-net shape components from one piece of equipment. As a result, many advantages over conventional processing techniques are possible. The process is a waste free, because it is performed in a high purity inert gas environment in which powder not fused by the laser is recycled. This feature makes it particularly attractive for expensive high performance materials or hazardous materials which require containment during processing. Also, DLF is a single step process in which material in powder form is fabricated directly into a near-net shaped part. The advantages of single step processing include the cost saving associated with the avoidance of conventional machining, forming, or powder processing operations. Furthermore, a reduction in handling and storage may be realized as there are no intermediate processing steps. Finally, rapid fabrication technologies hold promise to significantly reduce the factory footprint both in terms of square footage but also in terms of capital investment and human resources.

In addition to economic and manufacturing flexibility opportunities associated with the rapid fabrication of complex geometries, key areas of advanced materials production are evident with DLF. For example, two-dimensional components have cooling rates in excess of $10^4$ K/s, and these cooling rates on bulk samples actually provide a mechanism to capitalize on many aspects of rapid solidification that, to date, have not been achieved. Rapid solidification yields many novel properties in materials, but processing methodologies typically rely on at least one refined dimension for rapid heat extraction. DLF processing results in deposition layers that are continuous and fully dense, achieving rapidly solidified bulk product. Another opportunity being pursued with the DLF process is the rapid fabrication of fully dense test specimens of high temperature intermetallics and refractory metals. Multiple variations of monolithic and dual phase intermetallic alloys can be produced within a short period, permitting complete alloy design test matrices of near-net shape specimens.

Summary

Directed Light Fabrication offers discernable advantages over conventional thermomechanical processing methodologies with (1) single step processing of complex geometries (2) high solidification/cooling rates of fully dense components, and (3) an ability to produce near-net shapes of refractory alloys. As a result, unique opportunities are possible through the production of conventional and advanced materials.

References


