LA-UR-96- 1964

Title:

Materials Analysis of Deposits Made by the
Directed-Light Fabrication Process

Author(s):

Gary Lewis, MST-6
Ron Nemec, MST-6
Dan Thoma, MST-6

Submitted to:

DOE Office of Scientific and Technical
Information (OSTI)

RECEIVED
JUL 19 1986
OSTI

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

MASTER

Form No. 836 R5
ST 2629 10/91

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ex

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

Materials Analysis of Deposits Made by the Directed-Light Fabrication Process

Gary Lewis*, Ron Nemec, and Dan Thoma

Abstract

This is the final report of a one-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The directed-light fabrication (DLF) process is a unique method of forming three-dimensional objects by fusing airborne powders in the focus of a laser beam. This process bypasses conventional ingot processing steps of casting, homogenization, extrusion, forging, and possibly some or all of the required machining. It provides a new "near-net-shape" fabrication technology for difficult-to-fabricate materials such as refractory metals, metal composites, intermetallics, ceramics, and possibly superconductors. This project addresses the solidification behavior during DLF processing to characterize the technique in terms of solid/liquid interface characteristics, cooling rates, and growth rates.

1. Background and Research Objectives

Directed-light fabrication (DLF) is a process invented at the Los Alamos National Laboratory that fuses powdered materials in the focal zone of a laser. By building up successive fused layers, a free-form metal part with full density and structural mechanical properties is fabricated. The part shape is defined by a solid model generated on a computer, which is used to establish machine commands that provide the relative motion between laser focal zone and deposit to produce the object. Computer model to near-net-shape component is achieved in a single step using the DLF equipment. With this capability conventional metal working processes such as forging, stamping, casting, machining and welding are eliminated.

Since DLF processing offers unique capabilities and advantages for rapid prototyping of complex metal components, an examination of the microstructural development is required to define and optimize the process. The intent of this study was to address the solidification behavior during DLF processing of simple geometries to characterize the technique. In particular, the solid/liquid interface characteristics, the cooling rates, and growth rates required definition.

* Principal investigator, e-mail: gkl@lanl.gov

2. Importance to LANL's Science and Technology Base and National R&D Needs

This project supports Los Alamos core competencies in nuclear weapons science and technology as well as nuclear and advanced materials. Specifically, it demonstrates new baseline technologies for materials processing. Fusing of powders in a laser beam to form weapons components would minimize personnel contact through reduced handling/machining, minimize waste generation, provide for rapid fabrication, and permit formation of unusual structures. This project also enhances the Laboratory's potential for industrial collaboration in the development and marketing of the rapid prototyping technology. There are at least thirteen companies involved in promoting different rapid prototyping technologies. Most if not all of these companies would be interested in extending their capabilities to form fully dense metal structures. Some companies have rapid prototyping technologies for plastics and are working diligently to extend the technology to metals but have not demonstrated the capabilities of the DLF process.

3. Scientific Approach and Results to Date

Our past work in developing the DLF process allows us now to make reliable deposits for analysis and extend the DLF process to other materials. Tungsten, tool steel, titanium alloys, nickel base alloys, NiAl, Moly Disilicide, carbon steel, iron-nickel, iron-aluminum alloys, copper and aluminum alloys are processed. Simple plate shapes are formed from these materials for microstructural analysis. Solidification microstructures, chemical segregation and dilatometer studies are performed to analyze the plate deposits. These properties are compared to conventionally processed materials to determine the advantages of DLF.

For the purpose of evaluating the solidification behavior in DLF, one-dimensional and two-dimensional experimental studies were conducted. The one-dimensional study consisted of only z-direction growth of rods (approximately 40 mm long and 3 mm in diameter). Plates (or walls) were produced for the two-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, Fe-24.8wt%Ni, 316 stainless steel, and Al-33wt%Cu. All starting powders were approximately 50 μ m in diameter and are commercially available.

Solid/Liquid Interface

Cross sections of the Ag-19%Cu, Fe-based alloys, and the eutectic Al-33wt%Cu rods and plates indicate continuous microstructural features along the growth directions of the

samples. For example, the solidification development in the Ag-19wt.%Cu samples illustrates continuous dendrites from the base to the top of the one-dimensional growth processing. In the plates of all alloys, continuous dendrites or lamellae are observed in the cross sections. With each beam pass in the growth of a plate, epitaxial growth off of the prior interface is apparent. Since the dendritic and eutectic microstructures in the DLF-processed sample display continuous morphologies, a constant solid/liquid interface must be maintained. Apparently, a molten layer of metal resides at the top of the rod and plates, 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.

The advantage of the continuous solid/liquid interface region in the DLF process is that fully dense components can be produced. This contrasts to other near-net-shape liquid powder techniques (e.g., thermal spraying) in that a molten droplet does not impact onto a solid substrate, and as a result, structural integrity degradations attributed to splat gaps and other pore defects are absent. Therefore, optimized mechanical properties of as-cast structures can be produced.

Cooling Rates

Micro- and macro-segregation in cast components leads to structural anomalies in terms of the physical properties of the materials. In fact, many studies have shown that reduced micro-segregation in cast components permits optimized strengths of the multi-phase materials, particularly steels. Increased cooling rates decreases secondary arm spacings in dendritic structures. For example, the secondary arm spacing, λ_2 , can be theoretically and experimentally shown to relate to cooling rate by $\lambda_2 = A \epsilon^{-n}$, where A is a constant, ϵ is the cooling rate, and $n = 1/3$. Using these relationships, the cooling rate in a variety of iron-based materials has been demonstrated to be on the order of 100 K/s for one-dimensional rods and 10^4 K/s for two-dimensional plates.

The obtainable cooling rates in DLF processing opens a marketable arena of research that has been ongoing for over twenty years: bulk rapid solidification processing (RSP). Rapid solidification, defined by cooling rates greater than 10^4 K/s, has always been limited to the processing of material with at least one dimension that is less than 50 μm so that heat extraction is high. Melt-spinning, atomization, laser glazing, and splat-quenching are a few examples of RSP techniques. However, the field of RSP has been limited by the consolidation of the materials while maintaining the desired microstructures. In particular, amorphous alloy formation has been a key area of interest. Metastable or amorphous materials have novel and unique properties, which cannot be obtained with conventional processing methodologies.

Bulk ferromagnetic materials with high efficiencies have been explored extensively to reduce energy costs in the United States economy. The experimental cooling rates in DLF, which have been successfully modeled in the past year, defines the ideal processing technique to process bulk amorphous materials with cooling rates on the order of 10^4 K/s.

Growth Velocities

Related to the benefits of achieving high cooling rates in DLF processing are high growth velocities during solidification. As growth velocities increase, eutectic spacings decrease, yielding finer lamellae microstructures. Al-33wt% Cu plates were analyzed with narrow growth velocity variations. The eutectic spacings, which are well-documented as a function of growth velocities, define the growth velocity to scale with the beam velocity. For example, based upon the eutectic spacing, growth velocities of 5 mm/s were obtained with beam-pass velocities of approximately 5 mm/s. These growth velocities in this eutectic alloy rival those obtainable in splat-quenching, where the cooling rates are much greater. Moreover, higher growth velocities with constant temperature gradients at the solid/liquid interface can produce more refined primary arm spacings.

One feature related to the growth velocities in DLF processing is the temperature gradients in the material. Ag-19wt%Cu was analyzed with growth velocities in one-dimensional rods from 1 mm/s to 8 mm/s. The secondary arm spacing was constant, implying a constant cooling rate. Constant cooling rates are possible if the heat transfer is controlled by conduction through the material or at the base plate. The cooling rate is the product of the growth velocity and the temperature gradient at the solid/liquid interface. As a result of the higher growth rates at constant cooling rates, the gradient must decrease. In fact, longer thermal zones are observed during processing with higher growth rates. Thermal imaging techniques have been explored to quantify this effect.

The high growth rates obtained in DLF provides a unique methodology to evaluate growth kinetics in directionally solidified product. These studies are the first quantitative studies at these high rates. Typically, these types of studies are performed with growth velocities much less than 1 mm/s. As a result, a new realm of science-based studies on solidification are possible.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.