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Submitted to:

ASME International Solar Energy Conference
Albuquerque, NM
June 15-17, 1998

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# Near Net Shape Processing for Solar Thermal Propulsion Hardware Using Directed Light Fabrication

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## ABSTRACT

Directed Light Fabrication (DLF) is a direct metal deposition process that fuses gas delivered powder, in the focal zone of a high powered laser beam to form fully fused near net shaped components. The near net shape processing of rhenium, tungsten, iridium and other high temperature materials may offer significant cost savings compared with conventional processing. This paper describes a 3D parametric solid model, integrated with a manufacturing model, and creating a control file which runs on the DLF machine directly depositing a fully dense, solid metal, near net shaped, nozzle component. Examples of DLF deposited rhenium, iridium and tantalum, from previous work, show a continuously solidified microstructure in rod and tube shapes. Entrapped porosity indicates the required direction for continued process development. These combined results demonstrate the potential for a new method to fabricate complex near net shaped components using materials of interest to the space and aerospace industries.

## INTRODUCTION

In this study we demonstrate the capability of DLF to produce a near net shaped rocket thruster shape from a solid model. The Directed Light Fabrication process is an innovative technology that forms parts by fusing metal powders in the focal zone of a laser beam. The process, invented at Los Alamos National Laboratory, is being developed to provide one-step processing of high-performance advanced materials, such as refractory metals, intermetallic materials for a wide range of commercial interests. Commercial technologies requiring rapid fabrication of complex metal shapes in a variety of refractory and lightweight materials, including titanium and rhenium, are found in the space and aerospace industries. A novel and cost-effective approach to fabricating space propulsion components could provide an alternative to the limitations of conventional processing methods. As an example, rhenium is a metal with unique properties (1,2) and a material of choice for solar-powered rocket thrusters and other space application (3). Rhenium possesses the second highest melting point of any pure metal, strength at high temperatures, a low coefficient of friction at high temperature, and high corrosion resistance. But it is hard to fabricate using conventional pressing, forging or chemical vapor deposition. We review previous work in which rhenium, iridium and other tantalum metal shapes have been deposited using the DLF process. In combining these results, we propose a method to produce solid metal objects which may provide a significant cost savings for the space industry.

## DESCRIPTION OF THE DLF PROCESS

### Summary Description

DLF is a free-form metal fabrication process (4 -10). That is, one can form a functional, fully dense, metal component without the use of a die, pattern, or mold, and without the use of metal casting or metal forming equipment. Consequently, it bypasses all traditional forming processes and powder metallurgy processing and reduces them to a single, rapid deposition step to near net shape. During processing, powder which is not fused may be directly reused because it is not contaminated by the process. This feature makes the process nearly waste-free which is of great benefit in processing expensive materials. The process is performed in an environmentally contained, high purity inert argon atmosphere of less than 10 ppm oxygen or water. No solvents or lubricants, such as those used in forming processes are used, improving the purity of the final product over conventional processing.

Plates, tubes, cones, angles, hemispheres, and cubes have been fabricated to demonstrate various geometric features such as overhangs, straight sides, sharp corners and bulk deposits. Demonstrated by the hemisphere, DLF allows deposition of 3-dimensional parts in orientations other than just the horizontal XY plane. It also has the capability to deposit material along complex three dimensional surface contours using 5 axis surface deposition paths. This capability eliminates the necessity of part support structures for overhangs, and special tooling required for "out-of-the-horizontal-plane deposition." The parts are uniform with straight sides, smooth contours and sharp corners. The surface is covered with a layer of partially fused powder particles. The average part surface roughness is generally half the powder particle diameter and therefore highly dependent on particle morphology.

With the current DLF technology, near net shape components can be produced. These parts can be produced within a 0.25 mm envelope of the desired finish dimensions and a final finishing operation might typically be expected to produce the desired surface finish and meet accuracy requirements. However, some parts can be formed to closer than 0.25 mm, depending on geometric complexity, and may even be used in service as-deposited by DLF.

DLF has been applied to free-form fabrication of a broad range of metals and intermetallic compound including 316 stainless steel, 410 stainless steel, iron-nickel alloys, P20 tool steel, aluminum-copper alloys, silver-copper alloys, titanium alloys, tungsten, rhenium, molybdenum disilicide, and nickel aluminide. Mechanical strength of 316 stainless steel, Titanium 6 Al -4 V and Inconel 690 plates and bars deposited by DLF compared favorably to properties of wrought conventionally processed material (10).

### Comparison to Other Fabrication Methods

The problem with refractory metals, is the difficulty to fabricate them at an acceptable cost using conventional processing. Because of its high-strain hardening characteristics, rhenium requires many iterations of forging and annealing to form a part by conventional metal working techniques. Consequently, powder metallurgy techniques and chemical vapor deposition (CVD) technologies are used. However, these are expensive and time consuming processes requiring multiple processing steps including fabrication of mandrels, patterns and dies. For example, CVD requires the fabrication of a suitable mandrel over which Re is chemically deposited at high temperature. The mandrel must then be removed by machining, melting or acid leaching. Electroforming is another method of processing this material. Multiple processing steps are required for conventional processing compared to a single step using DLF once the computer model is generated.

### Description of Hardware

The DFL equipment consists of a 2 kW continuous wave Nd:YAG laser delivered by fiber optics to a 5-axis motion control system. The motion control is mounted within a high purity argon glove box. Powder is delivered by an inert gas nozzle to the focal zone of the laser and remains co-focal with the laser in any orientation from vertical to horizontal. A molten pool, is generated and moved by computer command to deposit material, layer by layer, to form the part. To achieve computer control a solid 3-dimensional model is produced using commercial computer aided design (CAD) software, and then a tool path is created using computer aided manufacturing (CAM) software. The tool path code is then post processed to produce a computerized numerical control (CNC) code specific for controlling the DLF machine.

## APPLYING THE DLF PROCESS TO THE FABRICATION TYPICAL ENGINE/NOZZLE COMPONENTS

### 3D Solid Model

Pro Engineer$^{TM}$ CAD software, running on a Pentium II NT workstation, was used to create a three dimensional solid model of the object to be fabricated. In this example, a nozzle shape was rendered, providing 0.25 mm extra surface allowance to be removed, if required, by a post finishing operation. The solid model used is shown in Fig. 1. Density and volume calculations can be performed using the model to determine the amount of powdered material required to fabricate the final shape. The fully parametric solid model allows rapid sizing, scaling and modification in direct association with the manufacturing model for which it is used as input. This feature allows rapid recreation or modification of the deposition paths used to fabricate a newly shaped object and can be used to rapidly create an entire family of similar objects.

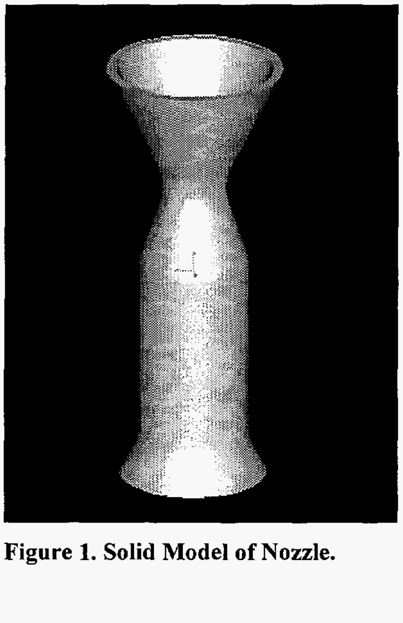

**Figure 1. Solid Model of Nozzle.**

## Manufacturing Model

Using the solid model part definition and a definition of the DLF processing work cell, a manufacturing model was created. The definition of the work cell included the type of operation (i.e. milling, turning, etc.), the number of axes and the type of machining operation (i.e. 5-axis profile motion). Also included within the manufacturing model was a definition of the original 3D solid part, a definition of the volume of material required to produce the part, the orientation of the part co-ordinate system with respect to the co-ordinate system of the DLF apparatus, and orientation of the component as it is being deposited. System parameters associated with the type of material being processed are included in this model. They are typically derived through experimentation and optimized for a specific material. In lieu of a parameter study to optimize for the highest possible density or speed of deposit, general parameters derived from preliminary studies may be selected. Various laser path options are available within the ProMFG™ CAM environment and allow deposition paths to be created and executed by the multi-axis DLF system. The fully integrated manufacturing model easily allows changes to the original part definition, the deposition volume, and specification of the deposition path parameters. A simple regeneration of the model allows rapid recalculation of the deposition path file output. Simulation of the process allows the computation of fabrication times and allows simulation of the deposition path for optimization. These process simulation trials can be compared to determine the trade-off between slower speed vs smaller deposition layers. The tool path was designed to deposit a single deposition path width wall thickness, although walls of any thickness could easily be obtained by modification of the manufacturing model. The final tool path created to deposit a rocket nozzle shape is shown in Fig. 2.

## Computerized Numerical Control File Creation

The CNC deposition path output file is post processed to create the machine command file used as input to the DLF system. NC Post Plus™ software was used to create the custom 5-axis post processor required for conversion of the CNC file to the DLF system control file. A library of post processing routines has been generated to serve the special requirements of DLF processing where material is deposited rather than being removed, as with conventional machining. Additional post processing functions allow operations to be performed on the deposition path file such as scaling, transposing, and patterning of the file to create multiple copies of the object at once.

## Fabrication Of A Typical Engine/Nozzle Component Using Titanium

Using the tool path generated from the manufacturing model described above, a solid metal rocket nozzle part was fabricated to demonstrate the design-to-part methodology of the DLF process. For demonstration purposes, and due to the cost of rhenium, titanium alloy Ti-6-4 was used. The layers were deposited using circular interpolation of the XY axis, a layer-to-layer step up height of 0.25mm and a surface speed of 90 cm/min. The nozzle part was deposited in approximately 30 minutes. The wall thickness of the part, as deposited, is 0.75 mm. The part displayed the characteristic DLF surface of partially fused powder particles. The inner surface would require finishing to meet the design requirements. A photograph of a rocket nozzle deposited using this technology is shown in Fig. 3. With the DLF manufacturing methodology, if cooling fins were required for thermal management and strength, the model could be modified and regenerated to produce a deposition path which would build the fin features concurrently with deposition of the nozzle wall feature.

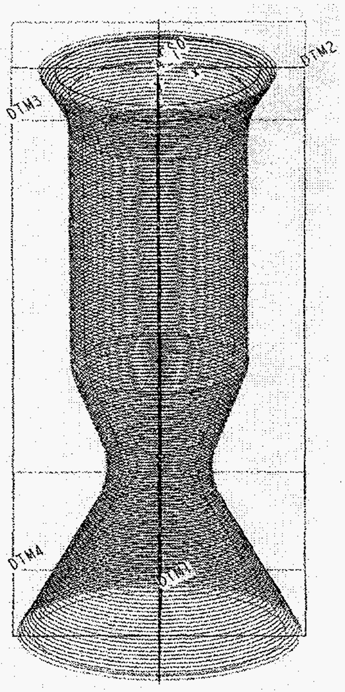

**Figure 2. Tool Path for Laser Deposition of Rocket Nozzle.**

## PREVIOUS DEPOSITION OF RHENIUM, IRIDIUM AND TANTALUM SPECIMENS

### Fabricability Of Rhenium, Iridium And Tantalum

The primary factors which have limited the use of these alloys are their cost and difficulty in fabrication using conventional methods. Forming and machining these alloys is difficult and costly with much waste associated with processing. Casting technology is not feasible for the highest melting temperature refractory alloys due to temperature limitations and constraints on crucible and mold materials. Powder metallurgy techniques have been applied to these materials, such as high temperature hot isostatic press (HIP) bonding and compacting. These techniques also have their limitations with

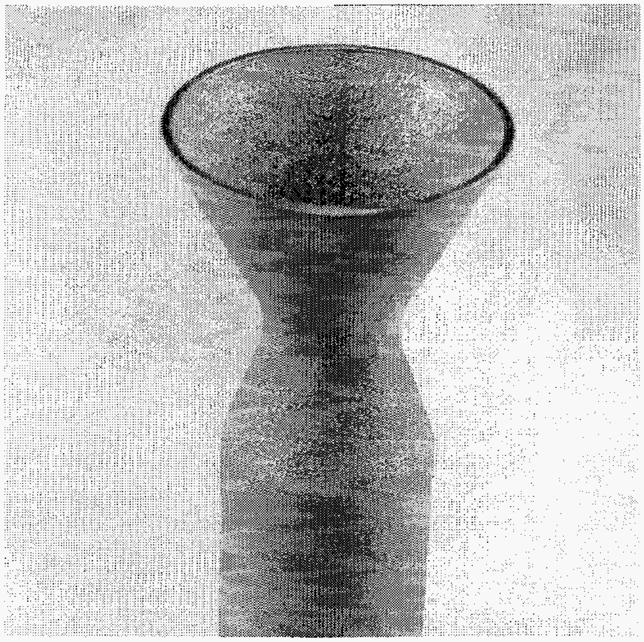

**Figure 3. Titanium Nozzle Deposited By DLF.**

respect to cost, speed, achievable geometry, required tooling and waste product.

## DLF Of Rhenium Specimens

Rhenium was deposited using a Lumonics, Nd:YAG laser focusing three beams into a single 1 mm spot by the use of fiber optic beam delivery [11]. This configuration was the first DLF system built, and is currently no longer in service. An argon gas purifying system was used with deposition performed at oxygen levels of 20 ppm. Rhenium rods were grown beginning on a steel substrate at 0.5 mm/s with an energy of 45 J to 60 J per pulse. The rhenium rods displayed rough, partially fused surfaces but were continuously fused at the core displaying a soft ductile bending behavior. They ranged in length from 38 mm to 70 mm and in diameter from 1 mm to 2 mm.

The DLF deposited rhenium was shown to be an as-cast microstructure, continuously fused into large polyhedral grains ranging in size from ASTM 3.0 grain size, less than 125 microns, to large grains of many hundred microns, > ASTM 1.0, as shown in Figure 4. This range of values may be a result of the variation in cooling rate inherent with the use of the pulsed laser heat source. Polarized light revealed a strong response, indicative of a highly random crystallographic orientation. Porosity was found in the deposited material with two distinct sizes, ranging from 2 μm to 5 μm, for the small porosity, to ~50 μm to 75 μm, for the large porosity. The mean hardness of the DLF deposit was HV 190, with a standard deviation of 29. The final bulk density was not measured. No attempt was made to characterize or reduce the level of porosity in these preliminary trials. Other past experiments, demonstrating the fusing of tungsten powder into wires, showed a much smoother deposit [4].

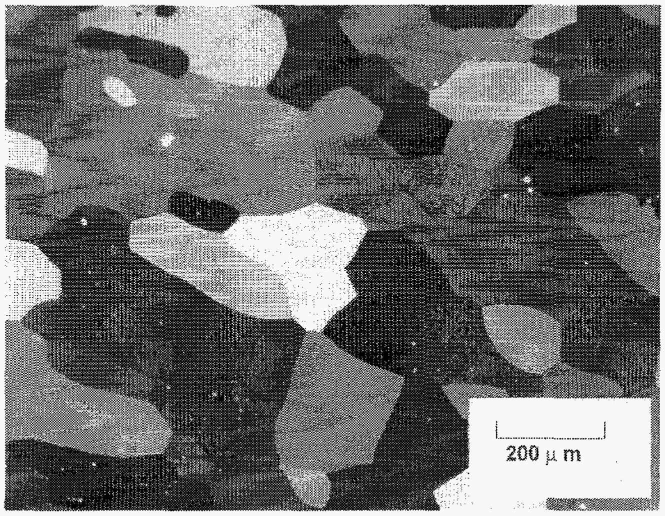

**Figure 2. Microstructure of DLF Deposited Rhenium.**

## DLF Of Iridium Specimens

Pure iridium rods and tube sections were deposited using the 5-axis DLF system in which a 2 kW Nd:YAG laser coupled to a 5-axis motion system. The DLF deposited 0.5" diameter tube section of iridium displayed a cast microstructure continuously fused into large polyhedral grains as shown in Figure 8. As similar to the rhenium, small and large pores were also observed with a qualitative reduction of porosity seen along the mid section of the tube wall. Coalescence of small porosity into large porosity as observed in the metallographic sections examined. This was indicated by a transition of pore sizes from small porosity near the first to solifiy wall region, to large pores in the last to solidify center regions of the deposit. The final bulk density was not measured. Thick rounded layers fused into one another were observed along the tube wall indicating an excessively large vertical increment of motion from one layer to the next for this material.

## DLF Of Tantalum Specimens

Tantalum metal shapes have been deposited using the 5-axis DLF system in the vertical and horizontal positions and demonstrated

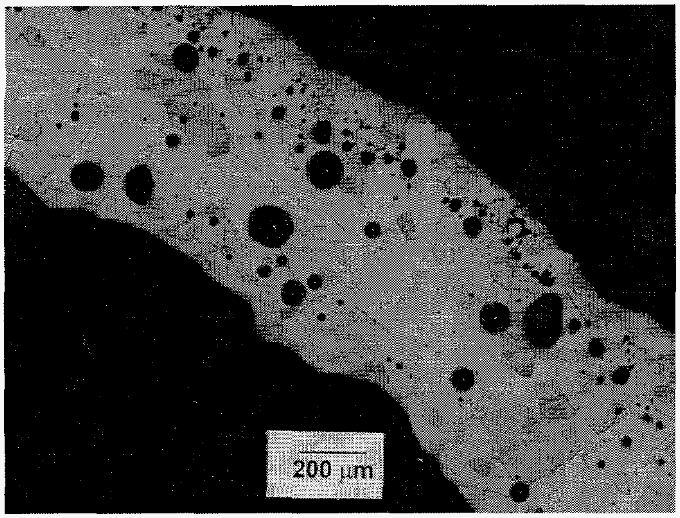

**Figure 5. Porosity Observed Within the Iridium Sample.**

improved surface finishes similar to stainless steel deposits [6] . Porosity was evident but may have been introduced into the melt pool by the porous powder and trapped within the rapidly solidifying structure due to the pulsed energy (high cooling rates) used. The powder used may also have been oxidized, though no attempt was made to ascertain this condition. Investigation into the ability of this process to refine the starting material through high purity atmosphere remelting or powder heat treatments [6] may be worthy of future study. Slower cooling rates associated with CW laser processing may provide opportunity for porosity to escape the molten pool through buoyancy and be replaced by liquid within the solidifying deposit. A larger and more spherical powder in the 50µm to 100µm range would be attractive with respect to better flow characteristics.

## CONCLUSIONS

A manufacturing model for DLF was presented as a near net shape fabrication technique applicable to the forming of complex parts directly from powder. DLF direct laser deposition of rhenium, tantalum and iridium powder was demonstrated. Evaluation of the microstructures revealed a continuously fused microstructure of equiaxed grains with entrapped porosity. A full parametric study is required to realize the extent to which entrapped porosity may be reduced by the selection of process parameters or pre-processing of commercially available powders. Future work should focus on slower deposition with and increased overlap between deposition paths allowing a greater degree of remelting and an increased opportunity for coalescence and removal of porosity. This research demonstrates the feasibility of forming complex rhenium and iridium metal shapes directly from powder.

## ACKNOWLEDGMENTS

The research was funded under DOE contract No. W-7405-ENG-36. The authors wish to thank R.B Nemec for operation of the DLF machine, Dr. R. Reiswig, P.Pappin, S. Herbert, J. Montoya (LANL) for metallographic interpretation and preparation. The authors would like to thank SyntheMet Corporation for the process simulation study and iridium deposition study.

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