CONF-9705215--

LA-UR- 97-3884

Title: FREE-FORM PROCESSING OF NEAR-NET SHAPES USING DIRECTED LIGHT FABRICATION

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Submitted to: 15TH INTERNATIONAL THERMAL SPRAY CONFERENCE TO BE HELD IN NICE, FRANCE ON MAY 25-29, 1997

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Free-Form Processing of Near-Net Shapes Using Directed Light Fabrication

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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 with accurate and precise tolerances. The DLF technique offers unique advantages over conventional thermomechanical processes or thermal spray processes in that many labor and equipment intensive steps can be avoided to produce components with fully dense microstructures. Moreover, owing to the flexibility in power distributions of lasers, a variety of materials have been processed, ranging from aluminum alloys to tungsten, and including intermetallics such as Mo_5Si_3. Since DLF processing offers unique capabilities and advantages for the rapid fabrication of complex metal components, an examination of the microstructural development has been performed in order to define and optimize the processed materials. Solidification studies of DLF processing have demonstrated that a continuous liquid/solid interface is maintained while achieving high constant cooling rates that can be varied between 10 to 10^5 K s^{-1} and solidification growth rates ranging up to 10^{-2} m s^{-1}.

NEAR-NET SHAPE PROCESSING techniques aim towards the production of geometries in a single step. In this manner, a minimization of handling steps, waste products, and production footprints can be achieved. As a result, lower costs in the production of components are possible.

However, based upon the given design requirements for a desired near-net shape part, a preform (prototype) of the product is sometimes 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. With the requirement for a preform, steps associated with the production of the preform as well as the component become necessary, potentially increasing the manufacturing cost.

In order to derive the benefits associated with near-net shape production, but to eliminate the requirement for preforms, 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 described, and in addition, the microstructural development during solidification will be characterized.

Experimental Procedure

The DLF technique has been described previously [1-5], and the general features of the process will be described here. In the DLF process, a computer solid model is developed and a tool path program is generated from the solid model. A post-processor is used to create the machine code to drive a laser beam and positioning system. DLF uses the energy of a high power 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 delivery of the powder and the laser to remain co-focal, allowing deposition of material in any position without support structures. A five-axis positioning system enables the processing of three dimensional objects. For example, the multi-axis positioning system consists of motion axes that move the deposit or laser beam relative to each other, and the deposition is incrementally oriented to form the volume of the resultant part.

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 cm^3/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 material flexibility, widely ranging melting temperature materials (Al-33wt.%Cu and Mo_5Si_3) were compared. Finally, 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.

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 1. Plates, tubes cones, angles, hemispheres, and cubes can be produced, illustrating such features as overhangs, straight sides, sharp corners and bulk deposits. In addition, an *in situ* joining operation is demonstrated with the asymmetric cone attachment to the oval tube. The near-net shape components can be produced within a 0.25 mm tolerance. This tolerance is 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.

Material Flexibility

In addition to component geometry flexibility, the materials capabilities offer significant robustness. A variety of metals and metal alloys have been successfully processed. These metals include Ti alloys, Ta, Cu alloys, steels, Al alloys, Ni alloys, tungsten, and rhenium, as well as intermetallics such as NiAl, $MoSi_2$, Mo_5Si_3, and TiAl-base alloys. Example microstructures of a Al-33wt.%Cu plate and Mo_5Si_3 rod are shown in Figure 2. The fine lamellar spacings in the Al-33wt%Cu alloy actually indicates high growth rates, and this feature will be addressed later. The Mo_5Si_3 alloy, in addition to showing the capability of processing a fully dense, high-temperature, brittle intermetallic, also illustrates a parameter to control in processing, namely the volatilization of constituents. In this case, the second phase has been defined by x-ray diffraction and compositional analysis (energy dispersive spectroscopy (EDS) in a scanning electron microscope SEM)) to be Mo_3Si. Some silicon vapor loss did occur. Nonetheless, material limitations have not been encountered with metals having melting temperatures varying between 600°C to 3000°C.

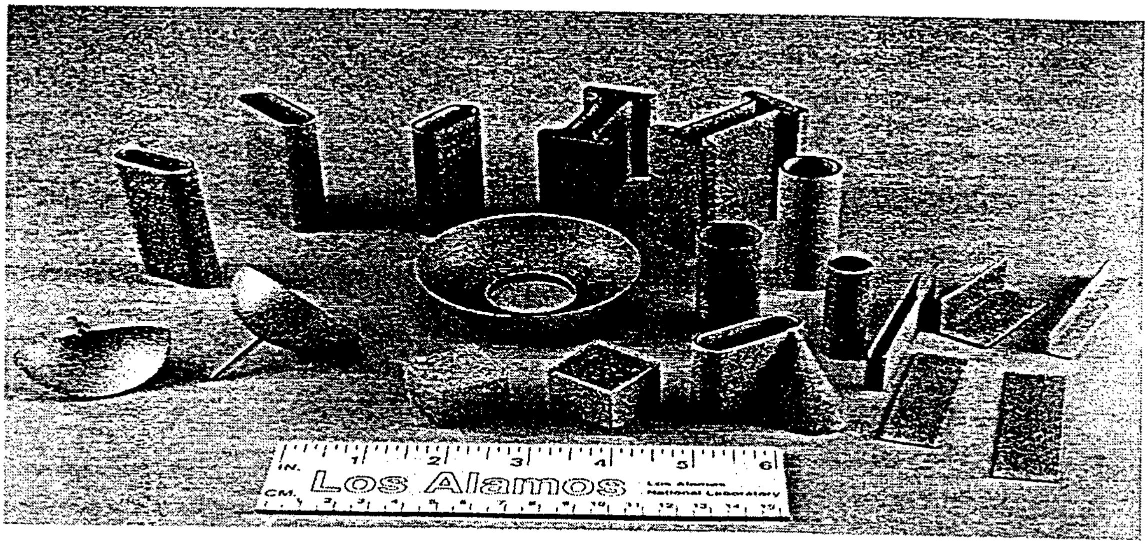

Figure 1 - Parts made by DLF to demonstrate the rapid fabrication of complex geometries.

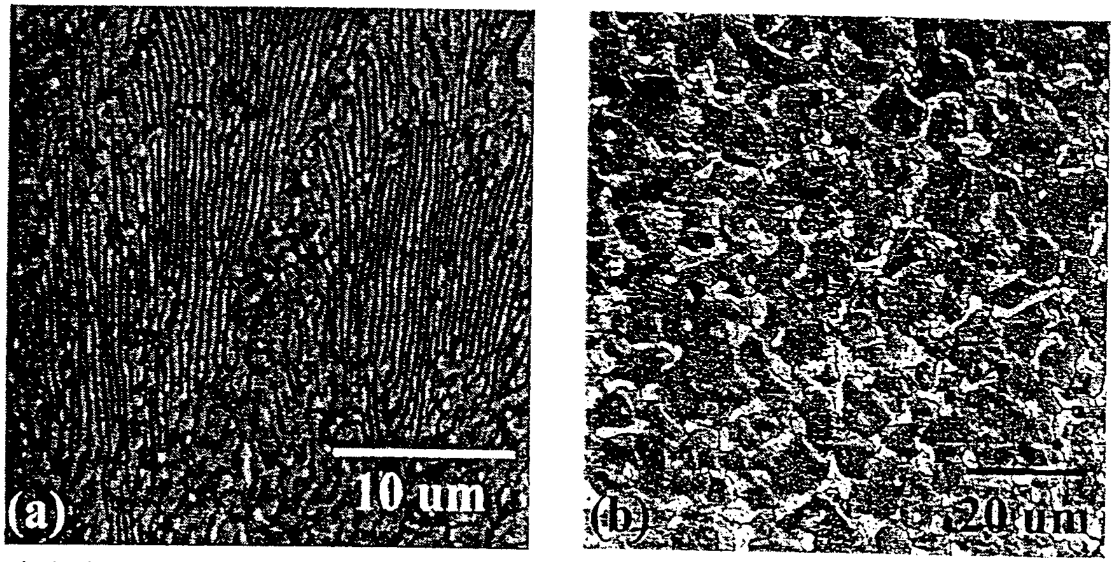

Figure 2 - Optical micrographs of a DLF processed (a) Al-33wt.%Cu plate and (b) Mo_5Si_3 rod

Solidification Behavior

Solid/Liquid Interface. A longitudinal cross-section of a Ag-19%Cu rod processed by DLF is shown in Figure 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. 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.

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. 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.

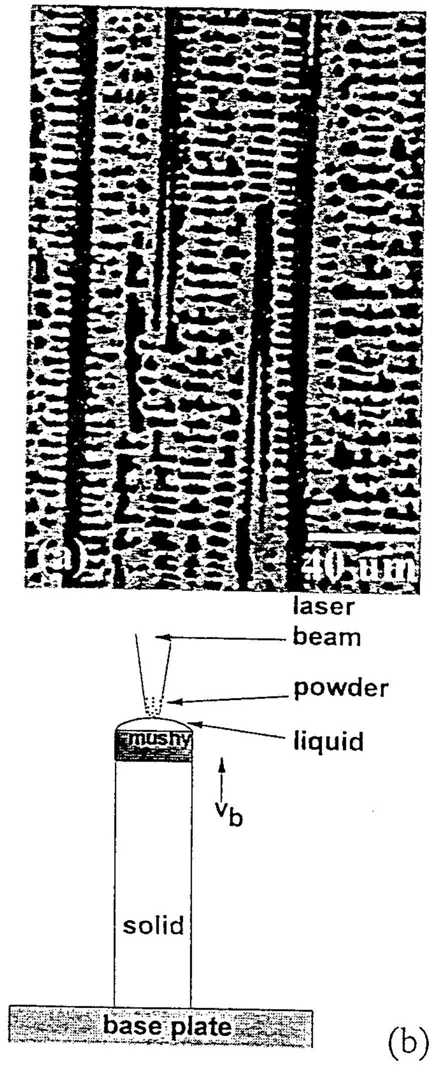

Figure 3 - (a) Cross-section micrograph of Ag-19wt.%Cu, and (b) a schematic diagram of the processing of a rod

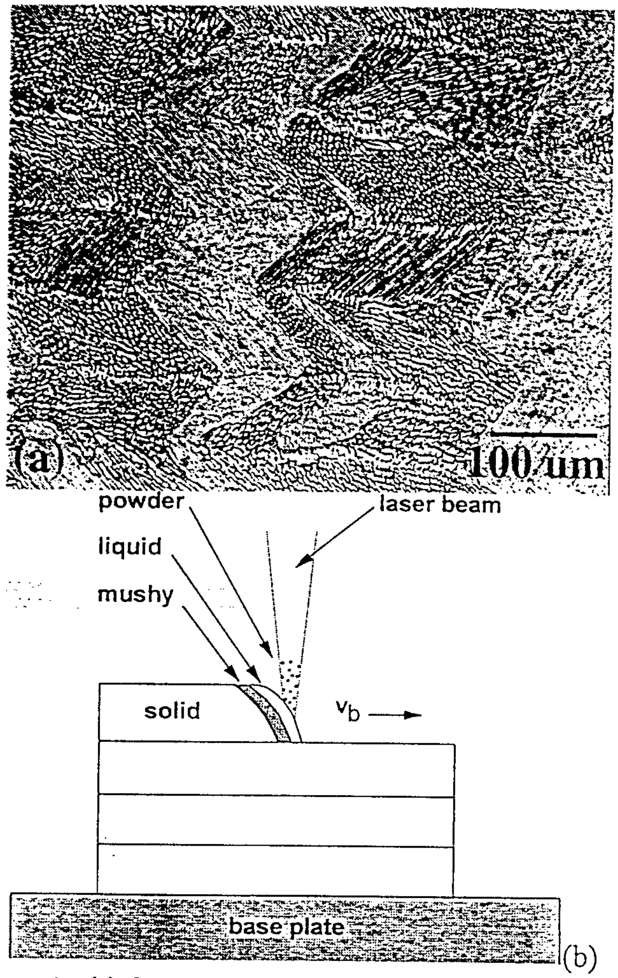

Figure 4 - (a) Cross-section of a 316 stainless steel wall, and (b) a schematic of the wall growth.

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 1×10^4 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 for plates using eutectic spacings as a basis for interpreting the solidification growth rates [3]. For example, in the Al-33wt.%Cu eutectic composition, experiments have established that the lamellar spacing, λ, is proportional to the growth velocity, V, by the equation

$$\lambda = CV^{-n} \tag{1}$$

where, $C = 1.04 \times 10^{-5}$ cm$^{3/2}$/s$^{1/2}$ and $n = 0.5$ [6]. The eutectic spacing in this alloy (Fig. 2a) is approximately 300 nm, which through the equation yields a growth velocity of ~1.2 mm/s. This growth velocity scales as a function of the laser motion speed [3].

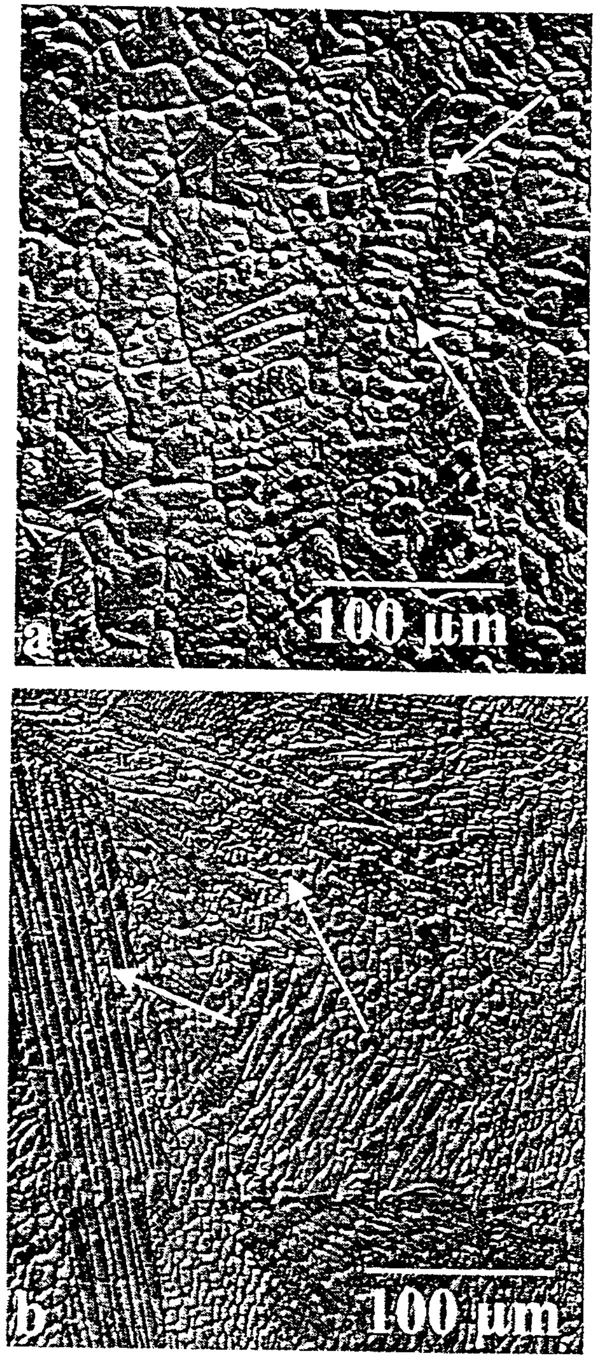

Figure 5 - Cross-section micrographs of an Fe-25wt.%Ni (a) rod, and (b) plate. Arrows indicate secondary dendrite arms

Segregation Profiles. The cooling rate, ε, 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. laser traverse speed 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. In fact, the length of the visibly radiating surface is much longer with high growth rates, which is qualitatively consistent with this argument. An approximate value of the gradient from typical cooling rates (100 K/s) and the laser traverse speed suggests temperature gradients being on the order of $G = 1x10^5$ K/m. This value is similar to computer simulation values [4].

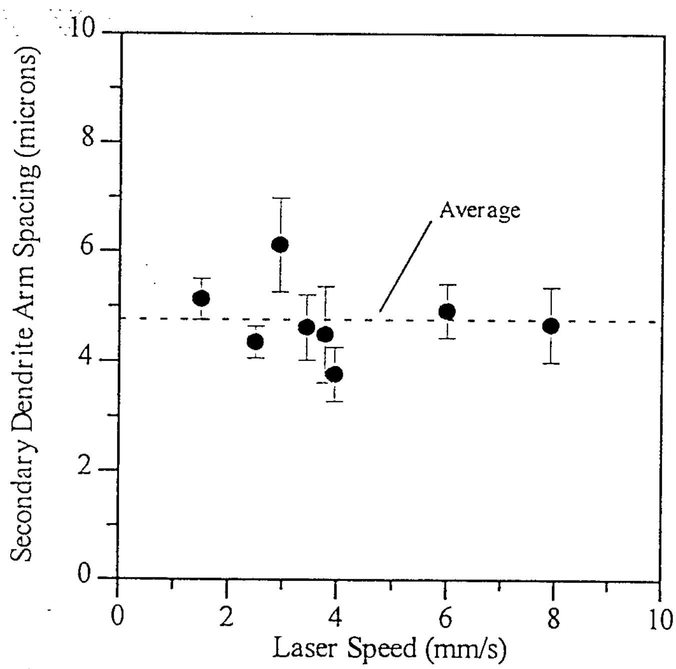

Figure 6 - Plot of dendrite arm spacing (Ag-19wt.%Cu) as a function of laser traverse speed.

Since the spacings are the same, independent of growth velocity, the segregation profiles should be similar. Segregation profiles across secondary dendrite arms were evaluated, and the data from V=1.5 mm/s and 3.78 mm/s are plotted in Figure 5. The EDS scans were taken from the middle of one dendrite, across a second, to the middle of a third dendrite. The total distance across two dendrites were then normalized to eliminate angle and spacing differences between dendrite arms. The segregation profiles do not appear to be distinguishably different. An equilibrium segregation pattern (with complete solid diffusion) as well as a Scheil segregation profile [7], were calculated and incorporated onto the plot. Although the overall composition of the alloys were determined to be Ag-19wt%Cu, the

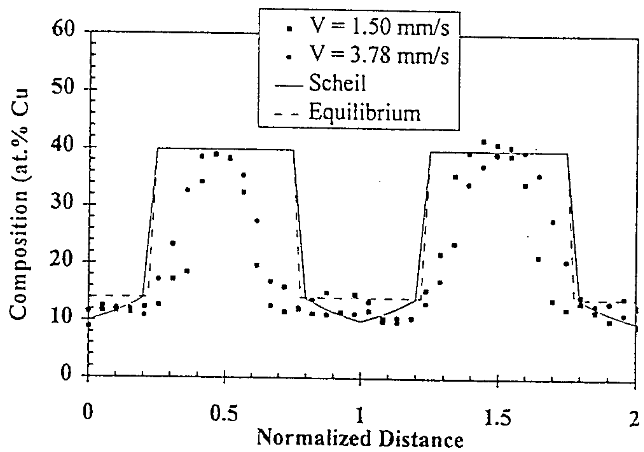

Figure 7 - Composition profiles (from EDS) across dendrites in Ag-18wt.%Cu (Ag-28.5at.%Cu) alloy. Also plotted as a function of normalized distance are calculated profiles.

segregation profiles across the dendrite arms actually fell between these two limits with an apparently shorter interdendritic eutectic distance. The compositions of eutectic regions appeared accurate. The sampling volume of the beam (1-2 μm in diameter) is actually much larger than the step size (~0.3 μm), and may account for an averaging of compositions. The averaging may account for a loss of resolution within the dendrites, yielding the flatter composition profiles, but would not account for the larger fraction of dendritic regions.

Rapid solidification theories have been developed to interpret experimental segregation profiles under high growth regimes (V=10 cm/s) in Ag-5wt%Cu [8]. The referenced study observed larger fraction solid regions with segregation profiles between that of a Scheil analysis and equilibrium distribution. The referenced result was evaluated in terms of the high solute build-up at the dendrite tip due to rapid solidification, resulting in the composition of the dendrite truck to be higher, and thus making microsegregation less pronounced. Despite the order of magnitude difference in growth velocities, the referenced results are consistent with the results of this study. Certainly, further efforts are required to accurately resolve the solute distribution in the DLF structures.

Discussion

Since the DLF process is contained in a controlled environment and requires no preform, mold or crucible to contain the molten metal during processing, flexibility is possible in the types of materials (conventional, reactive, hazardous, or advanced materials). In fact, the DLF technique is more appropriately labeled as an advanced processing methodology which permits the novel processing of materials.

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 discontinuously onto a solid substrate. 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.

Since continuous dendrite morphologies can be achieved through the continuous solid/liquid interface in DLF processing, the relatively high cooling and growth rates can be used to control and tailor microstructures, and therefore properties. Micro- and macrosegregation in cast components can lead to structural anomalies in terms of the physical properties of the materials. Studies have shown that reduced microsegregation in cast components permits optimized strengths of the multi-phase materials, particularly steels [9]. In addition, owing to the small molten pool, which is continuously fed with uniform composition of powder, macrosegregation is absent.

The refined microstructures in DLF processing are attributed to the controlled molten pool during processing and the high cooling and growth rates during solidification. The 2-dimensional plates exhibit higher cooling rates than the 1-dimensional rods. For the plates, the solidified material experiences a period of time for cooling before deposition occurs again. The cooler substrate provides a larger driving force for conduction cooling as compared to the rod, where the heat flux by conduction cooling is constant along the growth direction.

As a result of defining the solidification behavior in DLF processing, combined with the fully dense components, more diverse, novel, or advanced materials can be processed. For example, bulk intermetallic geometries can be produced for testing of properties without cumbersome fabrication or machining steps. In addition, controlled solidification science studies are possible. Growth and cooling rates for DLF are higher than in, for example, conventional directional solidification studies. Furthermore, bulk rapid solidification product (cooling rates > 10^4 K/s) can be produced without the necessity of additional consolidation techniques in order to evaluate the bulk properties. All of these efforts are currently in progress.

Summary

Directed Light Fabrication offers a viable technology for the free-form processing of near-net shape components. Solidification studies covering a variety of materials illustrate:

(1) a continuous solid/liquid interface is maintained during processing

(2) average cooling rates are on the order of 10^2 K/s for rods and 10^4 K/s for plates, and

(3) growth rates can vary from 1 to 50 mm/s.

As a result, the novel processing of almost any metal (high-temperature, reactive, or hazardous) can be fabricated while maintaining a fully dense product and uniformly refined microstructural and segregation features.

Acknowledgments

The authors wish to thank Ann M. Kelly for metallographic preparations. The support of the United States Department of Energy, contract No. W-7405-ENG-36 is gratefully acknowledged. One of the authors, DJT, would like to thank the support of the United States Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences.

References

1 Lewis, G.K., R.B. Nemec, J.O. Milewski, D.J. Thoma, M. Barbe, and D. Cremers, "Proc. ICALEO" (LIA, Orlando, FL) p. 17 (1994).

2 Lewis, G.K., D.J. Thoma, R.B. Nemec, an J.O. Milewski, "Advances in powder Metallurgy and Particulate Materials - 1996," MPIF, Princeton, NJ, p. 15-65 (1996).

3 Thoma, D. J., G. K. Lewis, and R. B. Nemec, "Beam Processing of Advanced Materials," (Materials Park, OH, ASM) p. 247 (1996).

4 Thoma, D. J., et al., "MRS Symp. Proc." 397 Boston, MA, MRS, p. 341 (1996).

5 Milewski, J.O., et al., "Rhenium and Rhenium Alloys," B. Bryskin ed., Warrendale, PA, TMS, (1997).

6 Burden, M.H. and H. Jones, J. of the Inst. of Metals, vol. 98, p. 249, (1970).

7 Flemings, M.C. "Solidification Processing," McGraw-Hill, New York, NY, p. 142 (1974).

8 Kurz, W. and D.J. Fisher, "Fundamentals of Solidification", 3rd ed., Trans Tech Publications, VT, p. 152 (1989).

9 Kattamis, T.Z. and R. Mehrabian, J. Vac. Sci. Technol. vol. 11 #6, p. 1118, (1974).

M98001532

Report Number (14) LA-UR--97-3884
CONF-9705215--

Publ. Date (11) 199705
Sponsor Code (18) DOE/ER, XF
UC Category (19) UC-404, DOE/ER

19980619 056

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