SOLID FREEFORM FABRICATION USING THE WIREFEED PROCESS

M. L. Griffith, M. T. Ensz, D. L. Greene, D. E. Reckaway, J. A. Romero,
T. B. Crenshaw, L. D. Harwell, T. E. Buchheit, and V. Tikare

Sandia National Laboratories
Albuquerque, NM 87185

Abstract

Direct metal deposition technologies produce complex, near net shape components from CAD solid models. Most of these techniques fabricate a component by melting powder in a laser weld pool, rastering this weld bead to form a layer, and additively constructing subsequent layers. This talk will describe a new direct metal deposition process, known as WireFeed, whereby a small diameter wire is used instead of powder as the feed material to fabricate components. Currently, parts are being fabricated from stainless steel. Microscopy studies show the WireFeed parts to be fully dense with fine microstructural features. Initial mechanical tests show stainless steel parts to have good strength values with retained ductility.

Introduction

Laser processing has the potential for revolutionizing the rapid prototyping field to impact rapid manufacturing of metallic components. Various groups are coupling high power lasers with metal powders to fabricate metallic components, layer additively (1-4). Typically, a laser beam is focused onto a substrate to create a molten pool into which powder particles are injected to build up each layer. The substrate is moved beneath the laser beam to deposit a thin cross section of the desired geometry. Subsequent layers are additively fabricated, thereby building a three dimensional (3-D) component.

While metallic powders work well for the described direct metal deposition technologies, they do have drawbacks. A key aspect is material or powder utilization. Typical systems require a high velocity spray of powder to insure consistent material build up; however, only a small amount of the powder is actually retained in the molten pool, approximately 20%. In the WireFeed process, powder is replaced with wire feedstock to fabricate components. With wire feedstock, 100% utilization is achieved during fabrication, since all wire injected into the molten pool is used to fabricate the part. Therefore no recycling system is required and faster build times can be accommodated. Furthermore, even flow of the powder material is crucial to the success of fabrication in laser/powder technologies, where control can be difficult to maintain. It is relatively simple to maintain constant wire feed rates. Another consideration is availability of material; many materials are readily available in wire form. Direct metal deposition with powder feedstock requires a good powder source, where size distribution and composition must be carefully controlled. This paper will describe the WireFeed process, the resultant material properties for as-processed 308L and 304L stainless steel, and modeling results of the microstructural evolution.

WireFeed Process

Figure 1 shows a schematic of the initial prototype WireFeed system. The system consists of a CW 600W Nd:YAG laser, a 4-axis computer controlled positioning system, and a wire feed unit (5). The positioning system and wire feed unit are mounted inside a box with localized gas purge capability. During fabrication, the workpiece and surrounding area are purged with argon to minimize oxidation of the workpiece. The laser beam is brought into the box through a window mounted on the top of the box and directed to the deposition region using a six inch focal length lens. The wire feed unit is designed to inject the wire into the molten pool from one side, and the lens and wire feed unit move as an integral subsystem.

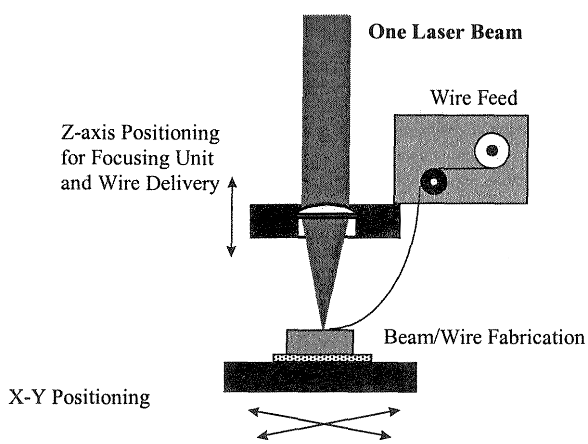


Figure 1: Schematic of the prototype WireFeed system showing laser perpendicular to substrate and wire feed from side.

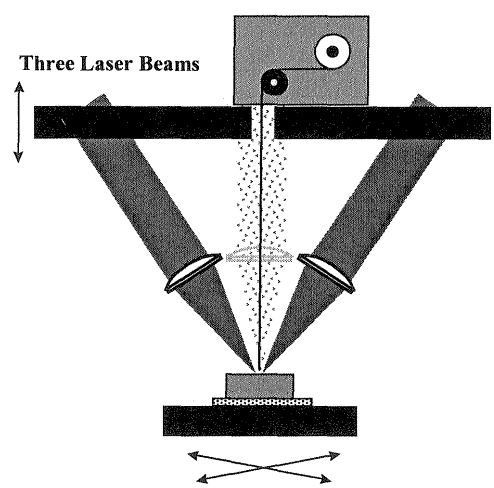


Figure 2: Schematic of improved system with three laser beams at 120° placement surrounding wire.

Geometries are written into a series of tool path patterns to build each layer. This file is combined with other commands to drive the laser, the positioning stages, and the wire feed unit to produce the desired component one layer at a time, starting from the bottom of the part. A solid substrate is used as a base for building the WireFeed object. The laser beam is focused onto the substrate to create a weld pool in which fine wire is injected, typically 250 micron diameter. The substrate is moved beneath the laser beam to deposit a thin cross section, thereby creating the desired geometry for each layer. After deposition of each layer, the wire feed mechanism and focusing assembly are incremented in the positive Z-direction, building a three dimensional component layer additively.

Shape Fabrication

Initially, test matrices were developed and implemented to identify the key factors controlling the WireFeed process. The key processing variables include: laser power, wire feed rate, wire feed direction and angle, and traverse velocity. From previous work with LENS (6), laser power, wire feed rate, and traverse velocity are the key factors to control deposition in direct metal fabrication. Along with those tests, extra experimental studies were required to understand the relationship between the wire and the weld pool for the system shown in Figure 1. This study included varying the wire feed direction, wire feed height (w.r.t. the substrate), and insertion angle. Diagnostic tools, such as high magnification video camera techniques, were used to monitor and understand the wire/molten pool interaction.

From these studies, it was determined that the wire must intersect the molten pool in such a manner to maintain stability along the solidification front. If the wire is inserted too high (w.r.t. the substrate or previous layer), it does not remain connected with the pool; if the wire is inserted too low, the wire either stubs on the substrate/layer or is pushed around by the force of the weld pool. After choosing the intersection point, the insertion angle and direction must be determined. An insertion angle of 45 degrees maintains the best stability, and uniform deposition is only maintained with wire insertion perpendicular to the deposition direction. The consistency of build is not maintained if the wire is inserted either from the trailing or leading edge of the weld pool, because the molten pool has difficulty forming and maintaining the bead as the source material or energy moves away.

Since the process was highly dependent on the position of the wire in relation to the deposition direction, a new system was configured to remove this geometric processing constraint. As shown in Figure 2, the wire is fed down the center and the laser beam is split into three beams (by use of fiber optics) to surround the wire. The laser heads are stationed 120 degrees apart from each other. Now, the wire always enters the pool at the 'hot spot' and there are no constraints on direction of travel. This new design was imperative for complex part fabrication.

From the process variable experiments, the laser wire deposition parameters were optimized to demonstrate feasibility of part fabrication. Test matrices were added to understand how layer thickness and hatch (fill) spacing affected part fabrication. Process studies to control the wire feed during layer increments for simple block shapes were a major activity. After a layer is fabricated in a serpentine draw pattern, the laser shutter closes, and the focusing and wire feed subsystems must increment in the positive Z direction to fabricate the next layer. Before the Z increment, the wire must reliably detach from the part. This knowledge is required for complex part fabrication with increasing area complexity.

Various shapes with increasing complexity are shown in Figure 3. We have fabricated four types of geometries: 1) uni-directional fabrication using a rotary stage to build hollow cylinders (Figure 3a), 2) bi-directional patterns to fabricate walls, and 3) with an understanding of wire detachment, hatch spacing and layer thickness, it was possible to fabricate dense, rectangular shapes from 308L stainless steel (Figure 3b). Finally, we have initiated complex part fabrication with the challenge of building two cubes, where each layer is deposited side by side (Figure 3c). This was only possible with the new WireFeed system design shown in Figure 2. All shapes possess 100% utilization of the wire, where the material inserted into the molten pool is directly used to produce a part. WireFeed parts are quickly fabricated, between 0.5 to 1 hour per cubic inch.

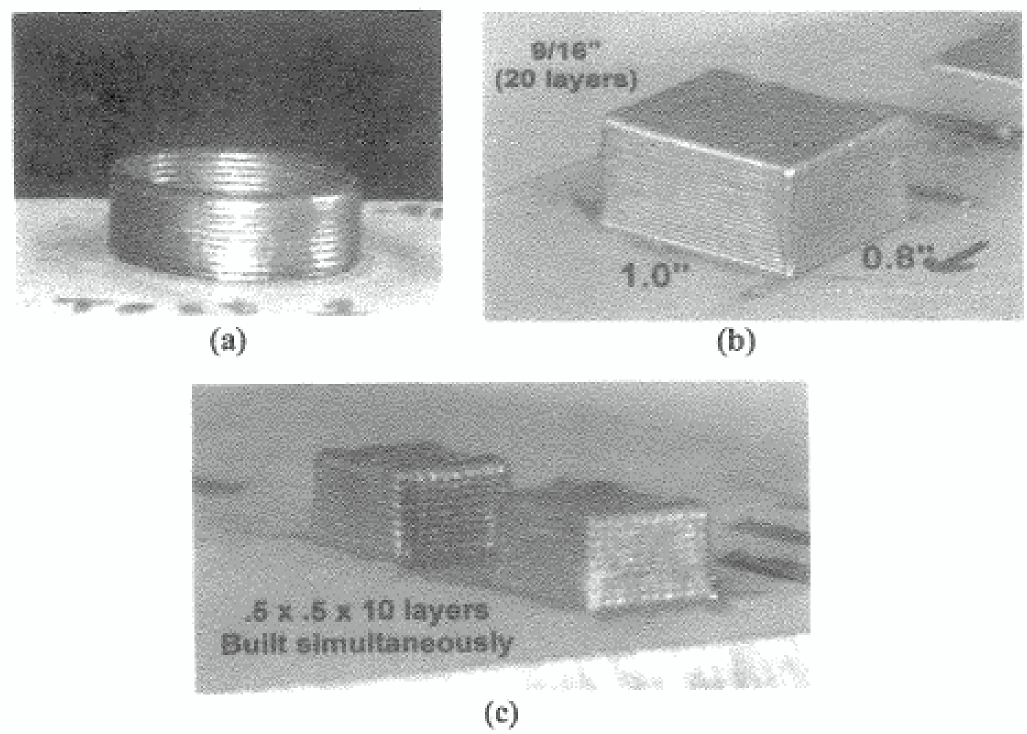


Figure 3: (a) cross-sectional micrograph of uni-directional fabrication, (b) block fabrication with wire detachment between layers, and (c) complex part fabrication with start and stop capability in each layer.

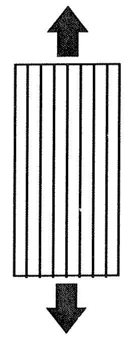
Materials Characterization

Mechanical Behavior

Coupons were machined from the as-processed 308L stainless steel for room temperature tensile testing, where the pull direction is parallel to the build plane in the WireFeed system (longitudinal). All samples had densities greater than 98%. The results for WireFeed-processed material is compared to typical annealed material in Table I. With grain size refinement, the WireFeed material possesses strengths greater than annealed, where the yield strength is 58 ksi as compared to 35 ksi for the annealed material. However, the ductility remains consistent with elongation values of 65-75%, which are slightly higher than the annealed values (55-65%). High strengths and hardness with retained ductility is a good combination for WireFeed-processed material.

Table I. Room temperature mechanical properties for as-processed 308L stainless steel compared to typical annealed material.

Property	WireFeed	Annealed material
Hardness	87 HRB	80 HRB
Microstructure feature size	4 Micron	40 Micron
Tensile strength (Yield)	58.2 ksi	35 ksi
Tensile strength (Ultimate)	94.2 ksi	85 ksi
Ductility (Elongation)	64.9%	55%
Ductility (Reduction in area)	74.6%	65%



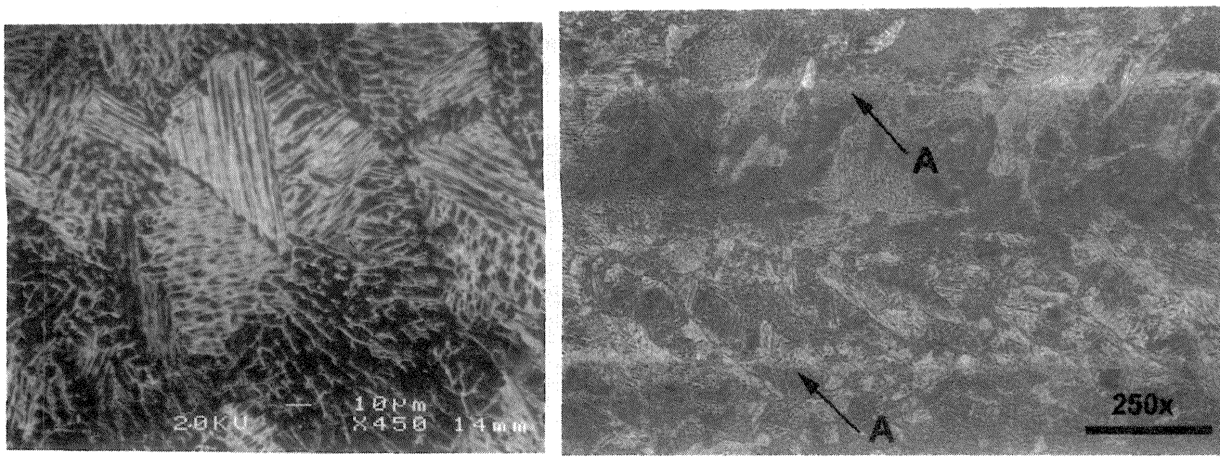
The effect of deposition style was studied for 304L stainless steel material. Two types of patterns were fabricated: 1) longitudinal and 2) cross hatch where every other layer is deposited 90 degrees to the previous layer. The results are shown in Table II. Both deposition patterns show similar strength properties, with yield values much greater in comparison to annealed material. However, there is a trade-off with a decrease in ductility, especially for the cross hatch pattern style. Any flaws in adhesion between layers would be more evident in the cross hatch deposition material because the weak layers are perpendicular to the tensile pull direction. Overall, the material properties for these stainless steel alloys show benefit in strength values compared to traditional annealed material and in some cases the ductility is maintained.

Table II. The effect of deposition pattern on room temperature mechanical properties for as-processed 304L stainless steel.

Property	Longitudinal Pattern	Cross Hatch Pattern	Annealed 304L
Tensile strength (Yield)	75.9 ksi	76.1 ksi	42.8
Tensile strength (Ultimate)	104.2 ksi	102.0 ksi	95.9
Ductility (Elongation)	48.3%	34.6%	56.0
Ductility (Reduction in area)	40.0%	32.8%	---

<u>Microstructures</u>

Metallographic analysis reveals dense, fine grain microstructures for 308L stainless steel produced by the WireFeed process as shown in Figure 4. Figure 4(a) is a cross-sectional view of a line drawn by the WireFeed process. Typical microstructural features are on the order of 4 microns, due to the high solidification rate in the WireFeed process. Figure 4(b) is a top view showing one full line and two partial lines (interfaces between lines marked at A). The fine microstructural features show directional solidification behavior resulting in textured features.



(a) **(b)**

Figure 4: Typical microstructures for 308L stainless steel, where (a) is a view inside a fabrication line (450x) and (b) is a view of three lines fabricated in a layer.

Simulation of Coarsening in WireFeed Microstructures

Components manufactured by the WireFeed process have unique microstructures. The prediction and control of these microstructures is important to tailoring the components to their respective application. We have extended the previously developed 2-D simulation (7) of coarsening during WireFeed to 3-D. A kinetic, Monte Carlo model was used to simulate coarsening in the presence of a non-linear, dynamic temperature profile. This model utilizes a cubic lattice populated by a canonical ensemble of domains. The equation of state is the sum of bond energies between unlike neighboring domains and simulates grain growth in response to capillary forces of the grain boundaries. The simulation was adapted to 3-D by extending the neighbor interaction energies from X- and Y-directions to X-, Y- and Z-directions. The mobility of the grain boundaries scales with temperature in the simulations. The temperature profile used in the simulations is the Rosenthal solution to a moving point source of heat given by:

$$T_m - T = \left(\frac{\alpha Q}{2\pi k r_p}\right)\exp\left(\frac{-C}{2k}(x_p + r_p)\right)$$

where T_m = melting temperature, T is temperature at r_p, the distance from the center of the laser spot and x_p, the distance from the laser spot along the direction of travel and are:

$$r_p = \sqrt{(x_p - vt)^2 + y^2 + z^2} \qquad \text{and} \qquad x_p = x - vt$$

and x is the laser travel direction, z is depth, vt is the current laser position along the x-direction, α is the heat transfer efficiency, Q is heat input, k is conductivity and C is heat capacity. The temperature profile at the surface is shown in Figure 5.

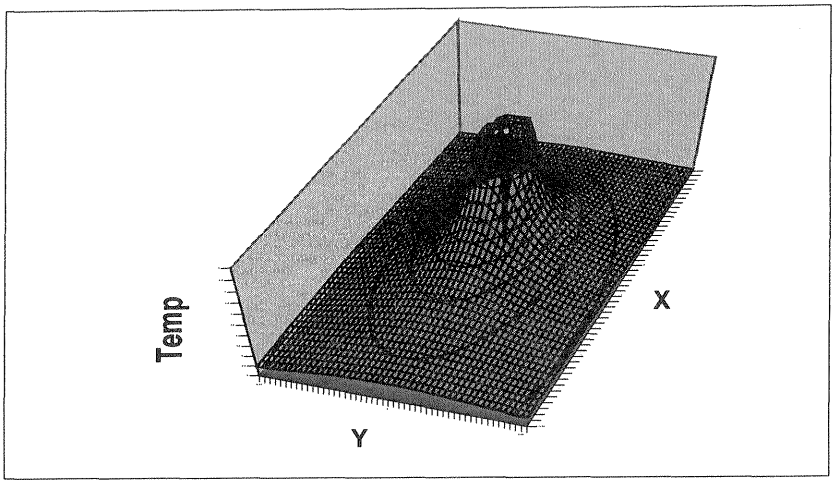
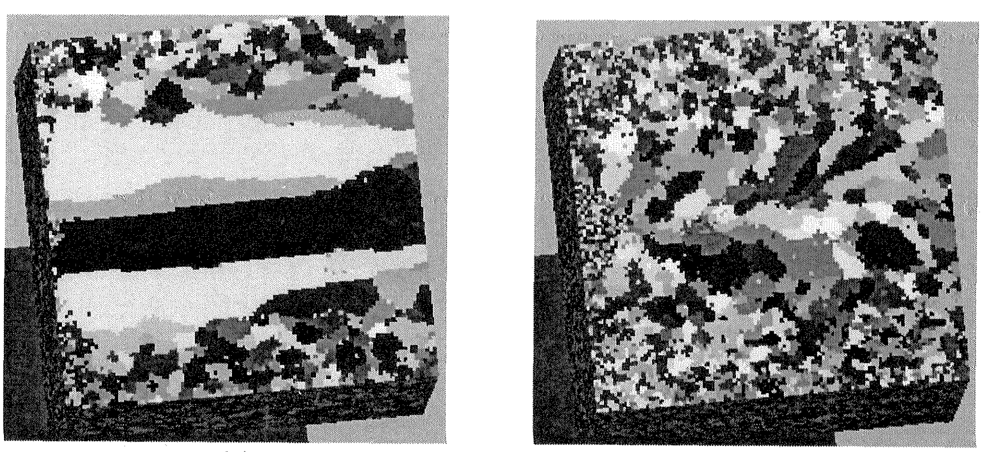


Figure 5. Rosenthal temperature profile at the surface, with heat source moving along the X-direction.

The results of the 3-D simulations are shown in Figures 6a and 6b, with simulated microstructures of grains after a laser has passed across at velocity ν = .01 and ν = .02 sites/MCS, respectively. The laser travel direction is from right to left, and features of the same shades are grains. The microstructures show that the grains grew faster in the center region, which is the hottest area and much slower at the outside cooler region as was expected since grain boundaries have higher mobility at higher temperatures. The elongation of the grains was dependent on the velocity of the laser. At slower laser velocity, grains are highly elongated as the grain boundary mobility is able to keep pace with the laser. At high laser velocity, the grains were smaller and less elongated because the laser velocity was faster than the grain boundary mobility. Furthermore, the direction of grain elongation was perpendicular to the Rosenthal isotherm as seen in Figure 6b. The microstructures in Figure 6b are similar to those of actual WireFeed microstructures as seen in Figure 4b.



(a) (b)

Figure 6: Simulated microstructures of grains at two laser velocities: (a) 0.01 sites/MCS and (b) 0.02 sites/MCS (where MCS = Monte Carlo Step). Laser travel direction is from right to left.

Conclusions

With the WireFeed process, high fabrication rates (one hour per cubic inch) can be achieved with 100% utilization of feed material. As-processed stainless steel parts have strengths greater than traditional annealed material, but with retained ductility if there are no flaws (porosity) during fabrication. Preliminary modeling of the WireFeed process shows the correlation between the laser beam profile and raster speed with the resulting microstructure. The WireFeed system is simple in design, requiring only a localized gas purge to removed unwanted oxidation during fabrication. This allows for easy part removal and change of wire material. Future work will develop complex geometry fabrication, where the theoretical model will be able to predict the resulting microstructure for a given material and process conditions.

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