ELECTRON BEAM FREEFORM FABRICATION: A RAPID METAL DEPOSITION PROCESS

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Abstract

Manufacturing of structural metal parts directly from computer aided design (CAD) data has been investigated by numerous researchers over the past decade. Researchers at NASA Langley Research Center are developing a new solid freeform fabrication process, electron beam freeform fabrication (EBF[3]), as a rapid metal deposition process that works efficiently with a variety of weldable alloys. The EBF[3] process introduces metal wire feedstock into a molten pool that is created and sustained using a focused electron beam in a vacuum environment. Thus far, this technique has been demonstrated on aluminum and titanium alloys of interest for aerospace structural applications; nickel and ferrous based alloys are also planned. Deposits resulting from 2219 aluminum demonstrations have exhibited a range of grain morphologies depending upon the deposition parameters. These materials have exhibited excellent tensile properties comparable to typical handbook data for wrought plate product after post-processing heat treatments. The EBF[3] process is capable of bulk metal deposition at deposition rates in excess of 2500 cm^3/hr (150 in^3/hr) or finer detail at lower deposition rates, depending upon the desired application. This process offers the potential for rapidly adding structural details to simpler cast or forged structures rather than the conventional approach of machining large volumes of chips to produce a monolithic metallic structure. Selective addition of metal onto simpler blanks of material can have a significant effect on lead time reduction and lower material and machining costs.

Background

Advantages of Solid Freeform Fabrication

Solid freeform fabrication (SFF) encompasses a class of processes that can be used to design and construct parts using a layer-additive approach. SFF processes are an outgrowth of rapid prototyping processes such as stereolithography for plastics and welding repair techniques employing laser, electron beam, or arc welding for repairing metal seal knife edges, turbine blade tips, or tooling dies. Current development efforts are expanding these repair techniques and applying principles from computer-aided design (CAD) and manufacturing as well as from rapid prototyping for wider applications. These development efforts are resulting in the production of a new class of SFF layer-additive processes to build structural metallic parts directly from CAD data rather than the traditional material removal approach.

SFF offers numerous advantages. At the core of these are reduced production and material costs, reduced development and lead times, and improved performance. However, not all of the current SFF processes are equally suited to provide all of these advantages. Factors such as efficiency, deposition rates, material compatibility, and process quality must be considered to assess the feasibility of inserting such processes successfully into a production environment.

Direct cost savings can be realized through repair and salvage of parts, reduced machining time, and reduced waste. SFF can be used to repair broken or out-of-tolerance parts at a fraction of the cost of remanufacturing. This can be particularly significant when there is a large investment, either in capital expenditures, high value materials, or large amounts of time already invested in a part. SFF processes can be used to build an entire structure, or to add detailed features to a simplified casting or forging. However, the replacement technology must be cost-competitive. Thus, issues such as high deposition rates, process efficiencies, process quality, and material compatibility are paramount to insertion of a new technology into a competitive metals forming market. Implementing these processes can thereby reduce the material wasted during machining operations, reduce lead time and raw material costs by reducing billet sizes, and enable production of a generic, simplified part by conventional methods with addition of specific details at a later time. Besides the raw material cost savings, there is an ease in handling smaller billets of raw feedstock and the by-products or scrap produced from a less-extensively machined part.

In addition to lead time reduction, SFF can also enable reduction in design cycle time. SFF permits direct production of prototype parts from a CAD file. Production of prototypes enables rapid product development, testing and insertion of improved designs into the existing production environment. This also allows flexibility in design for either unique part production or simplified part design in which detailed locations for items such as flanges, bosses, nozzles, or other features can be changed and modified late in the design cycle. Thus, SFF can

provide better opportunity for optimization of designs by allowing more time for determining details.

SFF also offers the potential for improved performance through control of microstructures and compositions at a much finer scale than parts machined from thick products. Typical thick sections have high degrees of microstructural inhomogeneity, leading to anisotropic mechanical properties. This is a direct result of differences in cooling rates and an inability to impart work evenly through a thick section. Working with smaller billets in conjunction with layer-additive processes can result in more optimal microstructural features, potentially improving the mechanical properties of the resultant part as compared to a similar part machined from a thick section billet. Finally, compositional gradients offer improved performance and reduced cost by allowing grading from an inexpensive material for the bulk of the product to an expensive material at the surface for enhanced wear resistance, corrosion resistance, etc.

Solid Freeform Fabrication Processes

Rapid prototyping is an emerging field which encompasses numerous different techniques and resulting product forms. Of specific interest are processes that are capable of producing fully dense metallic and hybrid parts in which the resulting parts may be used for loaded structure. Binderless processes are attractive because they eliminate contaminants and minimize secondary processing. Layer additive techniques offer the potential for graded microstructures and compositions, and production of near-net shapes with minimal secondary processing required.

Over the past several years, a number of SFF processes have been developed to directly produce structural metallic parts. Several processes such as Selective Laser Sintering (SLS) and Electron Beam Melting (EBM) operate in a powder bed, tracing the part in a layer of powder with a high energy beam and repeating for subsequent layers. [1, 2] These processes may require secondary processing to produce fully-dense components. Other emerging SFF processes that focus on low heat inputs include Precision Metal Deposition (PMD), laser deposition with flat wire [3], and ultrasonic consolidation (UC) of layered metal foils to form 3-D parts using ultrasonic welding, a solid state process. [4] Direct laser deposition processes, including Direct Metal Deposition (DMD), Laser Additive Manufacturing (LAM) and Laser Engineered Net Shaping (LENS™), feed powder directly into a molten pool created by a laser. [1, 5] Electron beam freeform fabrication (EBF³) is another recently developed process, similar to direct laser deposition but employing a focused electron beam and wire feedstock. [6, 7, 8] Many of these processes are complementary and selection of the appropriate process is dependent upon the desired applications.

Direct laser deposition, one of the most mature of the SFF processes, was introduced around 1991 and has been the focus of extensive research activity at many institutions. A laser beam, typically either CO_2 or Nd:YAG, is used to create a small molten pool on a metallic substrate in an inert atmosphere. Metallic powder is fed into the molten pool to build up a part, resulting in fully dense, structural parts directly produced from CAD models without molds, tooling, or machining (except for some finish machining to get final tolerances and surface finishes). Feedstock material is usually pre-alloyed powder, although elemental powder blends are also used. This process results in near net shaped parts with fine grained microstructures due to rapid solidification kinetics and a small melt pool. [1, 5]

Most commercial laser based systems have limited size build envelopes and operate at low deposition rates, limiting application on large parts. Typically, these processes use a tightly (approximately 0.05 cm (0.02 inch) diameter) focused beam which enables fine details to be fabricated. However, there is a tradeoff between feature size and deposition rate, with fine feature size resulting in low deposition rates (8 to 33 cm^3/hr (0.5 to 2 in^3/hr) and low powder capture efficiencies, typically less than 50%. Energy efficiency of laser processes tends to be low; less than 10% of the input energy is converted to beam energy, and much of the beam energy may be reflected from the part (up to 98% in the case of highly reflective materials such as aluminum and copper). Diode laser based systems have improved energy efficiencies approaching 40% but still exhibit the same reflectance losses as other lasers. [1]

Electron Beam Deposition

Electron beam freeform fabrication (EBF³) is an emerging cross-cutting technology for producing structural metal parts. The process can be used to build a complex, unitized part in a layer-additive fashion, although the more immediate payoff is for use as a manufacturing process for adding details to components fabricated from simplified castings and forgings or plate products. Figure 1 shows a schematic of the primary elements of an EBF³ system. EBF³ employs a high power electron beam in a vacuum environment ($1x10^{-4}$ torr or lower). Wire feedstock is used

Wire feed   Electron beam gun
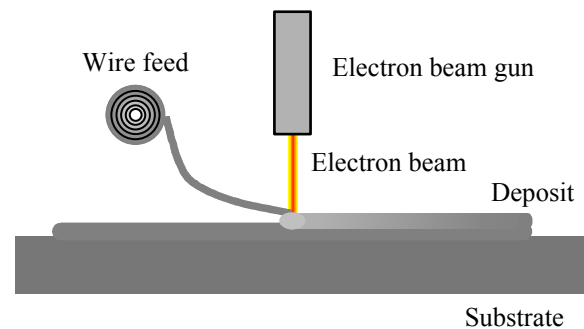Electron beam
Deposit
Substrate

Figure 1. Schematic of the EBF³ process.

due to difficulties feeding powder in a vacuum, since the carrier gas used to assist powder delivery will be ionized in the electron beam. Operation in a vacuum ensures a clean process environment and eliminates the need for a consumable shield gas, as is typically used in laser deposition systems. The EBF[3] process is nearly 100% efficient in feedstock consumption and approaches 95% efficiency in power usage. The electron beam couples well with any electrically conductive material, including highly reflective alloys, such as aluminum and copper. A variety of weldable alloys can be processed using EBF[3]; further development is required to determine if non-weldable alloys can also be deposited. Demonstrated deposition rates for EBF[3] are 330 to 2500 cm[3]/hr (20 to 150 in[3]/hr), with lower resolution in the ability to build fine details. Experiments are planned with fine diameter wires to attempt to construct fine details and large diameter wires to increase deposition rate. EBF[3] offers viable solutions to issues of deposition rate, process efficiency, and material compatibility for insertion into the production environment.

Recent work with the EBF[3] system at NASA Langley Research Center has focused on understanding the process and characterizing the resulting microstructures and mechanical properties to optimize the process for 2219 Al and Ti-6-4. Aluminum alloy 2219, which has a nominal composition of Al-6 wt % Cu, is a common aerospace alloy with excellent weldability and good strength and toughness. Ti-6Al-4V is also commonly used in aerospace structures for high temperature applications and where its excellent strength and corrosion resistance are required. Extensive work has been done with Ti-6-4 in the laser deposition arena, providing a baseline for comparison with the EBF[3] process.

A fundamental examination of the effect of processing parameters (translation speed and wire feed rate) for 2219 Al was conducted to establish some basic processing-microstructure-mechanical property relationships. In this work, one of these two variables was continuously changed, while the beam power and the other variable were held constant. The resulting deposit dimensions, microstructures, and tensile properties were documented. Over the range of parameters tested, microstructures varied from a fine-grain equiaxed grain structure to a solidification microstructure with larger grain sizes and dendritic grown, as shown in Figure 2. This shows the range of microstructures obtained over a wide processing envelope. The light bands are dendrites formed in the interpass region where portions of a previously deposited layer remelted during deposition of the following layer.

Increasing translation speed resulted in a decrease in both width and height of the deposited layer. Higher translation speed produced more rapid cooling and resulted in a homogeneous microstructure with smaller equiaxed grains (see Figure 2). Increasing the wire feed rate resulted in a narrowing of the deposit width and an increase in the deposit height. At higher wire feed rates, the cooling rate increased providing a smaller equiaxed grain structure with good homogeneity and no evidence of dendrite growth in the interpass region as compared to the microstructure developed at the lower wire feed rate. [7]

Figure 3 shows the ultimate tensile strength, 0.2% offset yield strength, and total elongation to failure for EBF[3] 2219 Al deposits as compared to typical handbook data for sheet and plate products. [9] The data for the as-deposited 2219 Al were averaged over duplicate tests for seven combinations of beam power, translation speed, and wire feed rate. Despite the wide range of processing conditions,
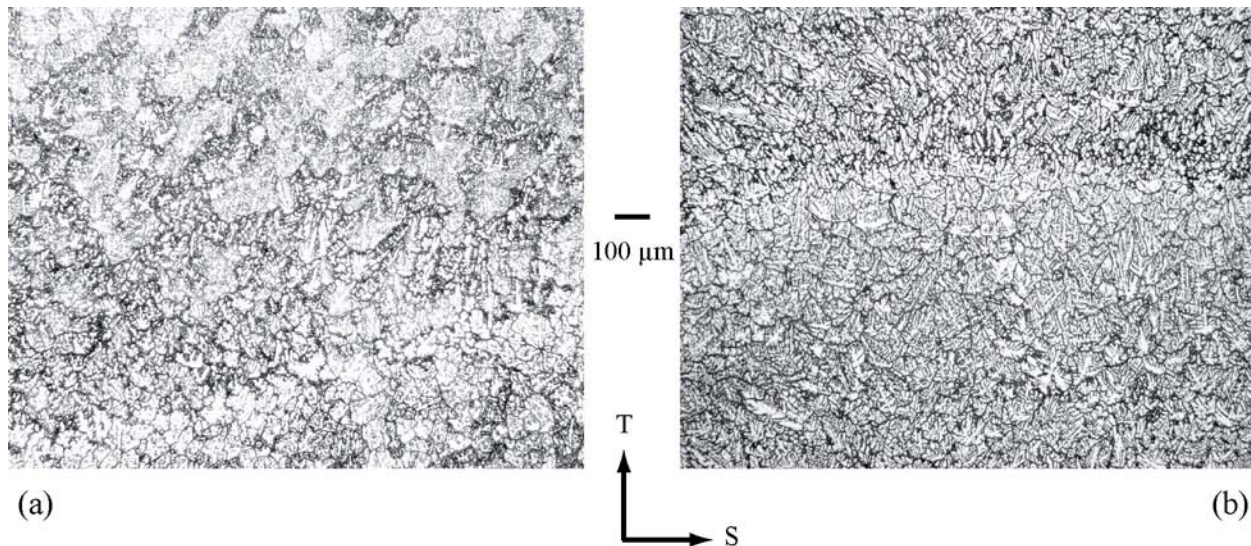

100 μm

T

S

(a)

(b)

Figure 2. Microstructures of EBF[3] 2219 Al deposits showing range of microstructures achievable: (a) low translation speed results in inhomogeneous microstructure and larger grains, and (b) higher translation speed produces more homogeneous microstructure with smaller equiaxed grains. [7]
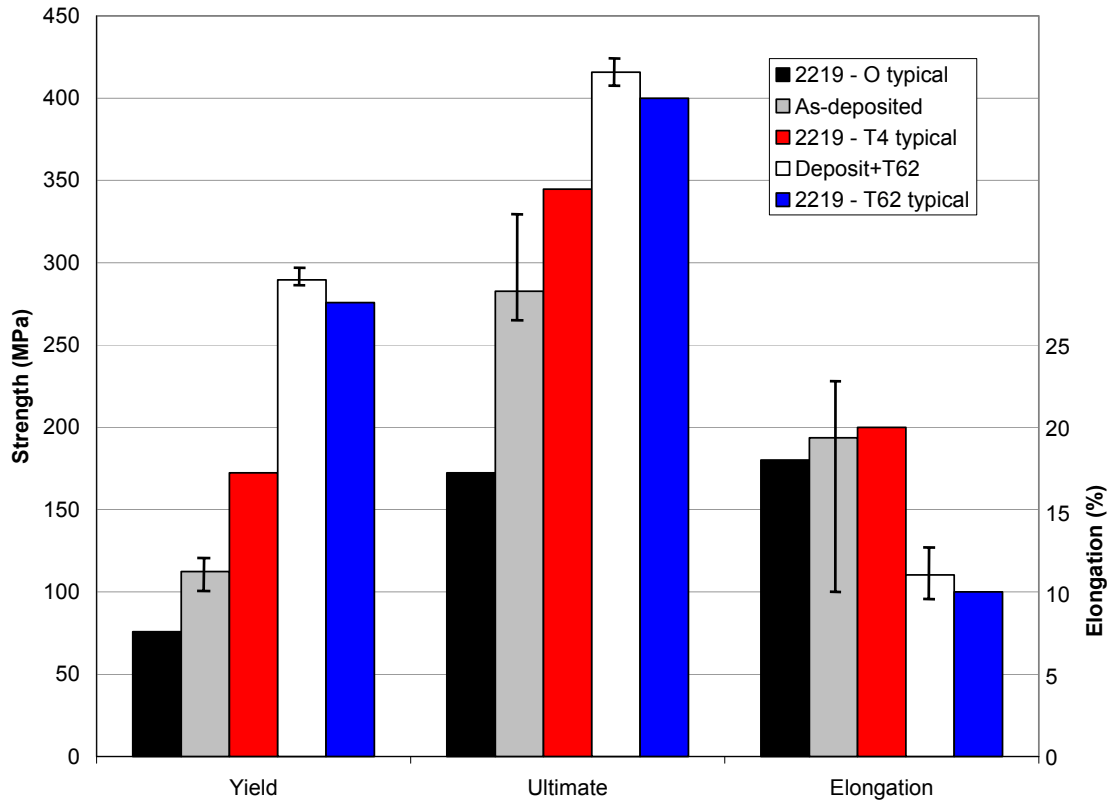
Figure 3. Tensile properties at room temperature of EBF[3] deposited 2219 Al as compared to typical handbook values for 2219 Al sheet and plate. [9]

the majority of the as-deposited 2219 Al data fell in a tight band, as shown by the range bars in Figure 3. The properties of as-deposited 2219 Al were intermediate to those for annealed (O temper) and solutionized and naturally aged (T4 temper) 2219 Al sheet and plate. The 2219 Al deposits that were heat treated to the T62 temper also had a very tight data range and were equivalent to typical handbook properties for 2219-T62 sheet and plate product. [7, 9]

Similar work is now underway with Ti-6-4. The Ti-6-4 microstructure comprises extremely large columnar grains growing epitaxially from the substrate, as shown in Figure 4a. At higher magnification, as shown in Figure 4b, alpha-beta laths typical of the microstructures of alpha+beta titanium alloys can be seen. Brice and coworkers [8] have also researched Ti-6-4 EBF[3] deposition with similar results; the room temperature tensile properties of Ti-6-4 deposits were comparable to
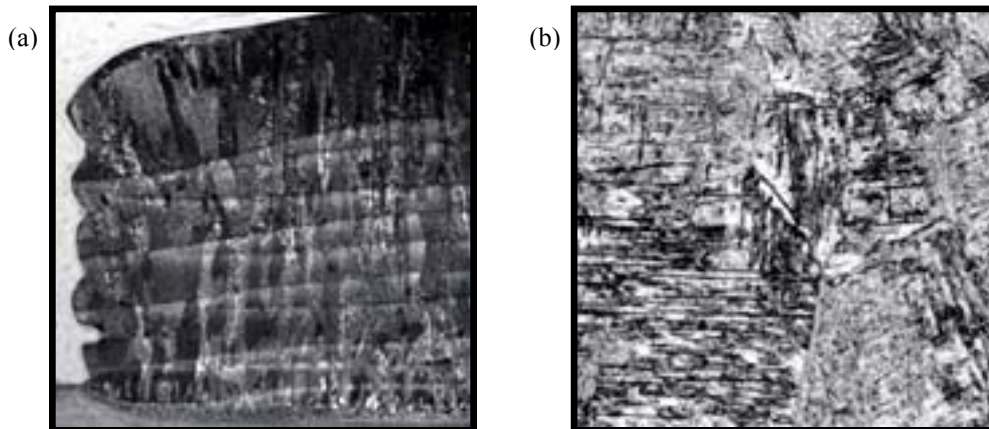

Figure 4. Microstructures of EBF[3] Ti-6-4 deposits showing range of microstructures achievable: (a) low magnification shows columnar grain structure, and (b) high magnification shows alpha-beta laths.

or better than properties for wrought products. They also reported that a Ti-6-4 F-22 AMAD bracket produced by EBF[3] successfully completed a two lifetime broad spectrum fatigue test with adequate residual tensile strength. [8]

In addition to processing-microstructure-property correlation, process programmability and control are currently being explored. Several 2219 Al parts demonstrating different deposition schemes are shown in Figure 5. Low and high deposition rates have been achieved, ranging from rates of 160 cm³/hr to 1300 cm³/hr (10 in³/hr to 80 in³/hr), with a change in deposit width from 0.25 cm to 1.25 cm (0.1 to 0.5 inches) for the low and high deposition rates, respectively. The cylinder in Figure 5a shows an EBF[3] part built using a high deposition rate. The square box in Figure 5b demonstrates the ability to change the motion vector of the part without a corresponding change to the wire feed orientation so that the entry point of the wire varies from the leading edge to the side or trailing edge of the molten pool. This had very little impact on the deposit except for a slight pushing of the puddle by the entering wire. This flexibility is significant because it enables simplified programming and construction of detailed parts. The airfoil-shaped pylon in Figure 5c demonstrates an ability to program and build a part with more complex curvature than the other round or square shapes built. The vase-shaped part shown in Figure 5d demonstrates the ability to build an unsupported overhang (50 degrees on the part shown) in either an expanding or contracting wall. Finally, a mixer in Figure 5e has been built to show transition from a circular part to a fluted edge.

All parts built to date have been near-net shape, requiring a final finishing step to obtain final surface finish and contour. Four identical pylons were finished using a variety of techniques and compared to an as-built pylon to demonstrate the ability to perform finishing operations. The 2219 Al EBF[3] parts were successfully finished using conventional milling, wire electric discharge machining (EDM), glass bead blasting, and electron beam glazing. The as-built EBF[3] part had good localized surface finish (smoothness) but larger long range surface irregularity (waviness) and mild tensile residual stresses. Machinability of the EBF[3] parts was comparable to standard wrought product for both the milling and wire EDM processes. Milling resulted in the best surface finish over long and short ranges and induced compressive residual stresses. Wire EDM induced high compressive residual stresses in the EBF[3] 2219 Al, but the surface finish required additional work to achieve adequate smoothness. Bead blasting was not aggressive enough to eliminate EBF[3] surface features, but succeeded in inducing compressive residual stresses. Electron beam glazing (using a defocused electron beam with the same EBF[3] equipment) produced a flat surface with fine-grained equiaxed microstructure at the surface, but did not significantly change the residual stress state of the as-built part. These experiments demonstrated that EBF[3] parts can be finished using conventional machining operations. In addition, electron beam glazing is promising for production of net shaped parts using EBF[3] and secondary processing in the same equipment.
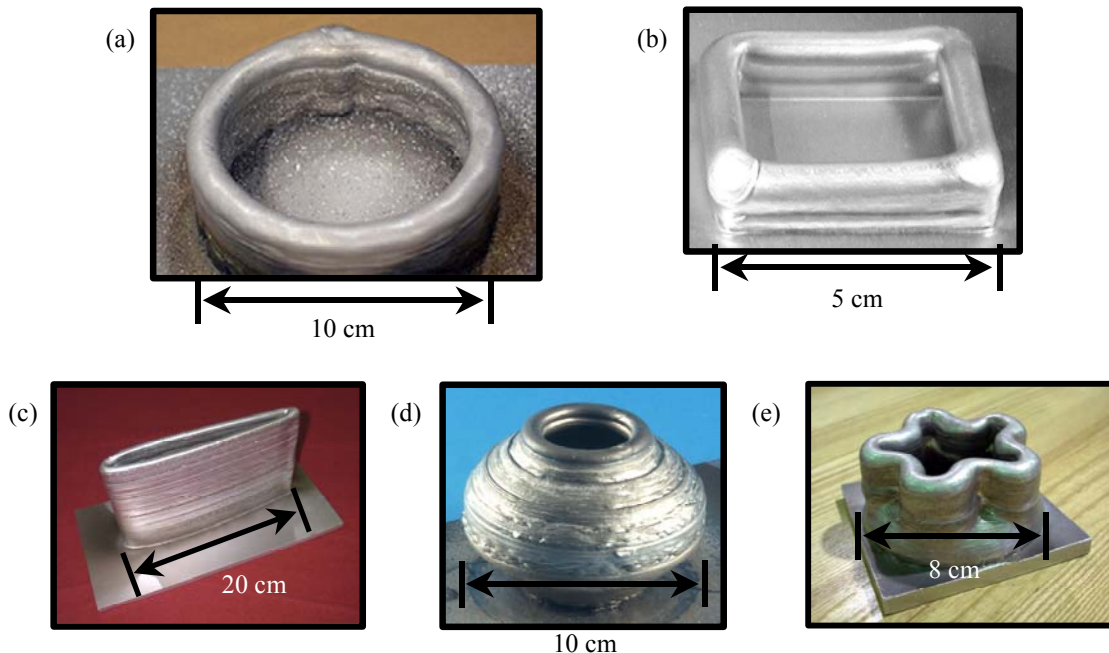

Figure 5. 2219 Al shapes built using EBF[3] demonstrate different deposition schemes: (a) high deposition rate, (b) varied wire feed angle, (c) complex curvature, (d) unsupported overhangs, and (e) transition from one geometry to another.

Future Plans

Researchers at NASA Langley Research Center are developing the EBF^3 process for manufacture and repair of aerospace structures. Materials of interest include aluminum alloys for subsonic aircraft and spacecraft, and titanium alloys, nickel-based alloys, titanium aluminides, and metal matrix composites (including titanium matrix composites) for hot structures and launch vehicles. In addition, we have interest in high strength steels such as Vascomax and 15-5 PH for production of wind tunnel models.

Future efforts will concentrate on understanding and improving various aspects of the EBF^3 process. Closed loop control and modeling of the process are important to ensure high quality and repeatability for certification of the process for applications on primary or secondary aerospace structures. A deeper understanding of the processing-microstructure-property relationships is necessary to support this development for continued process refinement. Process techniques will be developed to enable building parts with complex geometry, improved surface quality, and minimized residual stresses. Expanding the range of deposition rates and levels of detail achievable in a single system are also of interest to enhance the process flexibility. Finally, development of processing parameters for other material systems and exploitation of the layer-additive nature of the process to develop functionally graded parts will broaden the utility of the EBF^3 process. Ultimately, our goal is to develop the EBF^3 process into a robust industrial process for application in a variety of industries.

Summary

EBF^3 is a new layer additive process with high potential for use in numerous structural metallic applications. EBF^3 offers cost and lead time reductions in production of parts and performance improvements through optimized alloy chemistries and microstructures. Microstructures and mechanical properties obtained in aluminum and titanium alloys have demonstrated the potential for achieving a wide microstructural range with properties comparable to those of wrought product forms. EBF^3 offers viable solutions to issues of deposition rate, process efficiency, and material compatibility for insertion into the production environment. Although further process development and understanding is required, no barriers are evident to prevent the maturation of EBF^3 into a competitive commercial process.

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