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Electron Beam Freeform Fabrication (EBF^3) for Cost Effective Near-Net Shape Manufacturing

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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. EBF^3 deposits of 2219 aluminium and Ti-6Al-4V 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.

1.0 INTRODUCTION

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.

1.1 Advantages of Solid Freeform Fabrication

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.[1]

1.2 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.[2, 3] Other emerging SFF processes that focus on low heat inputs include Precision Metal Deposition (PMD), laser deposition with flat wire,[4] and ultrasonic consolidation (UC) of layered metal foils to form 3-D parts using ultrasonic welding, a solid state process.[5] 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.[2, 6] Electron beam freeform fabrication (EBF^3) is similar to direct laser deposition but employs a focused electron beam and wire feedstock.[7, 8, 9] Several arc-welding processes, using either wire or powder feedstock or both, have also entered the arena, including Plasma Transferred Arc Solid Free Form Fabrication (PTA SFFF) and Shaped Metal Deposition (SMD) which uses either Metal Inert Gas (MIG) or Tungsten Inert Gas (TIG) welding techniques in a layer-additive fashion.[10] Many of these processes are complementary and selection of the appropriate process is dependent upon the resources available, component to be produced, and the desired applications.[11]

1.3 Electron Beam Solid Freeform Fabrication

Researchers at NASA Langley Research Center have developed the electron beam freeform fabrication (EBF^3) process to produce unitized structures from high reflectance aerospace alloys such as aluminium and titanium. Near-term applications of the EBF^3 process are most likely to be implemented for cost reduction and lead time reduction thru addition of details onto simplified preforms (casting or forging). This is particularly attractive for components with protruding details that would require a significantly large volume of material to be machined away from an oversized forging. Future far-term applications promise improved structural efficiency through reduced weight and improved performance by exploiting the layer-additive nature of the EBF^3 process to fabricate tailored unitized structures with functionally graded microstructures and compositions.

Figure 1 shows a schematic of the primary components in an EBF^3 system. The EBF^3 process introduces metal wire feedstock into a molten pool that is created and sustained using a focused electron beam in a high vacuum environment ($1x10^{-4}$ torr or lower). The EBF^3 process is nearly 100% efficient in feedstock consumption and approaches 95% efficiency in power usage. The electron beam couples effectively with any electrically conductive material, including highly reflective alloys such as aluminium and copper. A variety of weldable alloys can be processed using EBF^3, and further development is planned to determine if non-weldable alloys can also be deposited. The EBF^3 process is capable of bulk metal deposition at deposition rates in excess of 2500 cm^3/hr (150 in^3/hr) as well as finer detailed deposition at lower deposition rates with the same piece of equipment, limited only by the positioning precision and wire feed capabilities. The diameter of the wire feedstock is the controlling factor determining the smallest detail attainable using this process: fine diameter wires may be used for adding fine details, and larger diameter wires can be used to increase deposition rate for bulk deposition. EBF^3 offers viable solutions to issues of deposition rate, process efficiency, and material compatibility for insertion into the production environment.

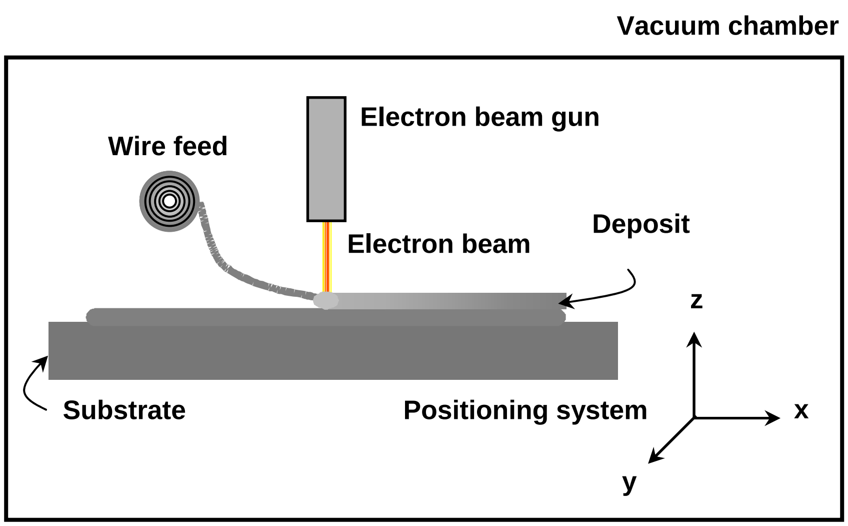

Figure 1. Schematic of electron beam freeform fabrication (EBF^3) system components.

NASA Langley Research Center has two EBF^3 systems, shown in Figures 2 and 3. The ground-based system (Figure 2) is a commercially-available electron beam welder that has been adapted for performing EBF^3 process development. This system includes a 42 kW, 60-kV accelerating voltage electron beam gun, a vacuum system, a positioning system, and dual wire feeders capable of independent, simultaneous operation. The two wire feeders may be loaded with either a fine and a coarse wire diameter for different feature definition, or two different alloys to produce components with compositional gradients. Positioning is programmable through six axes of motion (X, Z and tilt on the moving electron beam gun, and Y, tilt and rotate on the positioning table). This electron beam system requires a vacuum on the order of $5x10^{-5}$ torr and is housed in a vacuum chamber measuring 2.5 m by 2 m by 2.7 m (100 in. by 78 in. by 108 in.).

The second EBF^3 system (Figure 3) is portable and comprises a small vacuum chamber, fixed low power electron beam gun, four axis motion control system on the table (X, Y, Z and rotation), single wire feeder, and data acquisition and control system.[12] This second EBF^3 system is housed within a 1 m (38 in.)

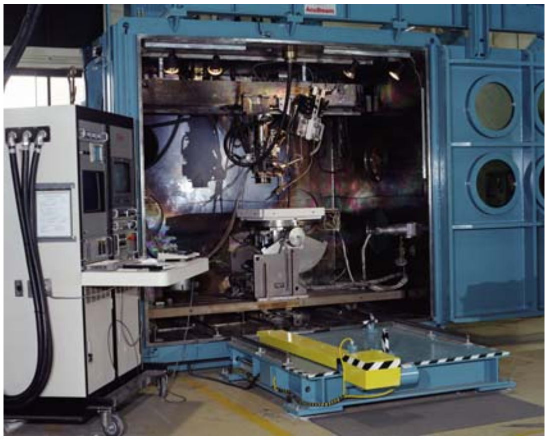

Figure 2. Ground-based EBF^3 system at NASA Langley Research Center.

Figure 3. Portable EBF^3 system at NASA Langley Research Center.

cubed vacuum chamber with the ability to fabrication a component 30 cm by 30 cm by 15 cm (12 in. by 12 in. by 6 in.) in size. This system is designed for portability so that it can be used in a variety of different locations. It has been successfully demonstrated in flight on an aircraft as well as on the ground in our laboratory. This system is well-suited for fabrication of smaller parts with intricate details due to the finer wire diameters that can be fed as well as higher precision on the positioning system.

2.0 EXPERIMENTAL PROCEDURES

To date, the EBF^3 process has been demonstrated on aluminum, titanium, and nickel-based alloys of interest for aerospace structural applications; ferrous-based alloys are also planned. This report will summarize results obtained on 2219 aluminum and Ti-6-4 titanium alloys. More detailed results can be found in other publications.[8, 13, 14] Aluminum alloy 2219 (nominally Al-6 wt% Cu) is a common aerospace alloy with excellent weldability and good strength and toughness over a wide range of temperatures. Ti-6-4 ELI (nominally Ti-6 wt% Al-4 wt% V, extra low interstitial) is a common titanium-based aerospace structural alloy used in higher stress and high temperature applications. Both alloys are readily available in wire form and proved to be well suited for EBF^3 processing.

Linear deposits similar to the one shown in Figure 4 were fabricated 25 cm (10 in.) long and one pass wide, with multiple layers to build up to approximately 2.5 cm (1 in.) in height for metallurgical analysis and tensile specimens. The width of the deposits varied from roughly 0.5 to 1 cm (0.2 to 0.4 inches), depending upon the processing conditions. The translation direction was selected so that the wire always fed into the leading edge of the molten pool. After each pass the substrate was rotated 180° to maintain the same relationship between the wire, the beam, and the translation vector.

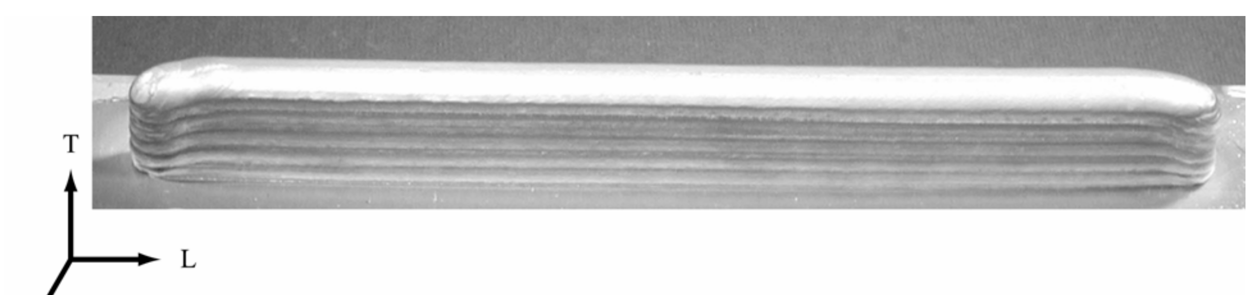

Figure 4. Coordinate system related to a typical EBF^3 deposit.

A coordinate system related to directions and orientations of the deposit is shown in Figure 4. The longitudinal direction (L) is defined to be parallel to the long axis of travel, the long transverse direction (T) is normal to the surface of the substrate, and the short transverse direction (S) is across the width of the deposited layer. This coordinate system was used to identify the orientation of tensile and metallographic specimens with respect to the fabrication directions. The tensile specimens were machined in the LT plane and tested in the L direction, and the metallographic specimens were sectioned perpendicular to the longitudinal travel direction and mounted and polished in the ST plane.

Standard metallographic techniques were employed for microstructural determination. Deposits were sectioned, mounted and polished, then acid etched to highlight grain morphology. Metallographic specimens were examined and photographed using optical microscopy. Tensile properties at room temperature were determined using standard 10 cm (4 in.) subsize dogbone specimens per ASTM E8.[15] The specimen thickness was slightly less than the deposit width, allowing for the surfaces to be machined flat and parallel to remove surface irregularities from the EBF^3 process.

3.0 DISCUSSION OF RESULTS

The EBF^3 process has numerous parameters that control the resulting microstructures and shape of the deposit.[8, 13] Three of the most significant of these parameters which are easily controlled are the translation speed, wire feed rate, and beam power. These three parameters were systematically varied and microstructural evaluation was conducted on the resulting 2219 and Ti-6-4 deposits to understand the effect of processing on the build quality and grain morphology. Over the range of parameters tested for the 2219 Al, resultant microstructures varied from a fine-grain equiaxed grain structure to a solidification microstructure with larger grain sizes and dendritic growth. Representative microstructures for high and moderate heat input (as influenced by the combination of translation speed, wire feed rate, and beam power) are shown in Figure 5 for as-deposited 2219 Al in the ST plane of the deposit. The light colored bands are dendrites that formed in the interpass region where portions of a previous layer are remelted during deposition of a subsequent layer. Although dendrites can be seen contained within the grains, pervasive dendritic formation is minimal in the interpass regions of the deposit produced with the moderate heat input conditions.

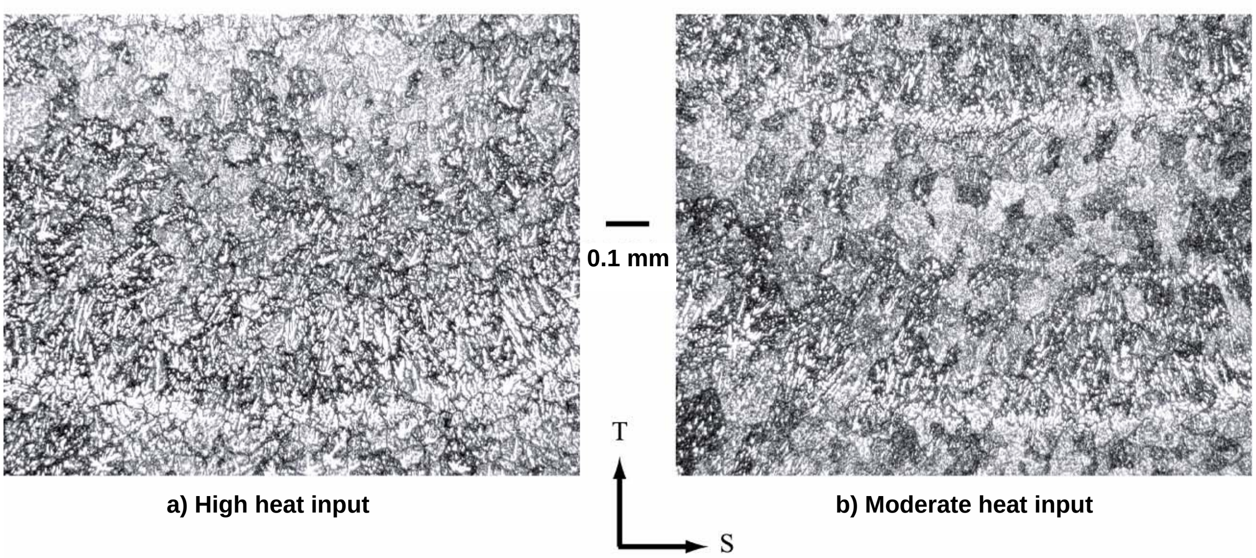

Figure 5. Typical microstructures of 2219 Al deposit: a) shows dendrite growth in a deposit with high heat input and higher deposition layer height; b) shows less dendrite growth and formation of equiaxed grain structure in the bulk deposit with more moderate heat input and a smaller deposition layer height.[8]

Experiments performed on Ti-6Al-4V resulted in the formation of large columnar grains growing epitaxially from the substrate, as shown in Figure 6a. At higher magnification, as shown in Figure 6b, alpha-beta laths typical of the microstructures of alpha+beta titanium alloys can be seen. Through rigorous process control, it has been demonstrated that the size of these columnar grains can be controlled by limiting the heat input during the deposition process.

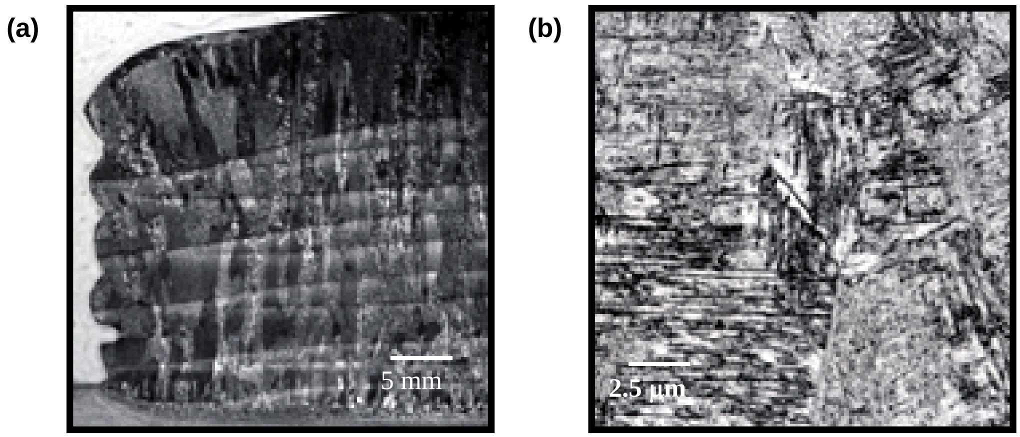

Figure 6. Microstructures of EBF[3] Ti-6-4 deposits: (a) low magnification shows columnar grain structure in LS plane, and (b) high magnification shows alpha-beta lath structure in ST plane.

Figure 7 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.[16] The data for the as-deposited 2219 Al were averaged over duplicate tests for seven combinations of beam powers, translation speeds, and wire feed rates. Despite the wide range of processing conditions, the majority of the as-deposited 2219 Al data fell in a tight band, as shown by the range bars in Figure 7. The properties of as-deposited 2219 Al fell between those for 2219 Al sheet and plate in the annealed (O temper) and solutionized and naturally aged (T4 temper) tempers. This is as expected considering the thermal history that the layer additive processes experience. The 2219 Al deposits in the T62 temper also had very little scatter and were equivalent to typical T62 handbook properties for sheet and plate product.[16] As with the 2219 Al, the Ti-6-4 exhibits tensile properties comparable to those of annealed wrought product,[17] as shown in Figure 8.

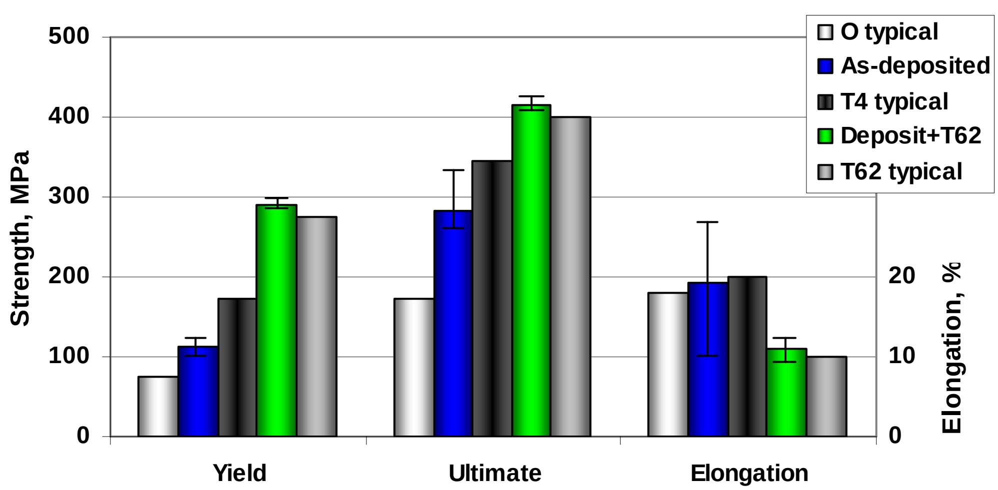

Figure 7. Tensile properties at room temperature of EBF[3] deposited 2219 Al as compared to typical handbook values [16] for 2219 Al sheet and plate.

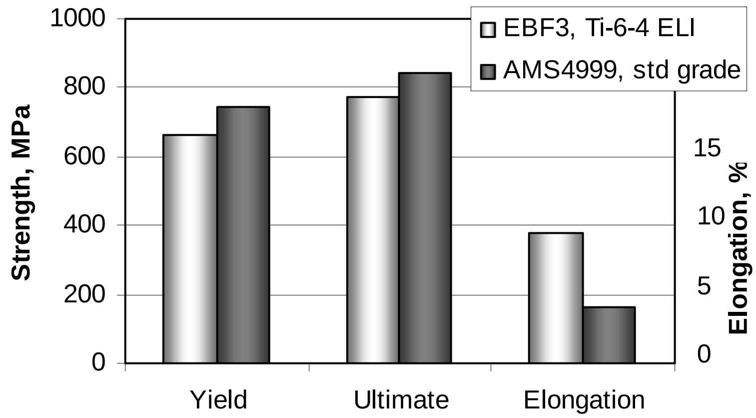

Figure 8. Tensile properties at room temperature of EBF^3 deposited Ti-6-4 ELI as compared to AMS 4999 Ti-6Al-4V minimum specification (standard grade Ti-6-4).[17]

For both the 2219 Al and the Ti-6-4, it has been demonstrated that controlling the heat input through careful selection of the translation speed, wire feed rate, and beam power can influence the microstructure that is developed in the deposited material.[8, 13] Finer grained, equiaxed microstructures are obtained at the lower heat input conditions, which typically correspond to narrower deposits and lower deposition rates. Larger grains, including epitaxial growth from the baseplate in the Ti-6-4 and pervasive dendritic microstructures within the 2219 Al grains and in the interpass regions, develop during builds in which the heat inputs tend to be higher to achieve higher deposition rates. This demonstrates that there is a trade off between high deposition rates and fine-grained microstructures. However, examination of the tensile strengths of the EBF^3 deposited materials shows that, for 2219 Al and Ti-6-4, the tensile properties are not statistically affected by the variations within the microstructures obtained during higher versus lower heat input processing conditions. Furthermore, after post-deposition heat treatments, the tensile properties exhibit an even tighter range in the data than observed in the as-deposited condition. Thus, the range in microstructures documented for 2219 Al and Ti-6-4 appears to be small enough that it does not have a significant impact on the bulk tensile properties of the EBF^3 deposited materials. Additional work is required to examine other mechanical properties such as fatigue, fracture, and crack propagation to fully characterize any potential impact of the microstructural differences.

4.0 CONCLUDING REMARKS

EBF^3 is a new layer additive process with high potential for use in numerous structural metallic applications. EBF^3 offers the potential for cost and lead time reductions in production of parts and performance improvements through optimized alloy chemistries and microstructures. Microstructures and mechanical properties obtained in aluminium 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.

There is a trade off between high deposition rates and fine-grained microstructures for materials deposited using the EBF^3 process. The tensile properties for EBF^3 deposited 2219 Al and Ti-6-4 were very consistent over a wide range of processing conditions, indicating that the tensile properties are not statistically affected by the variations within the microstructures obtained during higher versus lower heat input processing conditions. Thus, the range in microstructures documented for 2219 Al and Ti-6-4 appears to be small enough that it does not have a significant impact on the bulk tensile properties of the EBF^3 deposited materials. Additional work is required to examine other mechanical properties such as fatigue, fracture, and crack propagation to fully characterize any potential impact of the microstructural differences.

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14. ABSTRACT
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