

# CHARACTERIZATION OF 2219 ALUMINUM PRODUCED BY ELECTRON BEAM FREEFORM FABRICATION

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## Abstract

Researchers at NASA Langley Research Center are developing a new electron beam freeform fabrication (EB F<sup>3</sup>) technique to fabricate metal parts. This process introduces metal wire into a molten pool created by a focused electron beam. Potential aerospace applications for this technology include ground-based fabrication of airframe structures and on-orbit construction and repair of space components and structures. Processing windows for reliably producing high quality 2219 aluminum parts using the EB F<sup>3</sup> technique are being defined. The effects of translation speed, wire feed rate, and beam power on the resulting microstructures and mechanical properties are explored. Tensile properties (ultimate tensile strength, yield strength, and elongation) show little effect over the range of processing conditions tested. Basic processing-microstructure-property correlations are drawn for the EB F<sup>3</sup> process.

## INTRODUCTION

Several solid freeform fabrication techniques developed over the past decade have the ability to produce structural metal parts directly from computer-generated designs [1] [2]. These techniques also lend themselves to fabrication of unitized structures that reduce part count, decrease weight, reduce assembly time and cost, and improve structural efficiency, as compared to conventional fabrication and assembly methods. However, many of these techniques rely on lasers, which are ineffective in processing highly reflective metallic materials. Researchers at NASA Langley Research Center have been developing a new electron beam freeform fabrication (EB F<sup>3</sup>) technique for producing unitized structures from high reflectance aerospace alloys such as aluminum and titanium. The EB F<sup>3</sup> process is also conducive for applications in space due to the ease of handling wire feedstock in zero-gravity, high feedstock consumption efficiency, and high power efficiency of this process. Applications in space include on-orbit fabrication of large space structures and repair and manufacturing of spare parts on long duration human exploration missions where resupply can be difficult and costly [3].

The EB F<sup>3</sup> process uses a focused electron beam to create a molten pool on a metallic substrate. The beam is translated with respect to the surface of the substrate and metal wire is fed into the pool in a layer-additive fashion. The electron beam can be controlled and deflected very precisely and couples very effectively with highly reflective materials. The EB F<sup>3</sup> process works with a very finely focused beam that is rastered over a larger pattern to control the size of the molten pool and facilitate capture of the wire. The wire is preheated by the beam, but is not melted until it enters the molten pool. This process is nearly 100% efficient in feedstock consumption and approaches 95% efficiency in power usage.

The EB F<sup>3</sup> system at NASA Langley Research Center is comprised of a high power electron beam gun and dual wire feeders capable of independent, simultaneous operation. Positioning is programmable through six axes of motion (X, Y, Z, gun tilt, and positioner tilt and rotate) within a build envelope of 72 in. x 24 in. x 24 in. The electron beam requires a vacuum on the order of 5x10<sup>-5</sup> torr, so the EB F<sup>3</sup> system is housed in a large vacuum chamber. This system was used to fabricate 2219 Al deposits using a variety of process conditions, and then the deposits were sectioned to analyze microstructures and tensile properties to correlate with processing parameters.

## **MATERIALS**

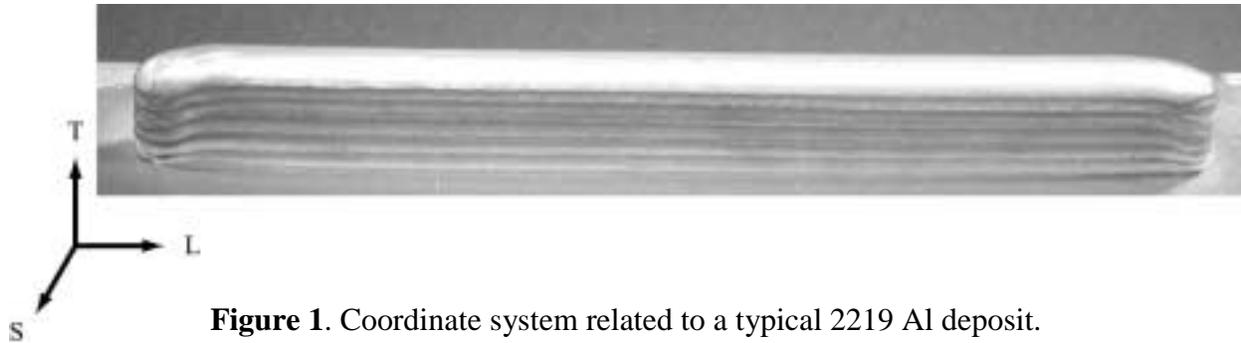
Aluminum alloy 2219 is a common aerospace alloy with excellent weldability and good strength and toughness over a wide range of temperatures. Alloy 2319 is the designation for the wire form used as filler wire for welding 2219 Al. The compositions of 2319 Al and 2219 Al are identical (nominally Al-6 wt% Cu) except for slight variations in trace element constituents. For the purposes of this report, the electron beam deposits will be referred to as 2219 Al because this is the common alloy designation for product forms other than wire and the properties of the EB F<sup>3</sup> deposited 2319 Al are directly compared to 2219 Al.

## **EXPERIMENTAL PROCEDURES**

The EB F<sup>3</sup> process has numerous variables that control the resulting microstructures and shape of the deposit. Three of the most significant of these variables which are easily controlled are the translation speed, wire feed rate, and beam power. These three variables were isolated for detailed microstructural and macrostructural evaluation to understand the effect of processing on the build quality and grain morphology. Deposits were built using seven different combinations of translation speed, wire feed rate, and beam power, then machined for tensile testing.

Linear deposits were built from 2319 Al wire onto 0.25 inch thick 2219 Al plate. Deposits for metallurgical analysis and tensile specimens were fabricated ten inches long and one pass wide, with multiple layers to build up to approximately one inch in height. The width of the deposits varied from approximately 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.

A coordinate system related to directions and orientations of the deposit is shown in Figure 1. 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. Tensile properties at room temperature were determined using standard 4 in. subsize dogbone specimens per ASTM E8 [4]. Flat tensile specimens were machined in the LT plane and tested in the L direction. The specimen thickness



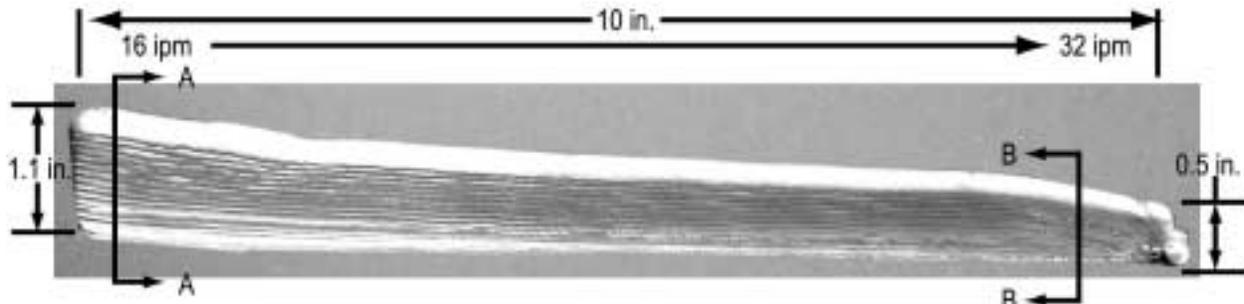
**Figure 1.** Coordinate system related to a typical 2219 Al deposit.

was approximately equal to the deposit width, with the surfaces machined flat and parallel to remove surface irregularities introduced by the EB F<sup>3</sup> process. Duplicate specimens from each of the seven different processing combinations were tested in the as-deposited condition. In addition, duplicate specimens from four of the seven processing combinations were heat treated to a T62 temper using a standard heat treatment schedule (solutionize at 995°F for one hour, cold water quench, and age at 375°F for 36 hours [5]) and tested.

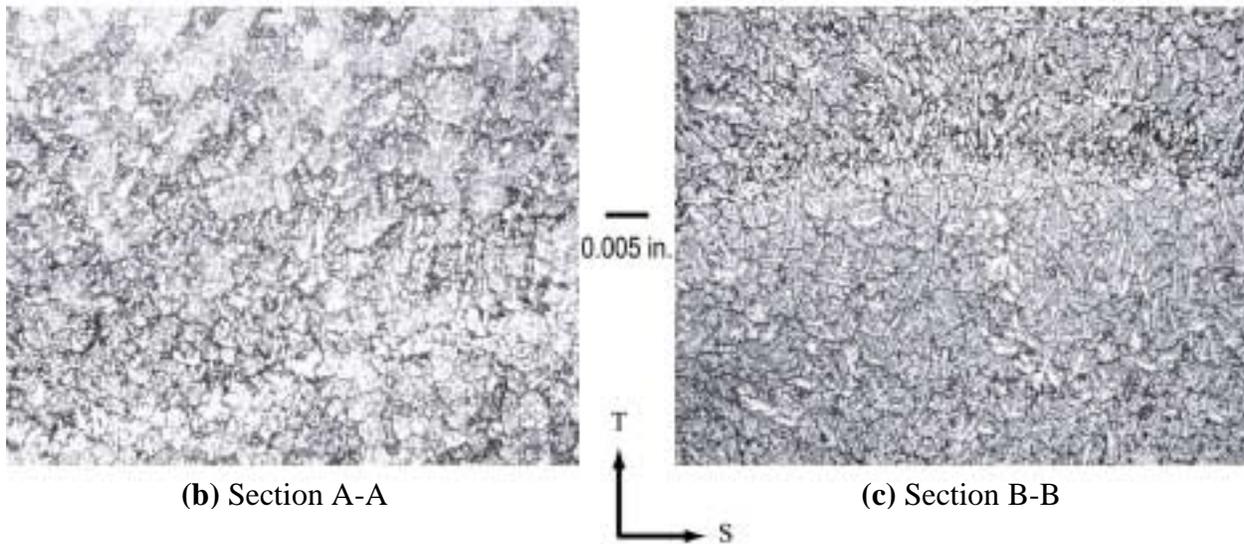
Standard metallographic techniques were employed for microstructural determination. Deposits were sectioned perpendicular to the travel direction and mounted and polished in the ST plane. The polished sections were etched with Keller's reagent to highlight grain morphology. Metallographic specimens were examined using optical microscopy. The chemical composition of the deposits were determined using inductively coupled plasma spectroscopy and compared with the starting 2319 Al wire feedstock.

## RESULTS AND DISCUSSION

To evaluate the effect of translation speed, multiple passes were deposited using constant beam power and wire feed rate, while the translation speed was continuously increased from 16 inches per minute (ipm) to 32 ipm during each pass of the deposit. Figure 2a shows the dimensions of this deposit and locations where cross sections were taken for microstructural evaluation. For higher translation speed, the lower heat input and lower volume of wire being fed into the molten pool result in a smaller diameter, shallower molten pool. This combined effect produces a decreasing taper in both the width and height of the deposit as the translation speed increases. Figures 2b and 2c show microstructures from the ends of the deposit at the lowest and highest translation speeds, respectively. Light bands of dendrites crossing the grain boundaries define the interpass region, where portions of a previous layer are remelted when a subsequent layer is deposited. A comparison of Figures 2b and 2c reveals that the higher translation speed produces more rapid cooling and results in a homogeneous microstructure with smaller equiaxed grains. Although dendrites can be seen contained within the grains, pervasive dendrite formation is minimal in the interpass regions of the deposit produced at the higher translation speed.



(a) Photograph of 2219 Al deposit made with increasing translation speed, constant beam power and constant wire feed rate.

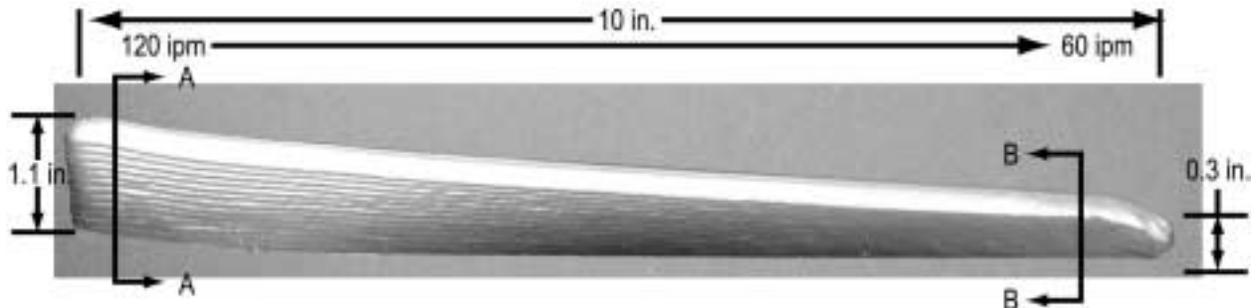


(b) Section A-A

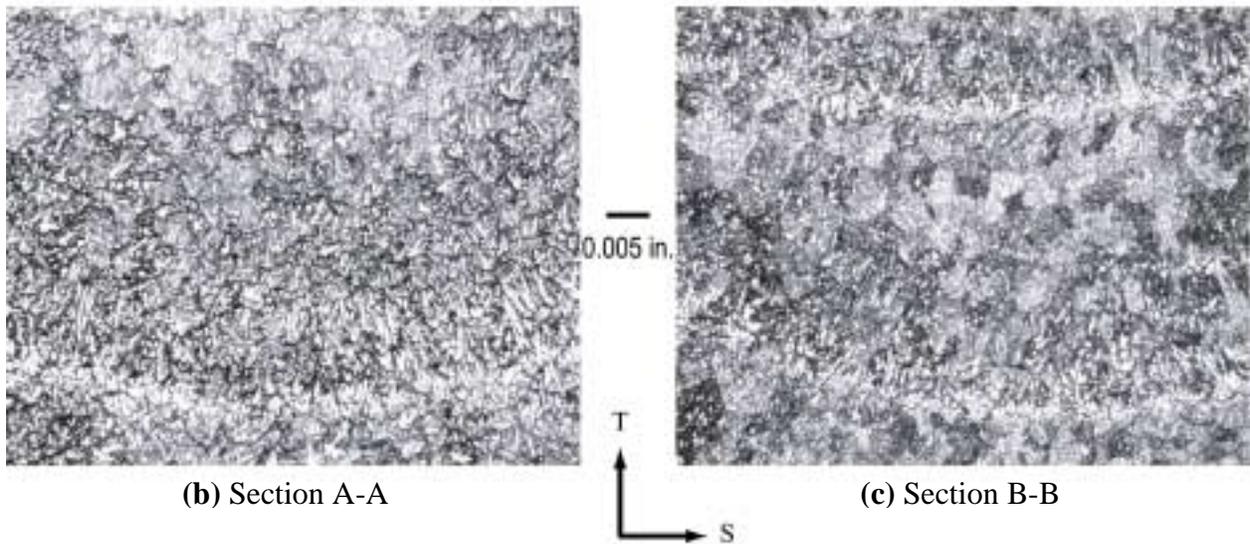
(c) Section B-B

**Figure 2.** Effect of varying translation speed on geometry and microstructure of 2219 Al deposit.

To evaluate the effect of wire feed rate, multiple passes were deposited using constant beam power and translation speed, while the wire feed rate was continuously decreased from 120 ipm to 60 ipm during each pass of the deposit. Figure 3a shows the dimensions of this deposit and locations where cross sections were taken for microstructural evaluation. Since the beam power and translation speed are the same for this case, the energy density is constant across the entire deposit. Increasing the wire feed rate increases the volume of material being fed into the molten pool, thereby increasing the percentage of the energy being used to melt the wire and reducing the amount of energy being absorbed by the part. This results in a narrowing of the molten pool and thus the deposit width, but a significant increase in the deposit height with increasing wire feed rate. Figures 3b and 3c show microstructures from the ends of the deposit at the fastest and slowest wire feed rates, respectively. With the higher wire feed rates, the cooling rate is 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. For the lower wire feed rate, the grain size is much larger and less defined.



(a) Photograph of 2219 Al deposit made with decreasing wire feed rate, constant beam power and constant translation speed.

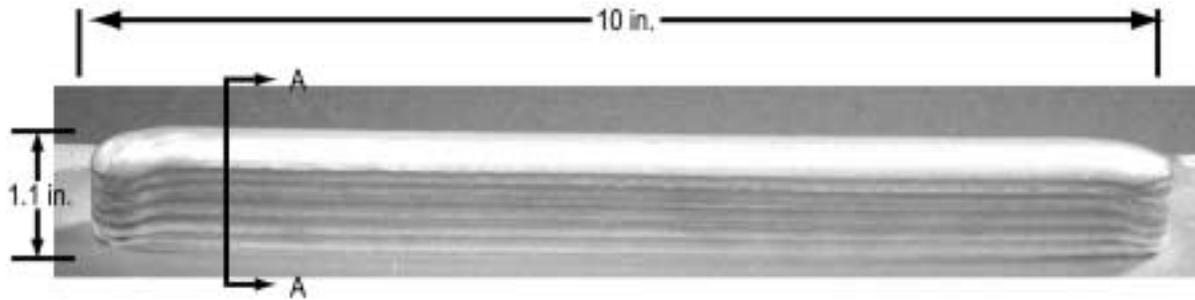


(b) Section A-A

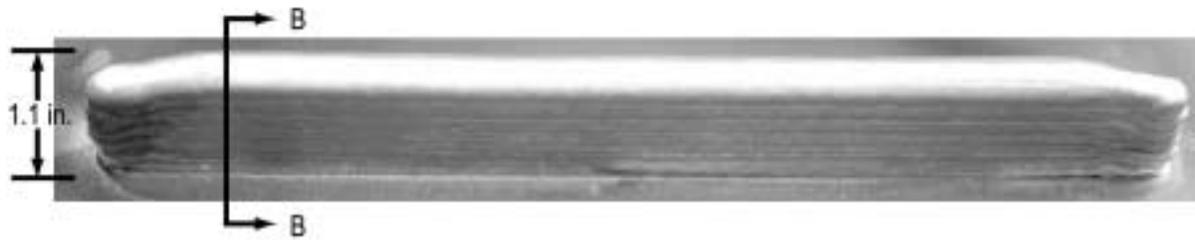
(c) Section B-B

**Figure 3.** Effect of varying wire feed rate on geometry and microstructure of 2219 Al deposit.

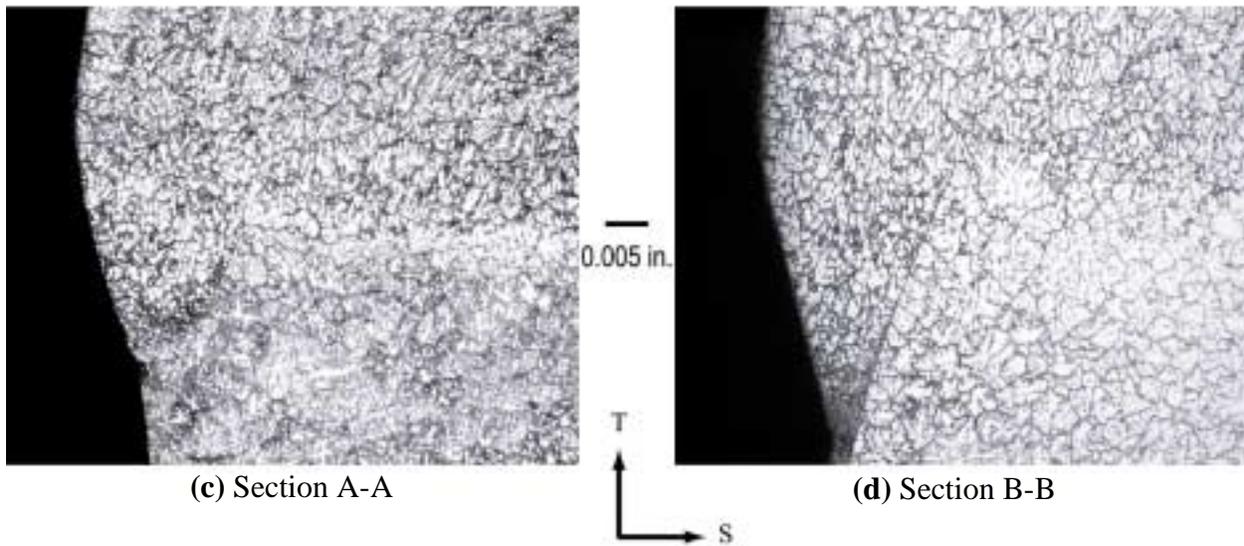
The effect of deposition rate was examined by comparing two deposits, each built with constant parameters throughout the build. The deposit with the lower deposition rate, shown in Figure 4a, was deposited using moderate beam power, moderate wire feed rate, and low translation speed. The deposit with the high deposition rate, shown in Figure 4b, was built using the same translation speed, but 50% higher beam power and 67% higher wire feed rate. The combined effect of higher beam power and higher wire feed rate is an increase in the width and height of the deposit. Increasing the beam power increases the heat input into the part, resulting in a deeper and wider molten pool. The increased wire feed rate adds more material to the molten pool, resulting in the greater deposition rate. Figures 4c and 4d show the microstructural features of the deposits built with lower and higher deposition rates, respectively. The higher deposition rate (Figure 4d) produces a larger grain size with significant dendrite growth, and inhomogeneity in the interpass region. There is also evidence of molten material rolling over the edge of previous layers, particularly on the part built at the higher deposition rate. This is a result of the higher heat input increasing the size of the molten pool so that the effect of gravity dominates over surface tension, and the increased fluidity of the aluminum coupled with this gravity effect causes the molten pool to flow over the side of the preceding layer.



(a) Photograph of 2219 Al deposit made with low deposition rate.



(b) Photograph of 2219 Al deposit made with high deposition rate.

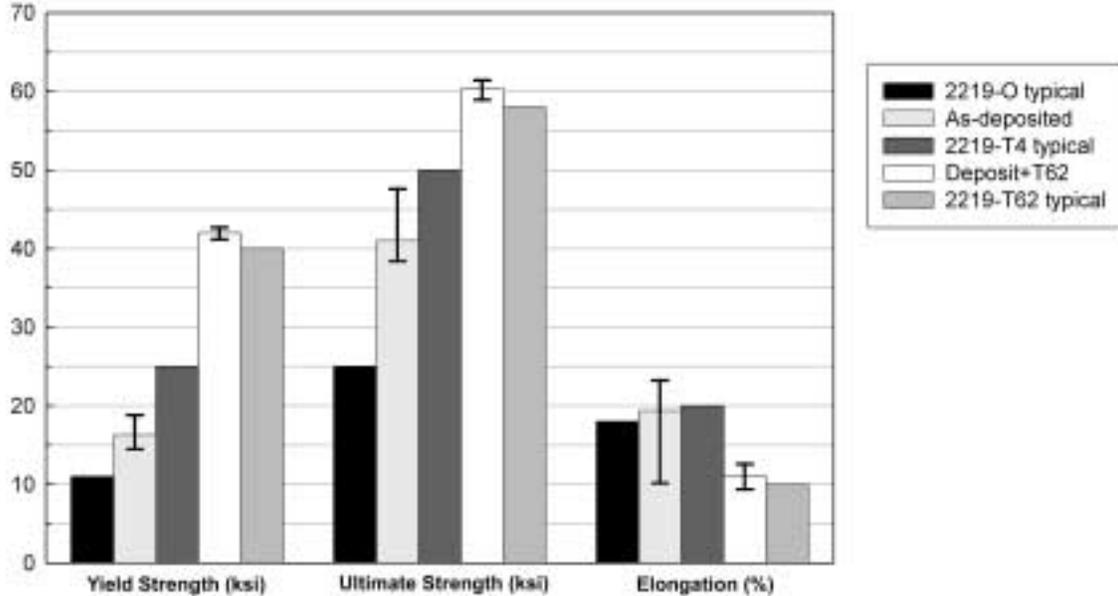


(c) Section A-A

(d) Section B-B

**Figure 4.** Effect of varying deposition rate on geometry and microstructure of 2219 Al deposit.

Figure 5 shows the ultimate tensile strength, 0.2% offset yield strength, and total elongation to failure for the EB F<sup>3</sup> 2219 Al deposits as compared to typical handbook data for sheet and plate products [5]. 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 5. 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. The 2219 Al deposits in the T62 temper also had a very



**Figure 5.** Tensile properties at room temperature of EB  $F^3$  deposited 2219 Al as compared to typical handbook values for 2219 Al sheet and plate [5].

tight data range, and were equivalent to typical T62 handbook properties for sheet and plate product [5].

Over the entire range of beam powers, translation speeds, and wire feed rates tested, the deposits exhibited very little porosity, no cracking, and complete fusion between deposited layers. The chemical composition of the deposits compared with the starting 2319 Al wire feedstock confirmed that the alloy compositions were unaffected by the EB  $F^3$  process. The tensile properties were also very consistent over a wide range of processing conditions. These results indicate that the EB  $F^3$  process is robust and provides a wide processing envelope from which 100% dense deposits can be made with useful mechanical properties. However, several processing combinations resulted in excess heat input into the molten pool, as evidenced by the widening of the molten pool, roll over at the edges of previous deposited layers, and dendrite formation and growth. Further process development is planned to optimize the thermal input to reduce distortion and residual stresses, and to improve the microstructure and mechanical properties of the resulting EB  $F^3$  deposited materials.

## CONCLUSIONS

1. The potential for building 2219 Al structures using the EB  $F^3$  process was successfully demonstrated.
2. The effects from varying the EB  $F^3$  processing conditions were correlated with the resulting microstructures and deposition features of 2219 Al deposits.

3. Tensile properties of the 2219 Al deposits produced using EB F<sup>3</sup> showed little variation over the wide range of processing conditions tested.
4. After T62 heat treatment, the 2219 Al deposits produced using EB F<sup>3</sup> possessed tensile properties comparable to typical handbook data for T62 sheet and plate product.
5. The EB F<sup>3</sup> process is robust, as evidenced by the wide range of processing conditions to achieve defect-free deposits and good tensile properties.
6. Process optimization is required to improve thermal management in the 2219 Al EB F<sup>3</sup> deposits.

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