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Effect of Orientation on Tensile Properties of Inconel 718 Block Fabricated with Electron Beam Freeform Fabrication (EBF^3)

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Abstract

Electron beam freeform fabrication (EBF^3) direct metal deposition processing was used to fabricate an Inconel 718 bulk block deposit. Room temperature tensile properties were measured as a function of orientation and location within the block build. This study is a follow-on activity to previous work on Inconel 718 EBF^3 deposits that were too narrow to allow properties to be measured in more than one orientation.

The tensile strength and yield strength of the as-deposited material from the block build were greater than those for conventional Inconel 718 castings but lower than those for conventional cold-rolled plate. The block exhibited a significant degree of anisotropy. Specimens machined from the bottom portion of the block had greater strength than those machined from the top portion of the block. The strength in the 45° direction tended to be greater than that in the longitudinal and transverse directions. In most cases, the ductility levels for the EBF^3 block were equal to or greater than the nominal ductility for Inconel 718 plate and castings. However, the ductility in the 45° and transverse directions for specimens machined from the bottom portion of the block were lower than that for the conventionally-processed material.

Previous work had shown that the EBF^3 process resulted in a low modulus value in the deposition direction for narrow Inconel 718 builds. The results from the bulk block in the current study confirmed a low modulus in the direction of deposition. The modulus values transverse and 45° to the direction of deposition were approximately equivalent to the nominal modulus for Inconel 718 plate. The estimated through-thickness modulus was intermediate between that for the deposition direction and that for the transverse direction.

The microstructure consisted of a layered distribution of dendrite colonies resultant from the rapid solidification of the EBF^3 deposits. The size of the dendrites and the colonies varied through the block thickness due to decreases in the cooling rate of the deposited materials as the deposition of the block progressed.

Introduction

Over the past several years NASA Langley Research Center (LaRC) has been developing Electron Beam Freeform Fabrication (EBF^3) for the manufacture of near-net-shape and net-shape metallic components (ref. 1, 2). EBF^3 offers the potential for efficient streamlined manufacturing of intricate components due to its ability to directly deposit material to only the regions where it is needed. Various markets are interested in this direct deposition technology, which can improve the materials usage efficiency by eliminating the need for machining large quantities of material from wrought blocks and forgings or the fabrication of highly-detailed molds for castings.

Utilization of the EBF^3 process for fabrication of Inconel 718 components for high-temperature structural applications is being investigated. Inconel 718 is a widely used superalloy with good weldability (ref. 3), which makes it a good candidate for the EBF^3 process. Previous work at LaRC (ref. 4) showed that the EBF^3 process resulted in good strength in the direction of deposition. The tensile strength and yield strength were greater than those for conventional Inconel 718 castings but less than those for conventional cold-rolled sheet. However, the modulus of EBF^3-deposited Inconel 718 was significantly lower than that for conventionally-processed sheet and castings. The EBF^3-deposited product forms used in that study were too narrow to allow for properties to be measured in directions other than parallel to the deposition direction. This present study was initiated to build a larger bulk block of Inconel 718 with dimensions on the order of 4 inches by 4 inches by 1 inch using the EBF^3 process so tensile properties in the off-axis directions could be determined as a function of orientation. Although a large bulk block of EBF^3-deposited Inconel 718 offers no advantages over wrought product forms for practical structural applications, this product form is necessary to facilitate measurement of mechanical properties in multiple directions.

Electron Beam Deposition

Figure 1 shows a photograph of the primary components of the EBF^3 system at NASA LaRC used for this investigation. The system uses a high-power electron beam gun in a vacuum environment. The wire feedstock is fed from a spool through the wire feed mechanism. The gun and the wire feed mechanism are mounted on a gantry with the capability of translating back and forth along the longitudinal axis, up and down along the vertical axis, and tilting. The substrate is supported on a table that travels in the transverse direction and has the capability to rotate and tilt. The system is housed within a vacuum chamber with approximate dimensions of 9 ft by 7 ft by 9 ft.

The EBF^3 system can be operated manually or via computer code to control the electron beam, wire feed, and translation/rotation parameters to build the desired geometric shapes. During operation, the tip of the wire feed nozzle is brought into close proximity to the substrate. At any given instant the electron beam forms a small molten pool in the substrate. The wire is fed into the beam and the molten pool, thus depositing material at that location. As the electron beam moves away due to the substrate/gun translation the molten pool rapidly solidifies. Detailed discussions of the EBF^3 process and this particular system can be found in references 1 and 2.

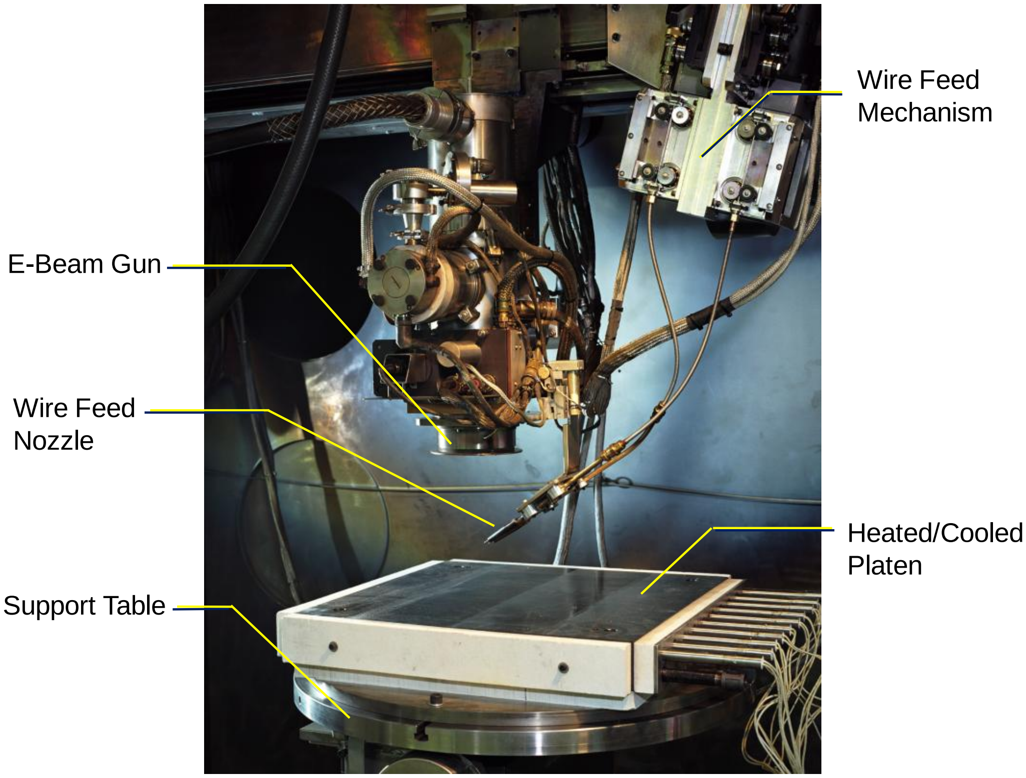

Figure 1. Electron beam freeform fabrication system.

Materials

The base plate and wire used for the EBF^3 block build were Inconel 718 alloy with nominal composition, in weight percent, of Ni - 19 Cr - 18 Fe - 5.1 (Nb + Ta) - 3 Mo - 0.9 Ti - 0.5 Al (ref. 3). The base plate was 6.5 inches in diameter and 0.5 inch thick. The wire diameter was 0.045 inch.

Experimental Procedures

Electron-Beam Freeform Fabrication (EBF^3) Process

The base plate was clamped to the support table at four locations at 90° intervals around the circumference of the base plate. The heated/cooled platen shown in Figure 1 was not used for these experiments. The system was evacuated to the 10^{-6} torr range. Parameters for electron beam gun power and deposition rates were selected based on previous work. The electron beam gun was used to preheat the base plate and remove surface oxides in the vicinity of the block build prior to deposition.

The dimensions for the block build were approximately 4.6 inches long by 4.1 inches wide with a height of 1.1 inches (see Figure 2). Individual bead deposits were approximately 0.150 inch wide. To produce a block with the desired width, 34 deposits were made side-by-side with a

0.125-inch center-to-center spacing. This spacing resulted in a 0.025-inch overlap between adjacent deposits to fully fill the volume and avoid porosity. Approximately 40 layers were required to build the block. To facilitate heat distribution, consecutive bead depositions were spaced at least 0.5 inch apart. For example, the first bead was deposited along the right-hand edge of the block; the second bead was deposited 2.375 inches from the right-hand edge; the third bead was deposited 0.5 inch from the right-hand edge. This process was continued until the 34 deposits were completed for that layer and the full cross-section of the block was covered with deposited beads. The block was allowed to cool for 1-2 minutes after each layer was deposited. After completion of each layer, the support table was rotated 180° such that the starting points for the new layer of bead deposits corresponded to the ending points of the beads from the previous layer.

On four occasions the bulk block build process was interrupted. During deposition of the second layer, the electron beam gun filament failed and had to be replaced. Deposition was resumed at the point in the deposit sequence at which it had been stopped. In addition, the process was interrupted at estimated build heights of 0.62 inch, 1.12 inch, and 1.24 inch to visually examine the build and to confirm the build height. After each interruption, two electron beam cleaning passes were made over the surface of the block prior to resuming the deposition.

Orientation Convention

Figure 2 also shows the orientation convention used throughout this paper. The directions within the EBF^3-deposited block (and their relation to directions in conventional wrought product) are as follows:

x = direction of deposition (longitudinal)

y = direction normal to deposition direction (transverse)

z = through-thickness direction (short transverse)

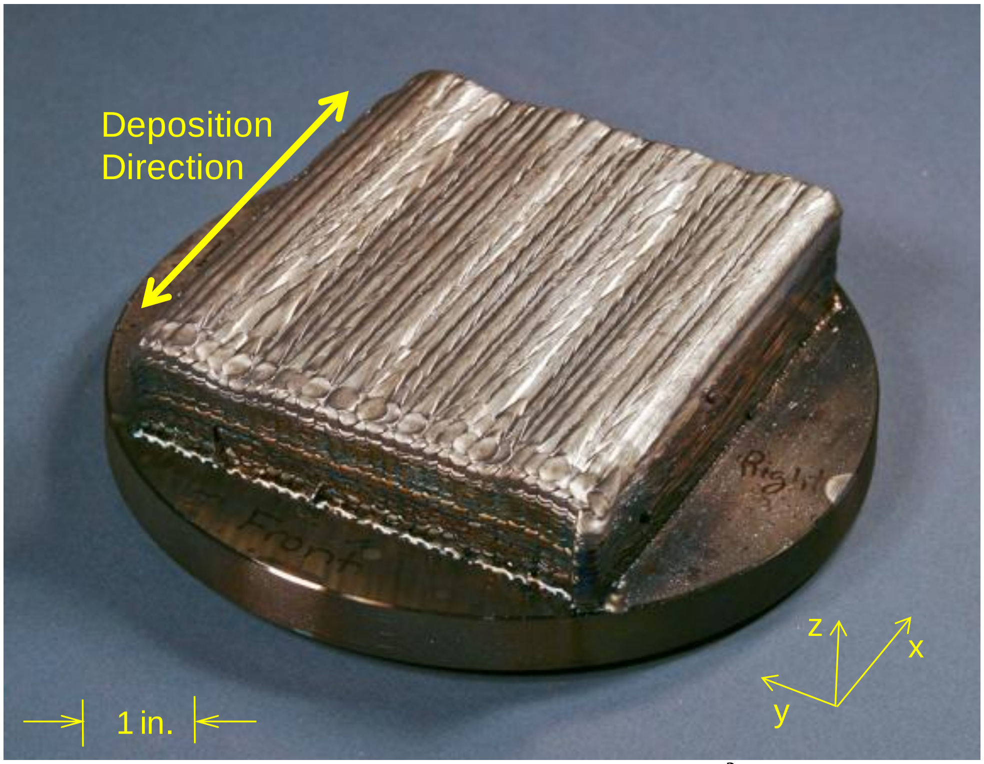

Figure 2. Inconel 718 block build fabricated using EBF^3 deposition processing.

Test Specimens

Figure 3 shows slicing information for the bulk block for test specimen fabrication. Four sections (A, B, C, Z) were cut from the block from the locations shown in the figure. Sections A, B, and C were oriented parallel, transverse, and 45° to the deposition direction, respectively. Section Z was oriented such that its length was in the through-thickness direction.

Sections A, B, and C were cut into lengthwise slices with thickness of 0.1 inch (see Figure 4). One tensile specimen was machined from the top portion and one from the bottom portion of each slice in order to evaluate differences in properties through the height of the block (see Figure 5). The centerline of the specimens machined from the bottom portion of the block was located about 0.4 inch above the interface between the base plate and the EBF^3 block. The center line of the top specimens was located about 0.9 inch above the interface. A total of 10 specimens were machined in each orientation: 5 from the top and 5 from the bottom portions of the block. Tensile specimens were machined in accordance with ASTM specification E8 (ref. 5), as depicted in Figure 6. Two replicate specimens were tested for each orientation and each location within the block (top or bottom). The remaining specimens were held in reserve to evaluate different conditions in parallel studies.

The block build was not thick enough to allow fabrication of standard tensile specimens in the through-thickness direction. Therefore, specimens for generating through-thickness modulus estimates were fabricated by cutting Section Z into four lengthwise slices with width of 0.45 inch and thickness of 0.1 inch (see Figure 7). Back-to-back strain gages with gage length of 0.062

inch were bonded to each slice. The center of the gages was located approximately 0.4 inch above the interface between the base plate and the EBF^3 block. This strain gage location corresponds to the same location within the block build from which the "bottom" tensile specimens were machined from Sections A, B, and C.

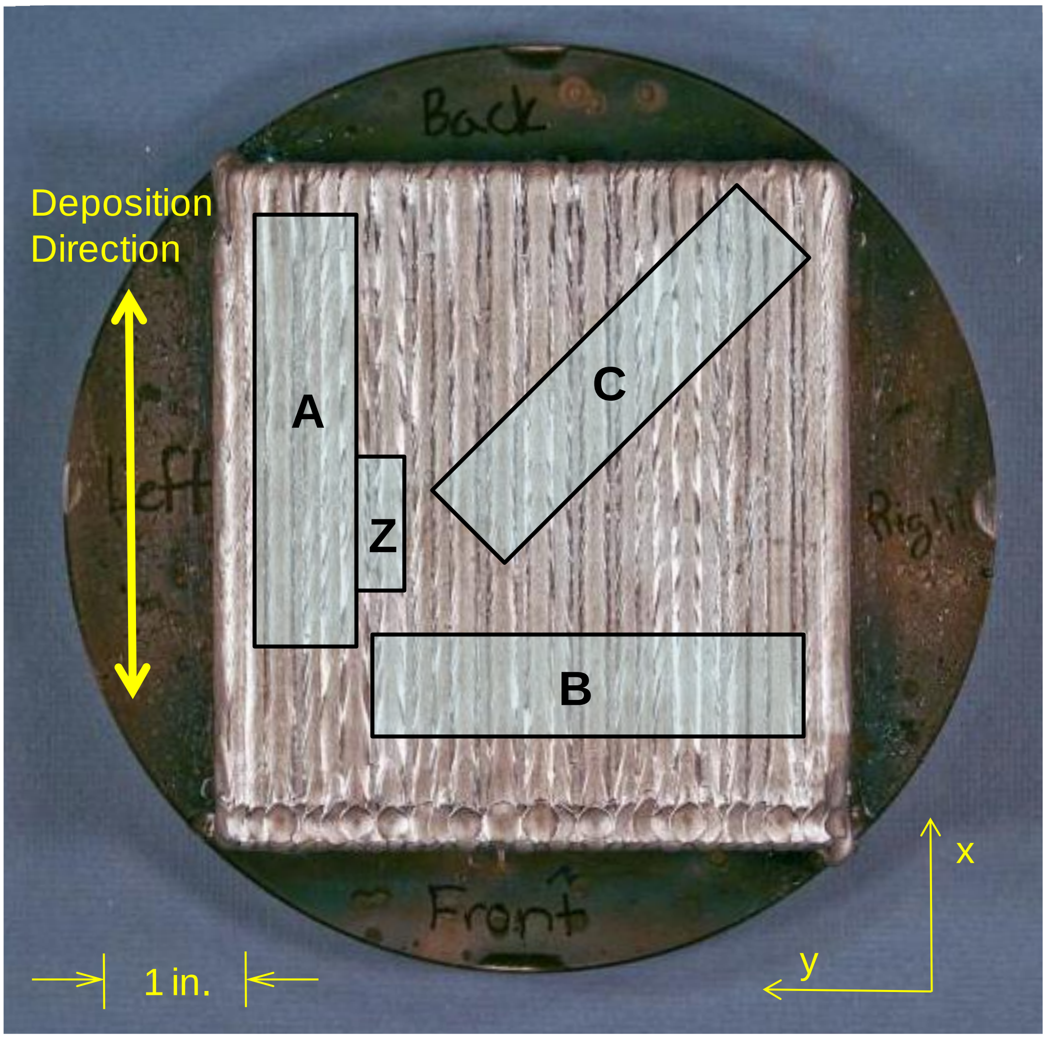

Figure 3. **Block sectioning for tensile specimen fabrication.**

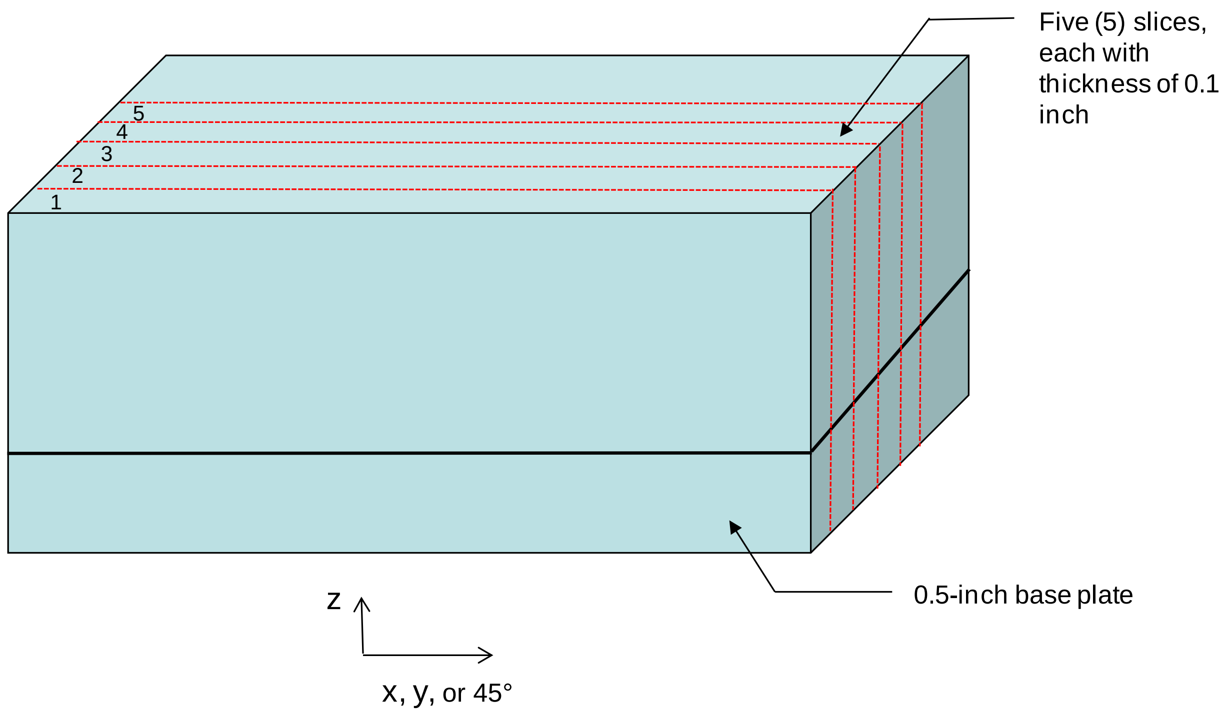

Figure 4. **Slicing diagram of block build sections for tensile specimens.**

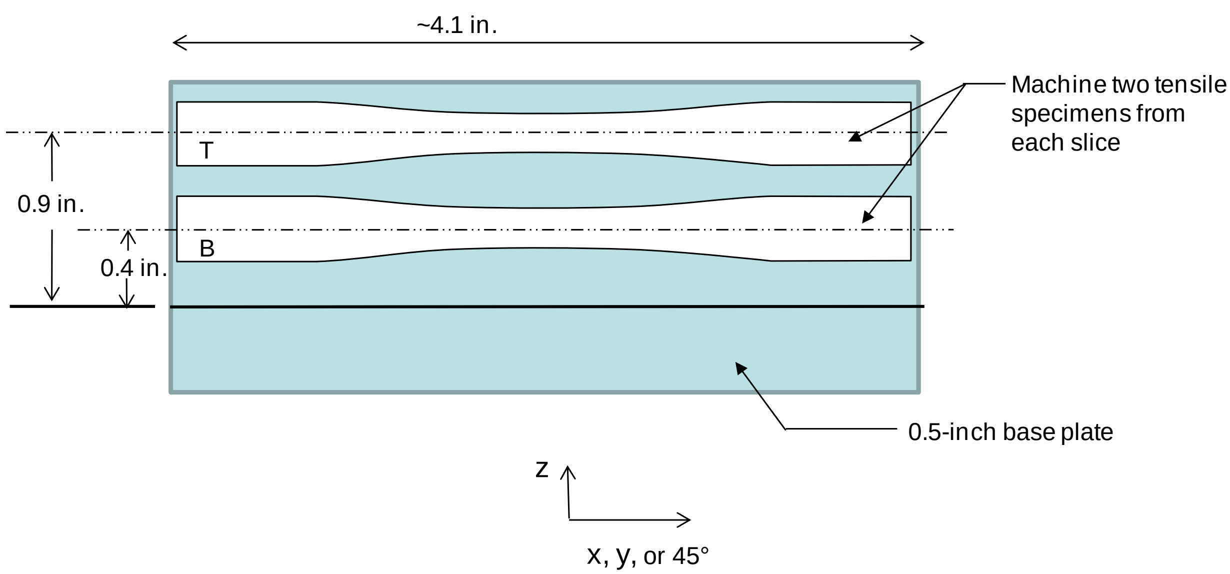

Figure 5. **Tensile specimen locations within block build slices**

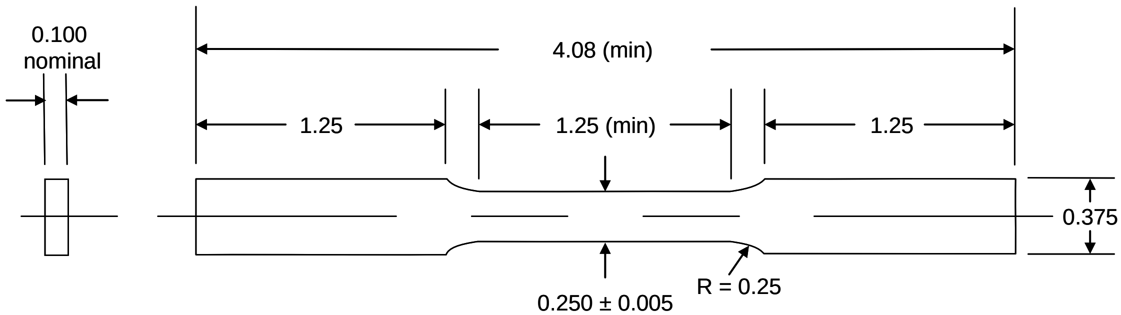

Figure 6. **ASTM E8 standard subsized tensile specimen (ref. 5). All dimensions are in inches with tolerance of ±0.010, unless noted.**

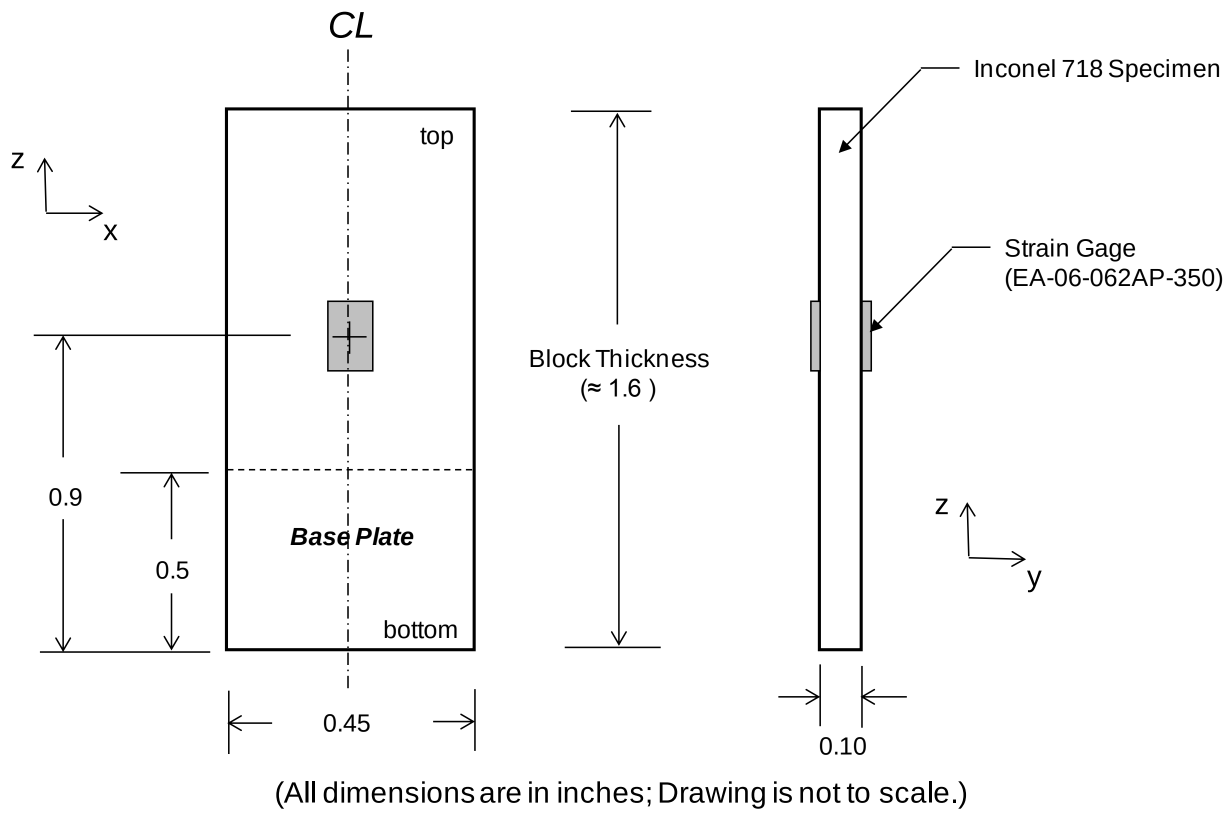

Figure 7. **Through-thickness modulus specimen.**

Precision modulus test procedures

Precision modulus tests were conducted at room temperature on the specimens in the longitudinal, transverse, and 45° orientations in accordance with ASTM specification E111 (ref. 6). Strain was measured using back-to-back extensometers with 1-inch gage length. The extensometers were calibrated to a full scale value of 1% strain for the modulus tests. Each specimen was loaded at a displacement rate of 0.010 in/min to a strain level of 0.1% and unloaded. This process was repeated at least three times. The precision modulus (E_{prec}) was calculated by taking a linear regression of the stress-strain data from the loading portion of each test.

Although the through-thickness specimens did not conform to the standard specimen configuration, ASTM specification E111 was used as a guide to generate estimated modulus values in the through-thickness orientation. Strain gages with 0.062-inch gage length were used to measure strain for these specimens. The through-thickness specimens were tested using the same loading procedures described above.

Tensile test procedures

Tensile tests were conducted at room temperature on the longitudinal, transverse, and 45° specimens in accordance with ASTM specification E8 (ref. 5). No tests in the through-thickness direction were conducted. Strain was measured using back-to-back extensometers with 1-inch gage length and a maximum extension range of 0.5 inch (50%). The specimens were loaded at a displacement rate of 0.010 in/min until a strain of 2% was attained; then the displacement rate was increased to 0.050 in/min until specimen failure. Ultimate tensile strength (UTS), 0.2%-offset yield strength (YS), total strain to failure (e_{tot}) and ductility in terms of plastic strain to failure (e_p) were calculated from the stress-strain data.

Microstructural Analysis

Microstructures were analyzed using optical microscopy. Bulk composition of the block build and the wire feed stock was measured using direct current plasma emission spectroscopy.

Results and Discussion

Chemical Composition

Table 1 shows the chemical compositions measured for the Inconel 718 feed wire, EBF^3 block build, and base plate. For comparison, the Aerospace Materials Specification (ref. 7 and 8) and the nominal composition (ref. 3) are shown. The specification is for both investment casting and wrought product forms (sheet, foil, strip, plate). The wire, block, and base plate have compositions that conform to the specification. The EBF^3 block and base plate have very similar compositions. A small decrease in Cr content and corresponding increase in Ni content was seen when comparing the deposited block with the feed wire. Although small (1.5 weight percent), this Cr and Ni elemental content difference between the wire and deposit is inconsistent with previous Inconel 718 EBF^3 builds in which there was virtually no difference between the feed wire and deposit compositions (ref. 4).

Table 1. Composition of Inconel 718 feed wire, EBF^3 block build, and base plate.

Element	Composition (wt %)				
	Specification (ref. 7, 8)	**Nominal** (ref. 3)	**0.045-in wire**	**EBF^3 block**	**base plate**
Ni	50.00 - 55.00	bal.	52.5	54.0	53.7
Cr	17.00 - 21.00	19	19.6	18.1	18.2
Fe	balance	18	17.8	17.5	17.9
Mo	2.80 - 3.30	3	3.0	3.2	2.9
Nb	4.75 - 5.50	---	5.3	5.3	5.2
Ta	0.05 max	---	0.0	0.0	0.0
Nb + Ta	----	*5.1*	*5.3*	*5.3*	*5.2*
Ti	0.65 - 1.15	0.9	0.9	1.0	1.0
Al	0.20 - 0.80	0.5	0.5	0.5	0.5

Tensile Properties

Modulus

Previous work (ref. 4) on EBF^3 narrow wall builds and a 1-inch-wide by 1-inch-tall block build showed that the modulus in the direction of deposition was significantly less than that of conventionally-processed Inconel 718. One of the objectives of this activity was to evaluate the modulus as a function of orientation within the block. Table 2 shows the modulus measured in four different orientations. Specimens labeled with "B" were machined from the bottom portion of the EBF^3 deposit and specimens labeled with "T" were machined from the top portion (refer to Figure 5). The modulus of the block build in the direction of deposition was approximately 20 Msi, which was significantly less than the 28.7-Msi longitudinal modulus of conventional Inconel 718 plate. The transverse modulus of the EBF^3 block build was approximately 28 Msi, which was much closer to the conventional plate transverse modulus of 29.9 Msi. The EBF^3 block modulus in the 45° orientation was similar to the modulus of the conventional plate. The modulus of specimens taken from the bottom portion of the block was consistently greater than for specimens machined from the top portion. The average estimated modulus in the through-thickness direction was 26.8 Msi. However, a substantial level of scatter was observed among the four specimens tested in this orientation. The data indicate a significant level of anisotropy within the EBF^3-deposited block. The modulus varies as a function of orientation as well as location within the block.

Table 2. Modulus of EBF^3 Inconel 718 block build.

Orientation	Location from block	Spec. No.	E_{prec} (Msi)
Longitudinal	top	A1T	19.6
		A2T	19.7
		ave	**19.7**
	bottom	A1B	20.0
		A2B	20.3
		ave	**20.2**
Transverse	top	B1T	27.9
		B2T	27.9
		ave	**27.9**
	bottom	B1B	28.7
		B2B	28.0
		ave	**28.3**
45°	top	C1T	28.5
		C2T	29.7
		ave	**29.1**
	bottom	C1B	31.4
		C2B	30.5
		ave	**30.9**
Thru-Thickness (a)	bottom	Z1	28.6
		Z2	27.6
		Z3	26.3
		Z4	24.5
		ave	**26.8**
Ref. Data (ref. 9)	rolled plate (0.250-in thick)	Long.	**28.7**
		Trans.	**29.9**

(a) Modulus estimate; Specimens did not conform to ASTM specification E111.

The narrow wall builds from the previous deposition study had an average modulus of 23 Msi in the direction of deposition (ref. 4). The large bulk block from the current study had modulus values in the range of 12% to 15% less than the wall builds.

Strength and Ductility

Table 3 shows the tensile properties measured for the block build as well as reference properties for conventionally-processed Inconel 718 (rolled plate and castings). The average UTS and YS values of the EBF^3 block were greater than those for as-cast Inconel 718 and less than those for rolled Inconel 718 sheet. This result is expected since the EBF^3 process is essentially a rapid-solidification casting process and does not include mechanical deformation processing associated with the rolled product. As was seen with the modulus, a significant level of anisotropy with respect to orientation and location was observed for strength and ductility.

Location within the block had a greater effect on strength than did specimen orientation. Specimens machined from the bottom portion of the block had YS values ranging from 20% to 28% greater than YS values for specimens from the top portion of the block. UTS values for specimens from the bottom portion of the block were 4 to 10% greater than for specimens from the top portion of the block. Transverse and 45° specimens had similar YS values, with the lowest YS values being associated with the longitudinal orientation. However, transverse specimens exhibited the lowest UTS values while longitudinal and 45° specimens had similar UTS values.

Ductility (e_p) was also affected by location and orientation within the block. Ductility in the longitudinal direction was greater than that for the other orientations and was relatively independent of location within the block. Transverse specimens had moderately greater ductility than did the 45° specimens. For the transverse and 45° orientations, ductility was significantly greater for specimens machined from the top portion of the block than for those taken from the bottom portion of the block. In most cases, the ductility levels for the EBF^3 block were similar to or greater than the nominal ductility for Inconel 718 plate and castings. However, the ductility in the 45° and transverse directions of specimens machined from the bottom portion of the block was lower than that for the conventionally-processed material.

The narrow wall builds from the previous deposition study had an average YS and UTS of 84.4 ksi and 132.6 ksi, respectively, in the direction of deposition (ref. 4). The specimens machined from the top of the large bulk block from the current study had YS and UTS values very similar to those of the wall builds. However, the specimens taken from the bottom portion of the bulk block had strength values significantly greater than those from the wall builds. These strength differences may be attributed to cooling rate differences through the block thickness. The ductility of the wall builds averaged 22.6% (ref. 4). The bulk block had ductility in the direction of deposition ranging from 25% to 45% greater than that for the wall builds. These data indicate that the bulk block properties were not completely representative of a narrow EBF^3 wall build, but the primary purpose of the bulk block was to determine orientation effects that could not be adequately measured with the narrow wall builds.

Table 3. Tensile properties of Inconel 718 EBF^3 block build.

Orientation	Location from block	Spec. No.	UTS (ksi)	YS (ksi)	e_{tot} (%)	e_p (%)	Notes
Longitudinal	top	A1T	136.1	86.6	30.6	29.9	(a)
		A2T	134.4	86.2	32.8	32.1	
		ave	**135.3**	**86.4**	**32.8**	**32.1**	
	bottom	A1B	150.1	105.1	29.1	28.4	
		A2B	146.5	102.0	29.8	29.1	
		ave	**148.3**	**103.6**	**29.5**	**28.8**	
Transverse	top	B1T	133.7	90.5	20.7	20.2	
		B2T	132.7	90.8	20.7	20.3	
		ave	**133.2**	**90.7**	**20.7**	**20.3**	
	bottom	B1B	137.0	113.1	7.1	6.6	
		B2B	139.6	111.3	10.4	9.9	
		ave	**138.3**	**112.2**	**8.8**	**8.3**	
45°	top	C1T	137.2	88.5	26.1	25.7	
		C2T	140.5	90.5	26.3	25.9	
		ave	**138.9**	**89.5**	**26.2**	**25.8**	
	bottom	C1B	144.2	113.4	8.9	8.4	
		C2B	154.3	115.3	14.3	13.8	
		ave	**149.3**	**114.4**	**11.6**	**11.1**	
Ref. Data (ref. 9)	rolled plate (0.250-in thick)	Long.	**198.5**	**171.5**	**----**	**21.5**	
		Trans.	**199.3**	**175.2**	**----**	**19.8**	
Ref. Data (ref. 3)	as-cast		**114.0**	**70.8**	**----**	**22.0**	

(a) Specimen did not fail; strain values not included in average.

Microstructural Analysis

Figure 8 shows low magnification views of the transverse microstructure of the Inconel 718 block build in the regions representative of the "top" and "bottom" tensile specimen locations. The longitudinal microstructure is shown in Figure 9. The layered nature of the microstructure is apparent. Figure 10 shows higher magnification views of the microstructure in the longitudinal orientation. The microstructure consisted of a dendritic structure resultant from the rapidly solidified melt pool. The regions of the block closest to the base plate exhibited small colonies of fine dendrites. These colonies were for the most part confined to individual deposition layers. The regions farther away from the base plate tended to have larger colonies of coarser dendrites with a significant fraction of the dendrites extending across multiple layers in the through-thickness (z) direction. The tendency for the bottom portion of the block to have greater yield and ultimate tensile strength than the top portion is most likely related to these through-thickness differences in dendrite structure.

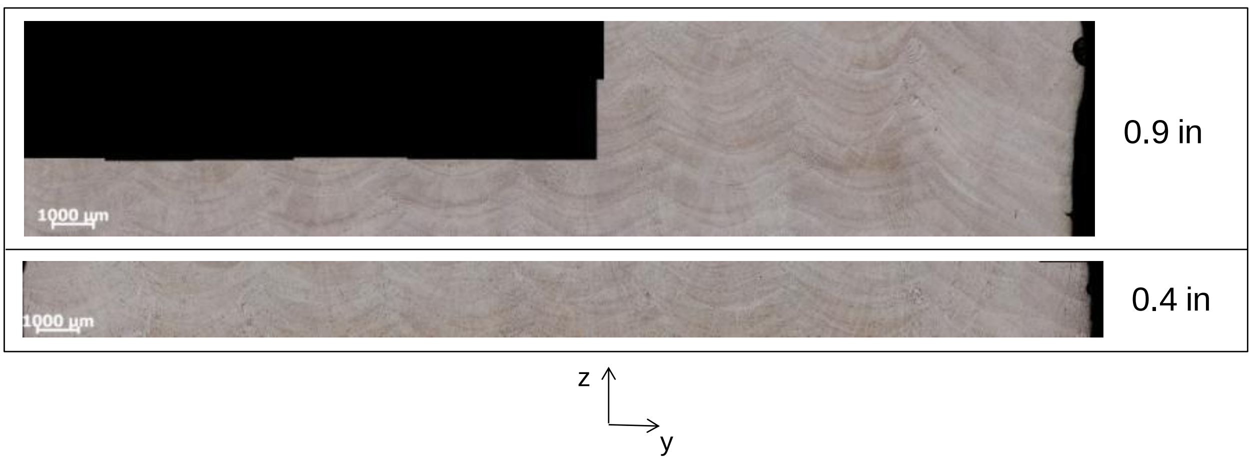

Figure 8. Low magnification view of microstructure of EBF^3-deposited Inconel 718 block build at 0.4 inch and 0.9 inch above the base plate interface. (Deposition direction is normal to the page.)

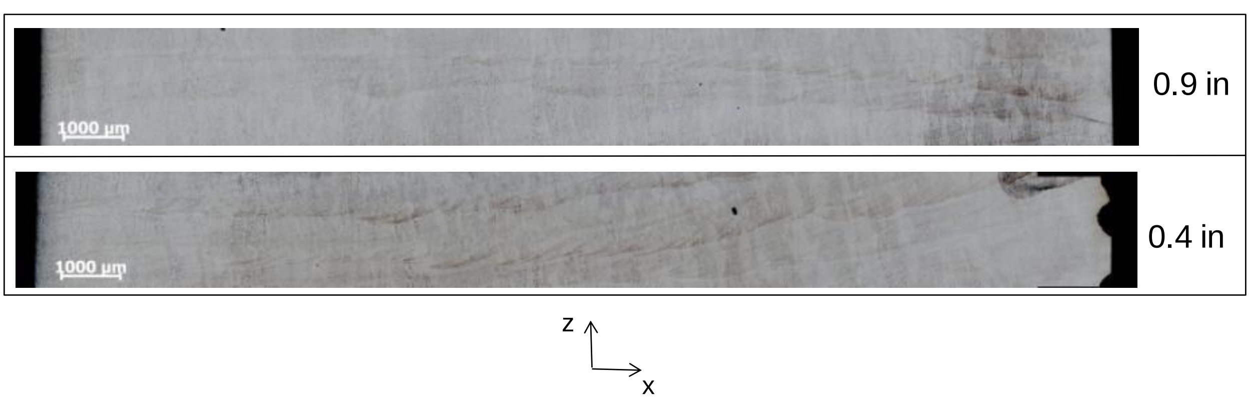

Figure 9. Low magnification view of microstructure of EBF^3-deposited Inconel 718 block build at 0.4 inch and 0.9 inch above the base plate interface. (Deposition direction is from side to side.)

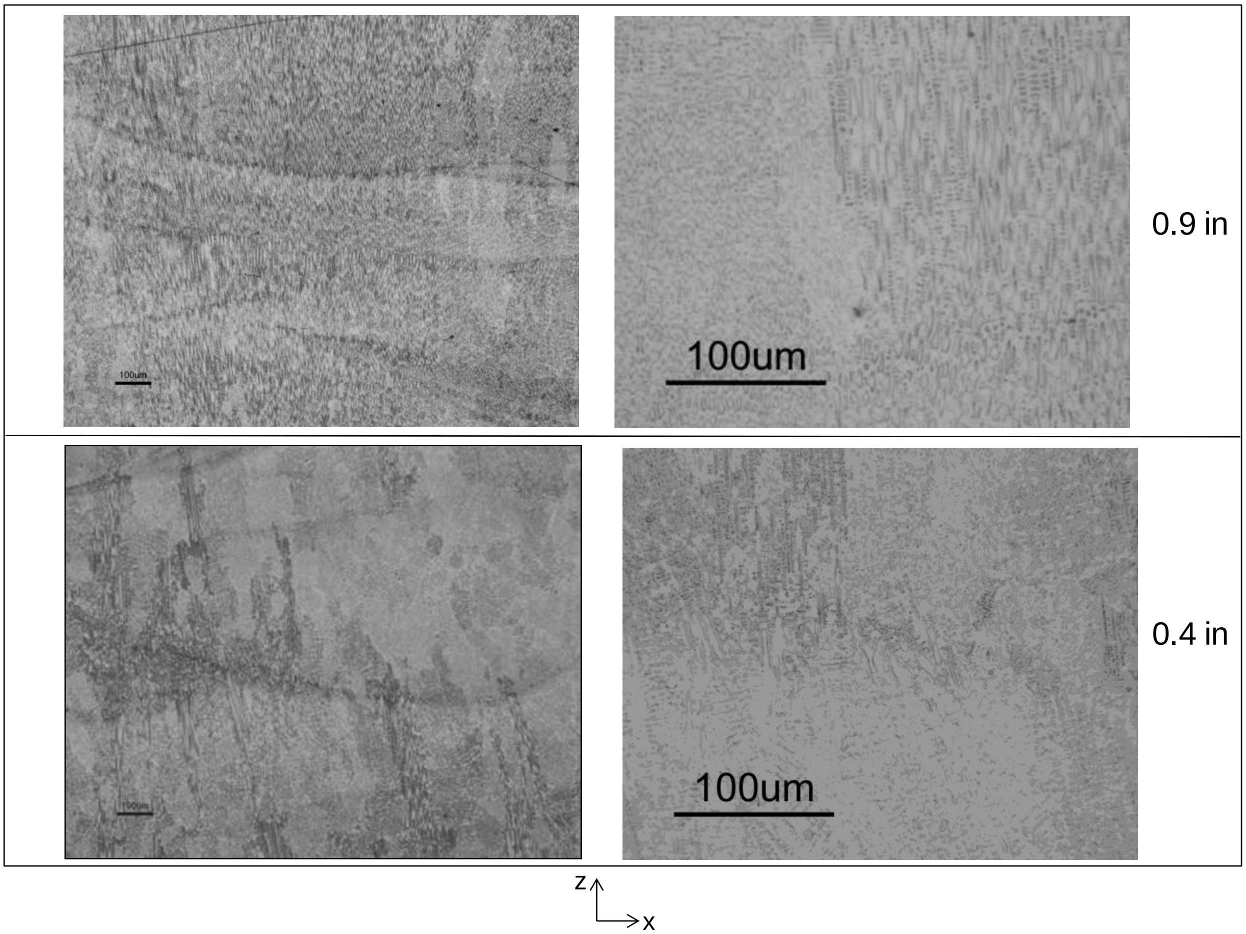

Figure 10. Higher magnification views of microstructure of EBF³-deposited Inconel 718 block build at 0.4 inch and 0.9 inch above the base plate interface. (Deposition direction is from side to side.)

The through-thickness microstructural variations are caused by the decrease in cooling rate during the deposition process. As the block is being fabricated during the EFB³ process, each deposition layer adds more heat to the block. The cooling rate of the deposited material decreases as the heat level in the block increases. Thus, the regions of the block closest to the base plate were subjected to greater cooling and solidification rates than were the regions farther away from the base plate. In addition to the variations in dendrite structure, it is likely that the deposition and solidification processes produced a preferred orientation within the build. The modulus dependence on orientation suggests a textured crystal structure that results in low and high modulus orientations within the block. A more extensive microstructural analysis will be required to verify and quantify this preferred orientation.

Concluding Remarks

Electron beam freeform fabrication (EBF^3) direct metal deposition processing was used to fabricate an Inconel 718 bulk block deposit. Room temperature tensile properties were measured as a function of orientation and location within the block build. This study is a follow-on activity to previous work on Inconel 718 EBF^3 deposits that were too narrow to allow properties to be measured in more than one orientation. Although this block configuration is not considered a product form for which EBF^3 offers practical advantages over wrought product forms, the large bulk deposit was needed to allow measurement of mechanical properties in multiple directions.

The tensile strength and yield strength of the as-deposited material from the block build were greater than those for conventional Inconel 718 castings. Since the EBF^3-deposited material had no cold work, the strength levels were lower than those for conventional cold-rolled plate. The tensile test results indicated a significant degree of anisotropy. Specimens machined from the bottom portion of the block had greater strength than those machined from the top portion of the block. The strength in the 45° direction tended to be greater than that in the longitudinal and transverse directions. In most cases, the ductility levels for the EBF^3 block were equal to or greater than the nominal ductility for Inconel 718 plate and castings. However, the ductility in the 45° and transverse directions of specimens machined from the bottom portion of the block were lower than the ductility for the conventionally-processed material.

Previous work had shown that the EBF^3 process resulted in a low modulus value in the deposition direction for narrow Inconel 718 builds. One objective of this activity was to evaluate the modulus in other directions. The results confirmed a low modulus in the direction of deposition. The modulus values transverse and 45° to the direction of deposition were approximately equivalent to the nominal modulus for Inconel 718 plate. Since the EBF^3 block was not thick enough to allow standard specimens to be fabricated in the through-thickness direction, non-standard specimens were used to obtain a modulus estimate in that direction. The through-thickness modulus value was intermediate between that for the deposition direction and that for the transverse direction.

The tensile properties of the bulk block in the direction of deposition were compared to those for narrow wall builds fabricated in the previous study (ref. 4). The data indicated that the bulk block properties were not completely representative of a narrow EBF^3 wall build. However, the primary purpose of the bulk block build was to determine relative orientation effects that could not be adequately measured with the narrow wall builds.

The microstructure consisted of a layered distribution of dendrite colonies resultant from the rapid solidification of the EBF^3 deposits. The size of the dendrites and the colonies varied through the block thickness due to decreases in the cooling rate of the deposited materials as the deposition of the block progressed. A more detailed analysis of microstructure and crystallographic orientations of EBF^3-deposited Inconel 718 is required in order to better understand the relationship between the deposition process and the properties, especially the low modulus values.

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14. ABSTRACT
Electron beam freeform fabrication (EBF3) direct metal deposition processing was used to fabricate an Inconel 718 bulk block deposit. Room temperature tensile properties were measured as a function of orientation and location within the block build. This study is a follow-on activity to previous work on Inconel 718 EBF3 deposits that were too narrow to allow properties to be measured in more than one orientation.

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